

**Title:**

Pilot Validation of a Computational Seated Human Model Using an Instrumented Chair

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**Abstract:**

This Master Thesis concerns the ethiology behind sitting-acquired deep tissue injuries (SADTI) that are the most serious type of pressure ulcers. In order to investigate the ethiology of SADTI a new approach under development. A musculo-skeletal model can predict forces at different seated positions and thereby find an optimum position where the risk of SADTI is minimized. This study focuses on validation of a musculo-skeletal model developed in the AnyBody Modeling System for predicting reaction forces on a wheelchair. A Wheelchair with force-measuring equipment was developed, an experiment was conducted, and the experimental results were compared with the predictions of the computational model. The results show that the model predicted the changes in reaction forces due to changes in the chair posture well. It was concluded that the experimental approach is satisfactory and more experiments should be carried out to completely validate the computational model.



# Master Thesis:

## *Pilot Validation of a Computational Seated Human Model Using an Instrumented Chair*

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### Content

Preface.....	5
1 Introduction.....	7
1.1 Pressure Ulcer Background .....	7
1.2 The Modeling Approach.....	8
2 Methods and Materials .....	11
2.1 Developing a Prototype Wheelchair for Testing Purposes .....	11
2.2 Designing the Experiments.....	18
2.3 Post Processing of Data .....	22
2.4 The AnyBody model .....	26
3 Results .....	33
3.1 Backrest Height .....	33
3.2 Relative Angle between Backrest and Seat While Seat is Horizontal .....	35
3.3 Seat angle .....	37
3.4 Other Results.....	40
<b>Appendix .....</b>	<b>43</b>
4 Homepage developing.....	45
4.1 Background.....	45
4.2 Where and How .....	45
4.3 The Menu .....	47
4.4 Conclusion .....	48
5 Able-bodied Vs. Paraplegic subjects.....	49
6 Force Measurements (Worst case estimate) .....	51
6.1 Worst case .....	51
6.2 The Backrest .....	52
6.3 The Footrest .....	52
7 Recording kinematic and force data .....	53

8 Thoughts on what to measure and why? .....	55
9 Literature study .....	57
9.1 Purpose .....	57
9.2 Search strategy.....	57
9.3 Experimental sitting related to pressure sores .....	57
9.4 Computational models of the buttock area .....	62
9.5 Cell response to stresses caused by sitting .....	64
9.6 Pressure Sore in General .....	65
10 Biomechanics Theory and Modelling .....	67
11 Matlab Scripts.....	81
11.1 Kinematic post processing.....	81
11.2 Force Post Processing.....	87
11.3 Generating the Input File for AnyBody .....	88
12 References .....	91

## Preface

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This project report is made based on the work done by Christian Gammelgaard Olesen as the 10<sup>th</sup> semester Master Thesis at the Department of Health Science and Technology, Aalborg University, Denmark.

The work that has been done should be seen as a small part of a greater Ph.D. project that will be conducted after the student receives his Master. Therefore some of the perspectives are a bit greater than what has been possible to during the relative short 10<sup>th</sup> semester, however they are meant to be accomplished during the consecutive Ph.D. project.

The report is constructed as two parts. The first and most important part is a paper written as a scientific journal paper. The second part consists of various worksheets supporting the paper. The report is basically built up the same way as the paper, but in greater detail. Each chapter holds all the information for the part of the paper with the same name as the chapter in the report. For example taking the first chapter in the report is called Introduction, this chapter is a worksheet that holds the reasoning behind the introduction in the paper. The report part of the project is in worksheet format, meaning that typos and grammatically errors can be present. The main focus should be at the paper.

At the end of the report there is an appendix, which is also worksheets written mainly for own purpose. For example there is a worksheet about basic mechanics, which was written because of the authors' background as a biomedical engineering student, and therefore did not know much about mechanics, which was a knowledge that was necessary to understand the literature on the pressure ulcer area.



# 1 Introduction

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## 1.1 Pressure Ulcer Background

Pressure ulcers are defined by the National Pressure Ulcer Advisory Panel (NPUAP) as a localized injury to the skin and/or underlying tissue usually over a bony prominence, as a result of pressure, or pressure in combination with shear and/or friction. A number of contributing or confounding factors are also associated with pressure ulcers; the significance of these factors is yet to be elucidated. [1]

As the definition also says there are several kinds of pressure ulcers, where the ones we are most interested in, is the sitting acquired pressure ulcers (SAPU) that are common for spinal cord injured (SCI) patients to get and therefore are feared. Spinal cord injured patient's sits in their wheelchair all day and because the tissue is not relieved from loading is in great risk of getting pressure ulcers. Healthy individuals don't get pressure ulcers, not even when sitting at an office chair all day, one reason could be because healthy individuals feel discomfort before it gets lethal for the tissue, and due to the discomfort feeling, healthy individuals would shift seating position and the soft tissue would be relieved from loading.

In SCI patients SAPU most often appear in the soft tissue regions underneath the buttock. They appear where the soft tissue is compressed between bony prominences and the supporting surface of for instance the wheelchair. [2] Anatomically around 65% of SAPU occur underneath the ischial tuberosities, sacrum, coccyx and trochanteric region of the buttocks. [2]

There are different stages of pressure Ulcers and a staging system has been made by NPUAP, where they divide the pressure ulcers into four different stages plus one unstageable. They start from stage I which is a spot on the skin that is different from the surrounding skin. Stage II is more like a small wound where there are a thickness loss of dermis or a serum filled blister. Stage III is tissue loss with fat visible but not bone and muscles. There could be undermining or tunneling caused by deep tissue injury. Stage IV Exposed bone or muscle and often include undermining or tunneling caused by deep tissue injury. [1]

The deep tissue injury (DTI) is the worst kind of pressure ulcers because they can spread underneath the skin without giving any warning. They can be hard to detect before spreading is extensive. Often they show them self on the skin as a localized purple area, just like it would be a stage I ulcer, but even though the skin is intact they can be spread out underneath. The DTI can be lethal to the patient if they are not detected in time. [3]

### 1.1.1 Focus of this project

This project will focuses on the sitting acquired deep tissue injury (SADTI) that occur on SCI patients. Little is known about the etiology of SADTI and how it is related to the sitting posture. The large amount

of confounding factors makes it hard trying to understand how the pressure ulcers develop and the understanding is not clear.

It is hard to conduct epidemiologic studies in order to characterize risk factors for SADTI, therefore not much is known about the etiology. Clinically there is usually nothing visible until the ulcer breaks through the dermis and shows up as a blister or small ulcer; however there can be a deep undermined area underneath the skin. Some cases of SADTI have spread all the way up to the shoulder from the sacral region. [4] By the time that serious tissue damage has occurred, the etiology will be impossible to understand because it will be masked by complications. Because of these problems animal studies have been carried out to investigate how muscles behave when they are subjected to loading. These studies have showed that muscles get stiffer after they have been subjected to loading which change the stresses distribution that the muscles are subjected to by a bony prominence. [5, 6] Another study by Kuroda & Akimoto [7] have showed that because of the formation of necrosis in SADTI the stress distribution change and further spreading of the necrosis will occur.

There are several studies that investigate the etiology of SADTI through finite element analysis (FEA) of the buttocks tissue. These studies have showed how the compressive and von Mises stresses acts around the iscial tuberosities. [3, 8-11] However the relationship between sitting posture and stress that the buttocks soft tissue are subjected to have not been investigated.

In order to investigate the stress distribution in the deep buttocks tissue with respect to the sitting posture a model is necessary. A lot of studies have tried to investigate the reaction forces that acts between a subject and a chair, with able-bodied subjects and SCI patients. [12-18]. They found several interesting result and located some risk factors, but not much that have contributed to a better understand of the pressure ulcer etiology. To identify how the relations between the sitting posture of a person and the stress distribution in the soft buttocks tissue a more analytical approach is necessary.

## **1.2 The Modeling Approach**

In order to model a seated person, obviously a model of a seated person is needed and that model would have to be validated in order to give the same output as if it was a real subject. Such a model can be created using the AnyBody modeling system. A human seated model is part of the free public domain repository. [19] The seated model from the repository has not been validated yet. Therefore the first task in the project will be to validate the model with respect to reaction forces on the chair. After the model has been validated it can be used to generate force data from different postures that can be used in a finite element analysis (FEA) of the relationship between seated posture and stress distribution in the human buttocks.

### **1.2.1 Validating the Model**

To validate a model means to provide evidence that the model is strong and power full for the task that it has been designed. [20] Since this model is intended to estimate reaction forces between the human model and a chair, it has to be validated with respect to that case. There are several ways of validating the seated model, one could be to develop a chair with build in load cells. A study with a few subjects



can then be set up and the reaction forces can be measured from the chair. The seated AnyBody model can be put in a posture similar to the one the subject was sitting in during the experiment. The forces acting on the chair in the modeling environment can be calculated and compared to the experimental measured forces. This approach would be validation using indirect measurement, which validate with respect to an absolute global measure. A model can in some cases be accepted as valid even though the model does not provide the correct absolute values. For instance a model can be validated with respect to trends. [20] In this case that could be that the reaction force and shear force acting on the seat of the chair, decreases and increases respectfully when the backrest angle increases. If this is true in the model and in the experimental setup then that would be a validation of the model.

Since the model is intended to give output that can help understanding the etiology of pressure ulcers, and people who get pressure ulcers are SCI patients, it would make sense to validate the chair with respect to this group of people. However doing experiments with SCI patients are not trivial, especially because of all the unknown factors as how paralyzed are the subject, is the sitting postures correct, and what is correct? Instead of doing experiments with SCI patients assumptions based on the literature regarding differences between sitting posture of SCI patients and able-bodied subjects.

SCI patients all sit differently and they need various types of support, which they would get with their own wheelchair that is fitted to them by a therapist. It is simply impossible to fit a prototype wheelchair with force plate and load cells to a SCI patient. It would simply be subjective assessment if the patient was sitting right or wrong. Instead of doing experiments on SCI patients, able-bodied subjects will have to do, later the assumptions regarding the differences between the two groups can be used. For instance Shirado, O et al (2004) [21] showed that SCI patients have a rotated pelvis compared to able-bodied which matches the findings of Bennett et al. (1984) and Hobson, D.A. (1992) [14, 16] that both saw greater shear force in paraplegic patients than normal subjects.

Therefore this project will have the goal to validate the seated AnyBody model using direct measurements and trends on normal subjects.



## 2 Methods and Materials

### 2.1 Developing a Prototype Wheelchair for Testing Purposes

In order to validate the seated AnyBody model a prototype chair with force measurement equipment had to be developed. The chair with build in load cells and force plate was build on a wheelchair frame with help from Wolturnus A/S, a Danish company that develops wheelchairs.

#### 2.1.1 Purpose

The purpose of building a wheelchair with build in load cells is to validate the Seated Human AnyBody model with respect to normal and shear forces acting on the different parts of the chair. The seated AnyBody model can be used as a powerful tool when designing office chairs, automotive seats and obviously wheelchairs. The model is like every other model only powerful when it is a good predictor for whatever situation it has been designed. Therefore it is necessary to validate the model towards its purpose of estimating normal and shear forces acting on a chair that a person is sitting on.

#### 2.1.2 Design Criteria's

Before designing the chair a set of minimum criteria's had to be set up. The criteria's were based on how a normal wheelchair works; therefore the setup was built on a wheelchair frame. Changing backrest inclination angle, seat angle and so on are possible adjustments on normal wheelchairs and therefore these adjustments should be possible to make at the test chair.

The criteria's were sketched up in a mind map that is showed in Figure 1.

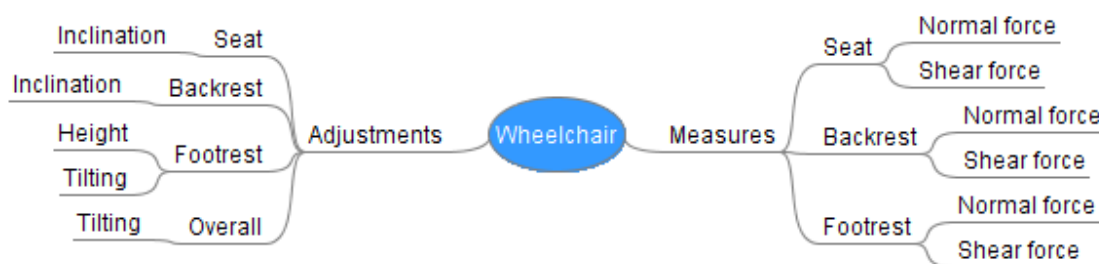


Figure 1 Show the design criteria's for the prototype wheelchair. The criteria's are divided into adjustments and measurements.

The mind map shows that there were two kinds of criterias, one that represents the adjustments that should be possible to make on the chair. The other one represent the measurement that will be necessary in order to validate the AnyBody model based on the measurements from the chair.

The adjustments represent adjustments that are normally used when fitting a wheel chair to a patient. The overall tilting is what was called squeezing by Maurer, C.L. and Springle, S. (2004). [12] The footrest

had to be designed adjustable in height and inclination because this would have a major effect on the forces measured on the seat. Obviously the backrest needed to be able to change in inclination angle. The seat also needed to be able to change in inclination angle.

The measurements were normal and shear force acting on the seat, backrest and footrest.

When designing the chair obviously the design criteria's were important but the nature of the model was also important. The AnyBody modeling system is a musculo-skeletal modeling system and the "attachment" between the chair and the model were modeled by small weak muscles attached in various sites and thereby imitating a chair seat with optimal support. During validation the weak muscles should only attach the chair and subject at the sites where there actually are contact between the chair and the back of the subject. Therefore the chair had to be designed with a backrest support that made it possible to know where the forces come from. For example it could be done with a backrest made by horizontal bars with load cells build in. It would then be possible to localize the force measurements. The numbers of horizontal bars should be as small as possible due to cost, but large enough to it will still be comfortable to lean back on the backrest.

### **2.1.3 Design Limitations**

The load cells and force plates were only available in a limited number and therefore the design of the chair had to take the available materials into consideration. The load cells that were available to this project were four AMTI FS6 where two could handle axial load of up to 1100 N and the other two up to 2200 N. The limitations of these load cells towards this project were their capability of handling moments, which was relative low. Further specifications can be found in the appendix.

The force plates that were available were of the type AMTI OR6-7 and they can withstand loads much greater than what a sitting person can subject them to. Further specifications can be found in the appendix.

### **2.1.4 Designing the Chair**

When designing the chair the above mentioned criteria's had to be fulfilled using the measurement equipment that were available in the lab. The wheelchair company Wolturnus A/S provided a wheelchair frame that the load cells and force plates could be built on top. During the design process the frame of the wheel chair was provided by the company as a CAD file, where attachments could be made to attach load cells and force plate. The load cells where drawn in Solid Works and is showed in Figure 2. The drawing is based on data from [22].

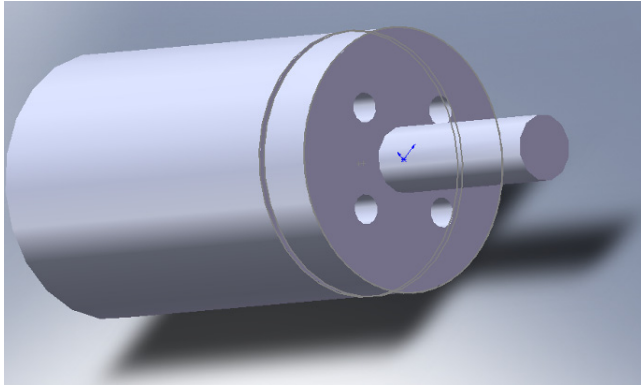


Figure 2 The load cell that are available in the lab. AMTI FS6

The force plate was also drawn in Solid works and is showed at Figure 3

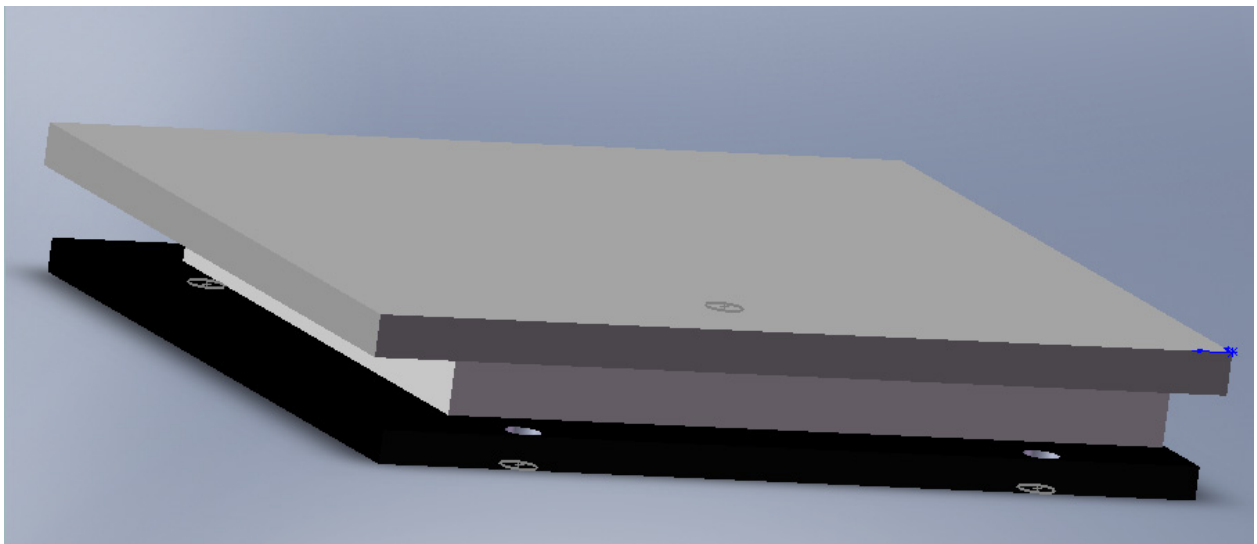


Figure 3 Drawing of the AMTI OR6-7 force plate

Figure 2 and Figure 3 illustrates the two types of measuring hardware that were available to us, the load cells and the force plates. If the limitations of the systems were taken into account it was realized that the seat of the wheelchair had to be a force plate to be sure not damaging the hardware during the experiments. The footrest could also be a force plate standing on the ground. The backrest was a bit trickier, since they should be made by a couple of horizontal bars that could slide up and down and thereby could be fitted to an individual subject.

The last piece of hardware that should be used was the wheelchair that has been kindly provided by Wolturnus A/S. The wheelchair was a W5 model and a CAD drawing can be seen at Figure 4. The wheelchair model was a basic model which the force plate and load cell should be built on to.

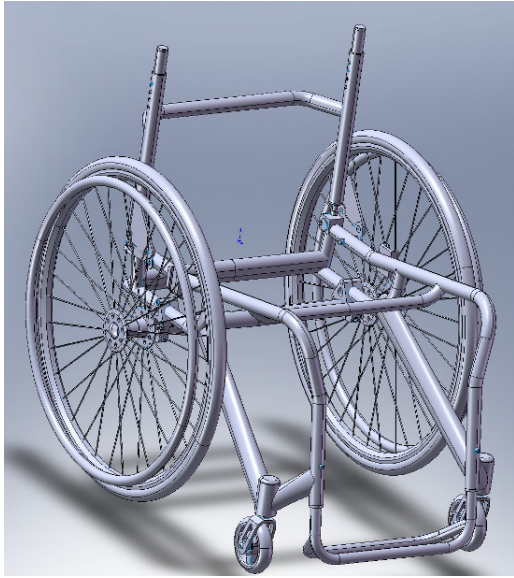


Figure 4 Drawing of the provided wheelchair frame from Wolturnus A/S. It is the W5 model.

### Fitting equipment to the chair

Fitting the measurement equipment on the wheelchair demanded a few mounting parts to be designed. The parts will be explained in the context they were used and the reasoning behind them will be given there as well. The parts will be used as an example of how a solution could look and explain the functionality that is needed. The way it is implemented does not necessarily have to be exactly the same way if for example Wolturnus A/S had a part in stock that did the same trick as one of the parts that was designed.

The first part that needed to be fitted was the force plate that needed to be mounted as the seat of the wheelchair. One design criteria said that it had to be possible to change the angle of the seat therefore there had to be designed a couple of mounts between the force plate and the wheelchair. Since there were only four holes for attachments on the force plate (one in each corner) the mount had to be constructed so it could be mounted on the force plate in a stable way with only one screw. The mounting is illustrated at Figure 5 and how the mountings are mounted on the force plate is illustrated at Figure 6. The two mounts that were attached to the force plate are the same except for the fact that they are mirrored. The seat can then be angled the way it is needed.

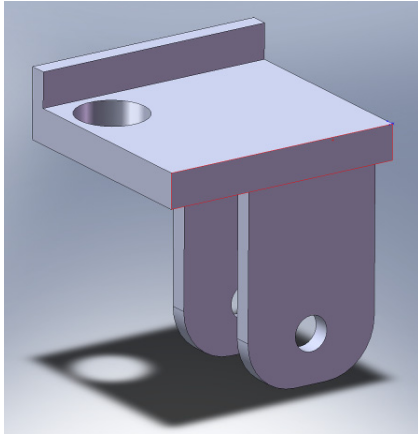


Figure 5 illustrates the mount between the force plate and the wheelchair frame that makes it possible to change the angle of the seat.

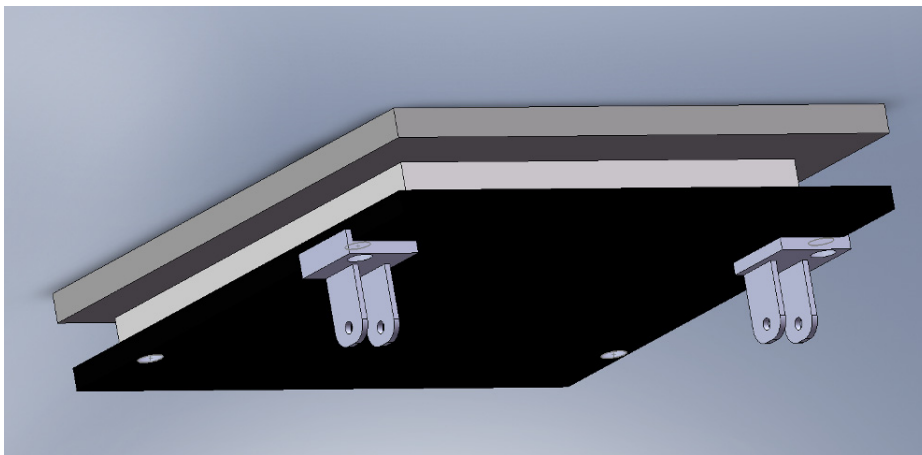


Figure 6 illustrates how the mounts fit on the force plate.

The backrest should integrate the load cells into a construction that would transfer the forces from the subjects back, when leaning against the backrest. The constructed backrest was designed to be attached to the vertical backrest bars at the wheelchair frame. The backrest consists of seven parts, where two of them are the load cells (number 2 at Figure 7). The horizontal bar that the subject will lean up against is number four at the figure. The load is then transferred to the part number three, which is two cups put together to transfer the force from the backrest bar to the load cell. The inner cup tightens the backrest bar and the outer one tightens the load cell, which is number two at Figure 7. The last piece on the figure is number one, which is the part that fastens the load cell and thereby the rest of the backrest to the vertical backrest bars on the wheel chair frame.

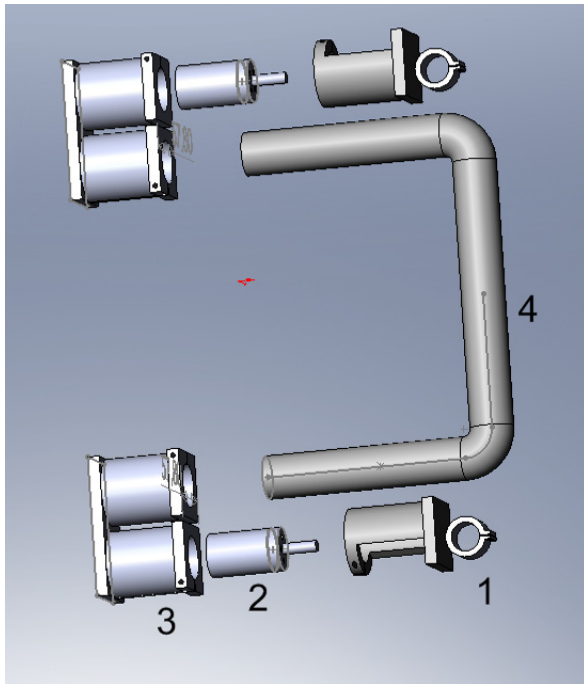


Figure 7 Show an exploded view of the backrest bar with load cells.

The backrest assembled and attached to the wheelchair is illustrated at Figure 8 which is seen from above the wheelchair.

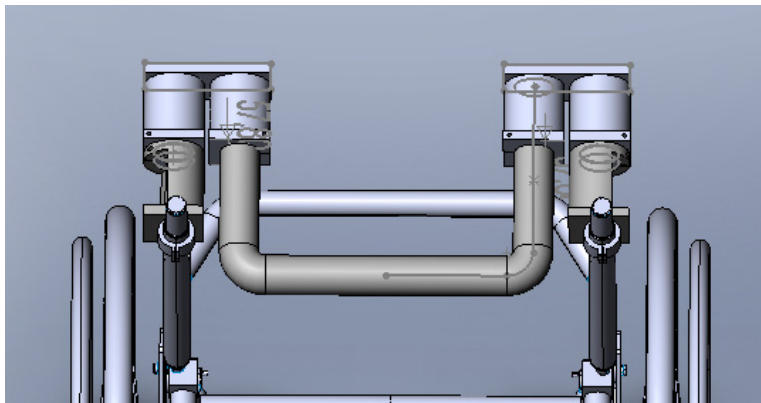


Figure 8 Show the assembled backrest attached to the vertical backrest bars from the wheelchair

### 2.1.5 Implementing the force measurer equipment at the wheelchair

Wolturnus A/S received the drawing that was made as an example of how the force measuring equipment could be fastened to the chair. The implementation was done by Wolturnus A/S therefore they changed a bit in the drawings in order to be able to use stock pieces instead of having to custom make a simple mount. All the changes were reviewed to ensure that the design criteria's were respected. The basics of the backrest bars were the same, but some of the mounts were changed, as it can be seen at Figure 9.





Figure 9 show the implemented backrest bars mounted on the wheelchair backrest.

The whole wheelchair can be seen at Figure 10 as a 3D model and after it was manufactured.

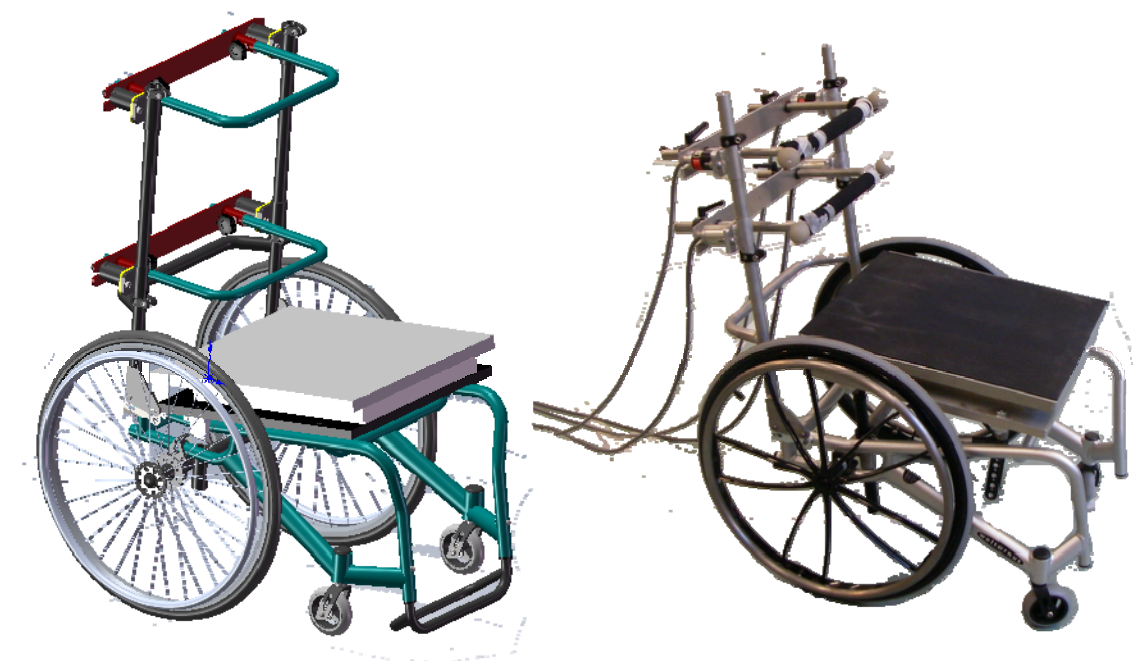


Figure 10 show the 3D model of the wheelchair and the manufactured wheelchair

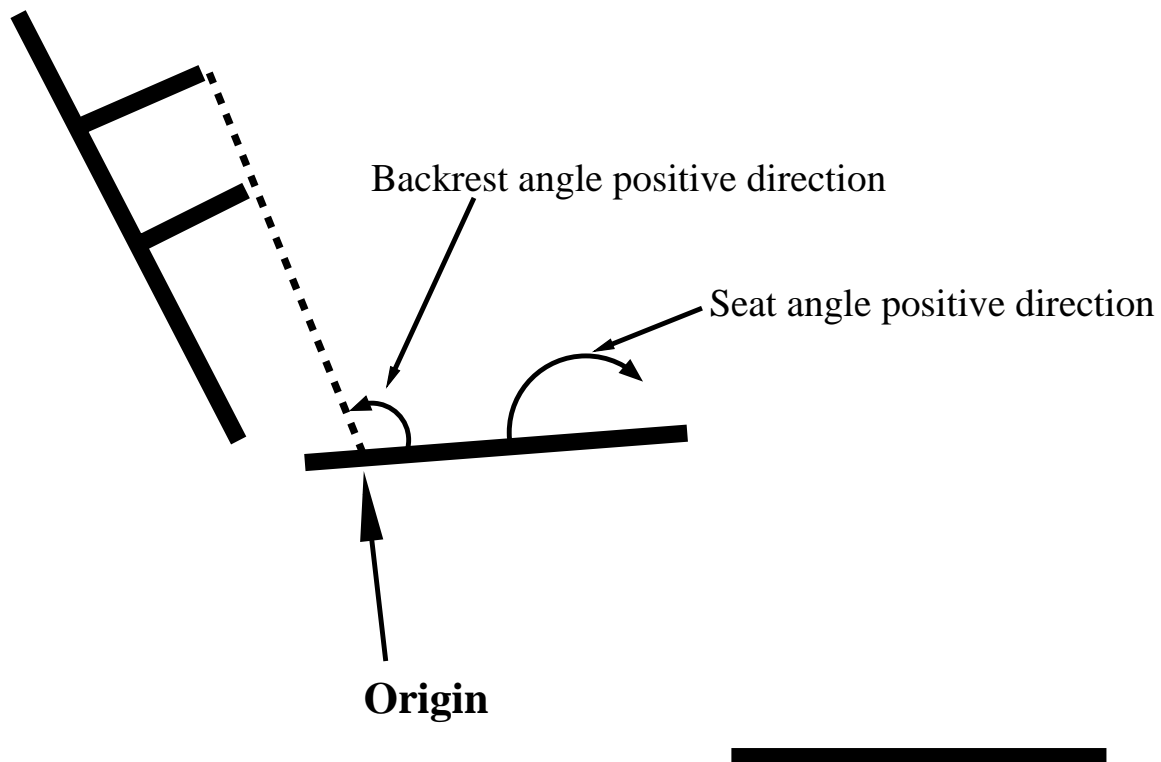


Figure 11 illustrates the positive directions for the backrest angle and seat angle

## 2.2 Designing the Experiments

Before starting the experiments a protocol had to be developed. The protocol will be the summary of this section. The first thing to consider when developing a protocol is “what is the purpose of the experiments?”

The purpose was to measure the forces acting between a chair and a subject sitting on the chair. The data measured will then afterwards be compared to a prediction of the same data, done by the Seated AnyBody model.

To validate the model with respect to absolute measures the experiment should be carried out with three different postures. The three postures should be three postures that are normal seated positions. The positions will be explained in section 2.2.2.

Mathematically the validation can then be expressed as:

$$\alpha = \sqrt{\sum_i (y_i - \hat{y}_i)^2}$$

Where  $\alpha$  is the validation measure with respect to absolute measures,  $y$  is the  $i$  measures from the experiment and  $\hat{y}$  is the prediction of the measure from the AnyBody model. The  $\alpha$ -value should then be small for all the subjects.

To be able to validate the model with respect to trends a set of seated postures with a common trend between them should be carried out. The trend could for example be that the seat-backrest angle increase between each measurement, then there should be a trend between the measured forces from the experiment, and also between the predictions from the model and further those two trends should be as close to similar as possible.

$$\beta = \sqrt{\sum_i (x_i - \hat{x}_i)^2}$$

Where  $\beta$  is the validation measure with respect to trends,  $x$  is the  $i$  trends from the experiment and  $\hat{x}$  is the trends predicted by the model.  $x$  is in this case a trend, for example a function describing a increase/decrease in force as a function of a change in backrest angle.

Some of the seated postures can be combined between the two types of validation, and thereby only need 5-6 experimental sitting postures. The sitting postures will be explained in section 2.2.2

### 2.2.1 Choosing subjects

Choosing the subjects for the experiment is related to the question: “What should be validated?” One objective with the study could be to validate the model with respect to an as broad group of people as possible, for example validate the model with respect to a skinny person, an overweight person, male, female and so on. The problem with this approach is that seated model has to be scaled relatively much, which might ruin the validation of the seated model with respect to sitting because after extensive scaling of the model it would be validation of a sitting scaled model. The scaling problem will most likely be a problem for the validation with respect to the absolute measures.

Therefore the most suitable subjects are subject that match the AnyBody model without too much scaling. The AnyBody model is constructed from different cadaver data, but should represent a 50<sup>th</sup> percentile European male, therefore the subjects should be around the size of the 50<sup>th</sup> percentile European male, i.e. weigh 79 kg and be 177 cm tall. Obviously the subjects can be of the same overall size as the AnyBody model and still have significant different anthropometric measures, therefore it can be that some scaling will be necessary.

### 2.2.2 Choosing the postures

The postures that the subjects should sit in should be as controlled as possible. The setting on the chair should obviously be the same, but also the way the subjects sit is important and should be measured.

The postures that the subjects should sit in are controlled by the settings on the chair that can be adjusted using the following parameters:

- Seat angle (SA)
- Backrest angle (BA)
- Height of backrest bars (HB)

The parameters can be set constant or changed between the different postures, what is important when validating with respect to trends is, to only vary one parameter.

All experiments should be conducted with a constant seat height

**Experiment 1:** SA = 0°. BA = 90°. HB=vary

**Experiment 2:** SA = 0°. BA = vary. HB=Constant

**Experiment 3:** SA = vary. BA = 100°. HB=Constant

The posture can still vary between the subjects even though the chair is set in the same settings. Therefore it is important to assess how the subject sits.

### **2.2.3 Posture assessment**

Since all subjects do not sit in the same posture even though the settings of the chair are the same, therefore the posture will be assessed using a ProReflex motion capture system from Qualisys with 8 cameras. To assess the posture with the Qualisys system reflective markers placed on bony landmarks are necessary. The number of markers necessary for the experiments is rather limited, since there are no degrees of freedom that need to be driven. However there are several purposes of putting markers on bony landmarks. For example to measure the length of the subjects bones and to make sure that the model have the same posture as the subject, and thereby give a better opportunity for the model to be a good predictor.

The markers should be placed at the following locations:

One marker should be placed at the Lateral Malleolus of Fibula which can be found on the lateral side of the ankle joint. One marker should be placed at the head of tibia which is can be found on the lateral lower side of the knee joint. One marker should be placed at the Greater Trochanter which can be found at the hip. One marker on the Iliac Crest which is part of the pelvis. One marker on the shoulder should be placed at the Acromion and in the end a marker on the forehead of the head.

Since the arms and the positions of these could change significantly on the output measure it is important that they are placed at the same position in all measuring situations. The positions of the arms should be assessed with markers as well as the rest of the body and those markers should be placed at the elbow and hand, more specifically at the lateral epicondyle of the humerus and at the dorsal side of the hand on the 2<sup>nd</sup> metacarpal bone.

### **2.2.4 Measuring forces**

Measuring the forces between the subject and the chair, obviously the load cells and force plates mounted on the wheelchair will be used for this purpose. The force measuring equipment will be

connected to amplifiers and analog to digital converters (ADC<sup>1</sup>) and a computer in order to sample the measured forces.

### **2.2.5 Timeline of Experiments**

The experiment was conducted with one subjects. The subject will have to go through some of the experiment three times to give a hint on how big the variation is within the same person.

### **2.2.6 Conducting the Experiment (Protocol)**

This subsection describes how the experiments was conducted.

#### **Purpose**

The purpose of the experiment was to validate the AnyBody Model, Seated Human with respect to forces acting on the seat, backrest and footrest while sitting.

#### **Hypothesis**

We hypothesize that the seated AnyBody model predicts the same normal and shear force amplitudes as measured on a subject, as well as the model predict a change in forces due to change in posture, the same way as measured.

#### **Subjects**

The subject included in the experiment should be as similar as possible to the AnyBody model, preferably a male at the size (height and weight) of the 50<sup>th</sup> percentile male.

The subject had to wear tied shorts during the experiment, to be able to palpate the bony landmarks.

#### **Measuring Equipment**

This part describes the measuring equipment used in the lab to measure the forces and posture.

##### ***Posture Assessment***

For assessing the posture Qualisys Proreflex MCU240 cameras was used for detecting passive reflective markers on the wheelchair and on the subject. The markers at the wheelchair was placed once. The markers at the subjected have to be placed at the bony landmarks listed below. The measuring was conducted over 10 seconds using a 20Hz sampling rate.

##### ***Force Measurement***

The forces was measured using the force plate and load cells built onto the wheelchair and the force plate build into the floor in the gait lab. Both force plates and load cells was connected to original amplifiers and from the amplifiers to an ADC that converts the signal to a digital signal that can be recorded by Mr. Kick. The measuring was conducted for 10 seconds with a sampling rate of 20Hz.

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<sup>1</sup> Analog to Digital Converter that converts the analog signal from the amplifiers into a digital value.

### Marker Positions

The markers were placed at the following bony landmarks while the subject sat in the wheelchair. In total a number of 16 marks were placed at the body of the subject. The markers were placed at the same places in both sides of the body in the following places:

Lateral Malleolus of Fibula

Head of Tibia

Greater Trochanter

Iliac Crest

Acromion

And one on the head

Lateral Epicondyle of Humerus

Dorsal 2. metacarpal (arms crossed over)

### Experimental Activities

When the subject came into the lab, a brief explanation of the measuring equipment was given. The subject took off all clothes except tied shorts. The markers were placed on the bony landmarks described above. The height from the floor to the posterior side of the knee was measured with a ruler from the floor to the bony landmark. The height of the footrest was adjusted so it was the same as the height of the knee. The force measuring equipment was zeroed and Mr. Kick was prepared for measurement.

The subject was carefully seated in the chair at the first position and told to sit there for 4 min. When the 4 min had passed the measurement was conducted for 10 sec. When the measurement was done, the chair was adjusted to the second position and the subject had to sit for 4 min before starting to measure. This protocol was carried out for all six positions.

When the experiments were finished the weight and height of the subject had to be measured using a scale and ruler.

## 2.3 Post Processing of Data

### 2.3.1 Measured data

The measured data from the experiment consist of force data and posture data from the motion capture system. The data should be used for two things. The motion capture data should be used to drive the AnyBody model so the model sits the same way that the subject sat in the chair. The force data should be compared with the force data that is predicted by the AnyBody model.

The first thing is the data from the motion capture program Qualisys. Each marker was identified and named as seen at Figure 12. After the naming the data was exported to a \*.tsv file that could be read by

MatLab. A script was developed in matlab that reads in the file generated from the Qualisys software. Each of the markers was identified and used for calculating inputs for the AnyBody model. Before any of the calculations were made the positions that were used for each of the markers were the mean position over the 10 seconds of sampling.

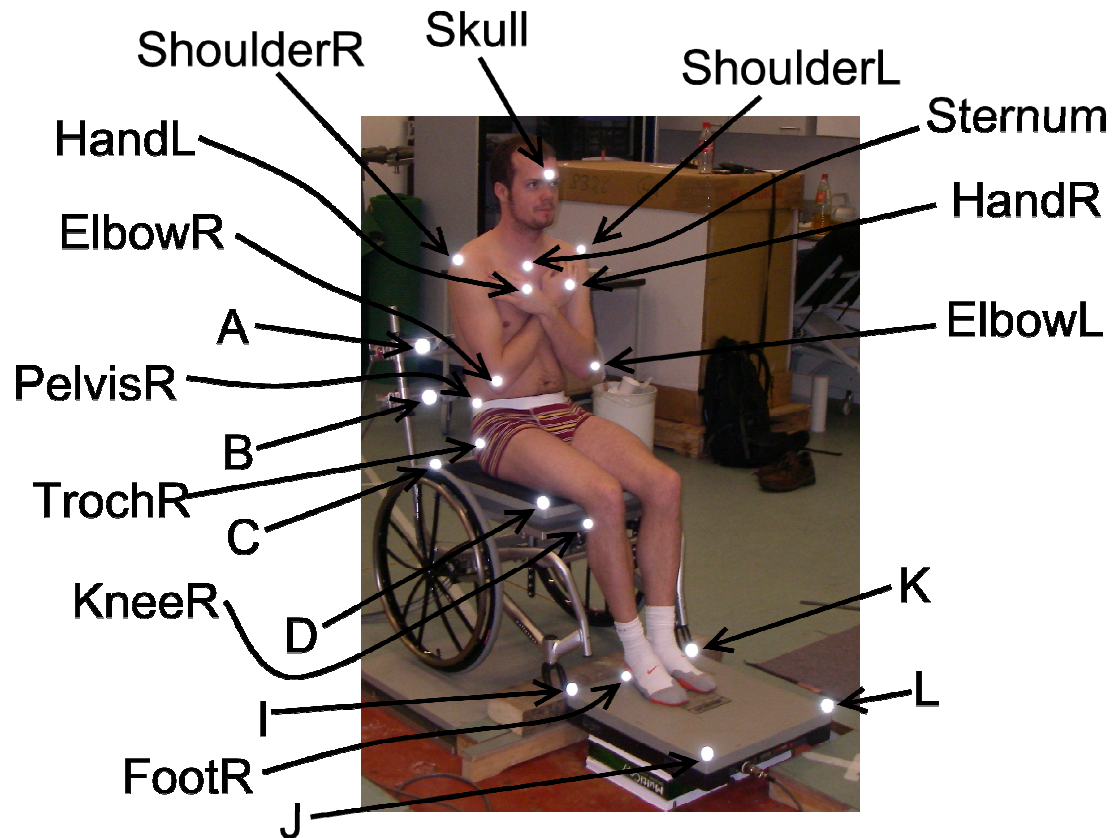


Figure 12 show some of the markers at the chair and at the subject

### 2.3.2 Environment markers from the experiment

Since the AnyBody model tries to mimic the experiment conducted, the chair settings should be the same in the model as during the experiment. There are placed 12 markers on the chair. One in each corner of the seat, two on each backrest bar and one in each corner of the footrest. Some of the markers can be seen at Figure 12 where the letters, A,B,C,D,I and J represents the six marks on one side of the chair. Marker A is representing the upper backrest bar, B is representing the lower backrest bar, C and D represents two of the four corners on the seat. I and J represent two corners of the footrest. The other side of the chair have markers names E,F,G,H,K and L.

### 2.3.3 Calculating input for the AnyBody model

The origo was estimated based on a line through the two backrest bars and down to the intersection with the seat. This position was used as the model origo and all other positions were calculated relatively to this, see Figure 11

The four markers on the seat were used for calculating the angle of the seat relatively to the vertical axis that is assumed to be aligned with the direction of gravity and checked during the calibration of the camera system with a spirit level.

The angle was calculated as the mean angle of the two sides relatively to the z-axis (vertical). The angle was calculated using the formula for the dotproduct:

$$\theta = \arccos\left(\frac{a \cdot b}{|a||b|}\right)$$

The angle of the backrest was calculated as a relative angle to the seat, therefore it was the angle between vector  $\overline{A}$  and  $\overline{D}$ . The dimensions of the seat, backrest and footrest are simply measured between the markers. The distanced between the seat and the backrest bares was calculated as the vector length of the vectors  $\overline{A}$  and  $\overline{B}$ .

The footrest position was calculated as the vertical and horizontal distance from the marker D.

### 2.3.4 The force data

The force data measured with the force plates and load cells were sampled and processed in order to compare it to the forces estimated from the AnyBody model.

The experiment included six devises for measuring forces. As described in 2.1.2. Four load cells were used for measuring the forces applied to the two backrest bars. The four load cells measured force in three directions and the moment around each axis. The Load cells that was used were the AMTI FS6. All six channels were sampled from all four load cells. The amplifiers used were two AMTI MCA-6, one AMTI DigiAmp DSA-6 and one AMTI MiniAmp MSA-6 amplifier [22]. They were all sampled using two National Instruments 16 channels ADC boards which were hooked up to a computer and they were controlled by Mr. Kick[23].

The experiment also included two force plates for measuring the forces applied to the seat and the forces applied to the footrest. The force plates were AMTI OR6-7000-1000 force plates that were connected to two AMTI MCA-6 amplifiers. One of the two amplifiers were connected to the same ADC board as the load cells and the other one was connected to a QUALISYS ADC that was controlled by the Qualisys Tracking Manager that also controlled the cameras that was used to measure the posture of the subject. The reason for another ADC was used for the foot rest force plate was that the National instrument ADC borads only had 32 channels and in total we had to measure on 36 channels. In principal lot of the channels were not interesting for the experiment, but in order to get a more accurate force measurement the cross-talk between the channels had to be used in the calculation as well.



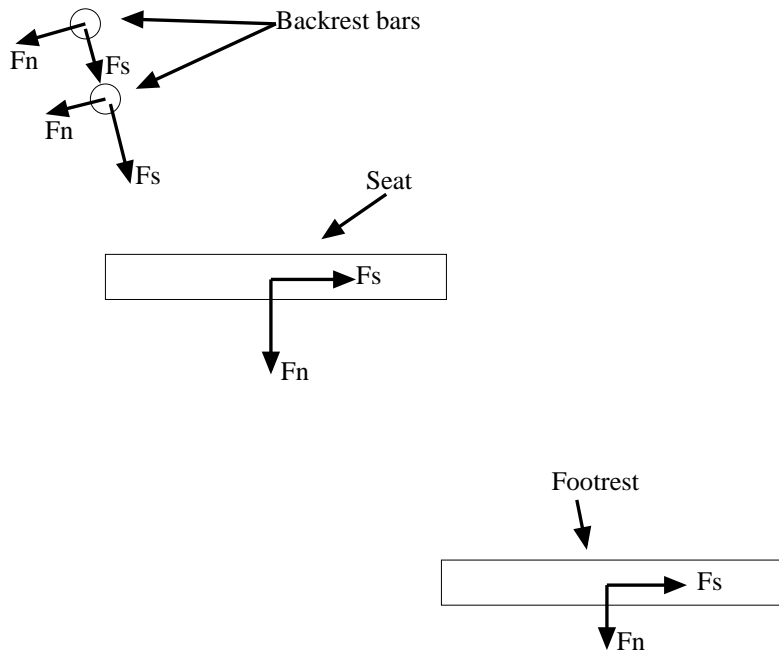


Figure 13 illustrates the positive directions of the forces from the chair.

All the force data were collected during 10 seconds using a sampling rate of 20 Hz. The amplification varied between the different force plates/load cells and was estimated during pilot studies to ensure that the voltage did not exceed the  $\pm 10V$ . Since it was static measurements it was assumed that the subject sat still during the 10 seconds only the standard filter build into the amplifiers were used because the 200 data points were averaged during the post processing.

After the data were collected it was exported from Mr. Kick and Qualisys and gathered in MatLab where the rest of the post processing was done.

### Calculating the Forces

The forces were calculated using the sensitivity matrices provided by the manufacture of the load measuring equipment. A sensitivity matrix is a 6x6 matrix where the diagonal is the sensitivity values in the three forces and the three moments for the sensor. The other values in the matrix are the covariance values that defines the cross-talk between the different channels.

The calculation looks like this:

$$V = F \cdot G \cdot V_{exc} \cdot S \cdot 10^{-6}$$

$\Updownarrow$

$$F = \frac{V}{G \cdot V_{exc} \cdot S \cdot 10^{-6}}$$

Where V is the measured voltage, F is the force, G is the gain, Vexc is the excitation voltage and S the sensitivity matrix with the unit of  $\mu V / V_{exc} / N$  so the micro volt measured divided by the excitation voltage per Newton. Using that sensitivity matrix gives us the result in Newton. This can also be done for

the moments then the unit will be Nm and the moment will be calculated with the Nm unit. The directions of the forces is illustrated at Figure 13.

## **2.4 The AnyBody model**

The AnyBody model that is being validated have to be seated in a chair that have the same characteristics as the chair that the subject sits on during the experiment. Therefore the first thing to setup is the environment in the AnyBody model. The environment consists of a chair with a seat, back- and footrest. The positions of the three parts of the chair have to be adjusted so the inclination angles are the same as the ones that the real chair have.

### **2.4.1 The seat**

The seat of the model is the part that is constrained relatively to the global coordinate system. It was constrained in all degrees of freedom (DOF) except for rotating around one axis to allow the seat an inclination angle. The last DOF is driven by a rotational measure that get the angle input from the generated input file. The model origin that all other markers in the model are positioned relatively to is positioned at the seat in the right side of the seat between the two markers. The origin can be seen in Figure 11.

### **2.4.2 The Backrest**

The backrest is build the same way as the one in the wheelchair i.e. two backrest bars. The two bars are positioned relatively to the seat and attached to the seat with a revolute joint that constrains them in all DOF except from one that allows the backrest to lean back. A driver is driving that angle with the angle calculated from the markers and written in the input file. To ensure that the places where the two bars are placed are also the places from where the human model get support from the backrest in the AnyBody model the support muscles are only allowed active if they are relatively close to the backrest bar. The attachment point at the two bars are made as a cylinder with a radius of 7 cm and if the node at the back of the model is within the cylinder the muscle is allowed to be active and create a support. The position of the backrest bars are driven from the values in the input file calculated in the MatLab functions. The angle between the bars and the seat are calculated and also the heights of the backrest bars are calculated.

### **2.4.3 The Footrest**

The footrest is places in the model also based on the positions calculated from the marker positions and it is also attached to the seat with a revolute joint, assuming it always being horizontal the revolute joint is driven with the inverse of the seat angle, recalling that the seat angle is relative to the global coordinate system.

### **2.4.4 Attachment to the chair**

The human model obviously has to be attached to the chair to apply force through to the environment. The attachment is done as also previously mentioned by very strong muscles that can push and pull. The model is attached to the seat by strong muscles between the seat and the pelvis and thighs. There are placed four support muscles between the pelvis and the seat and eight support muscles between the

thighs and the seat. Which muscles that is active is decided by the recruitment solver to figure out. The muscles can be active if the node placed at the pelvis/thigh is within a fictive cylinder, defined by a min max height and a radius. The radius is the radius of the cylinder around the center of the seat and the min/max height is then the height of the cylinder in both directions. The radius used at the seat is set to 70 cm in radius which practically means that the model can be placed everywhere on the seat and the support muscles can be used.

#### 2.4.5 The human model

The human model that should be placed in the chair obviously should be driven from the marker positions measured in the lab. The input file generated contains vectors from the origin to the markers placed at the subject in the lab. The markers placed at the subject are placed at the human model in AnyBody and those markers are driven with the vectors from the input file.

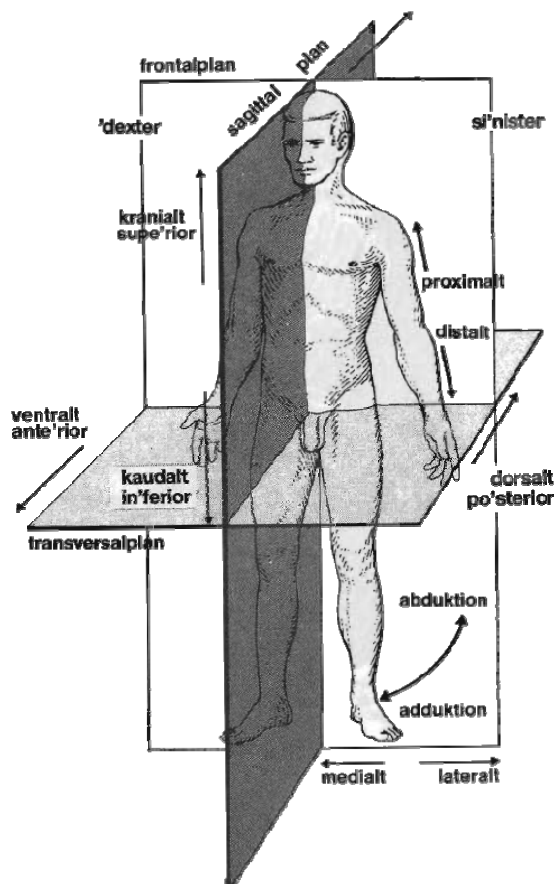


Figure 14 illustrates the anatomical directions and planes

#### Pelvis:

The pelvis is driven from two markers placed at the pelvis and at the greater trochanter, see Figure 15. The pelvis is constrained in rotating around the anterior and cranial axis, see Figure 14. It is also assumed

that the subject sits in the middle of the chair why the model is constrained laterally to sit in the middle of the seat. The three DOF that are left are driven with the two markers placed on the right side of the pelvis and on the right greater trochanter. The marker at the pelvis drives the position of pelvis in the anterior and cranial direction; the rotation of the pelvis is driven by driving the marker at the greater trochanter in the anterior direction.

#### Hip angle:

The hip angle is driven in two directions by the marker at the head of tibia one is illustrated at Figure 16 where the hip angle is driven in the cranial/caudal direction. It is also driven in the abduction/adduction direction.

#### Knee angle:

The knee angle is driven by the marker at the foot. The foot marker is illustrated at Figure 16 and is driven in the direction of the double arrow.

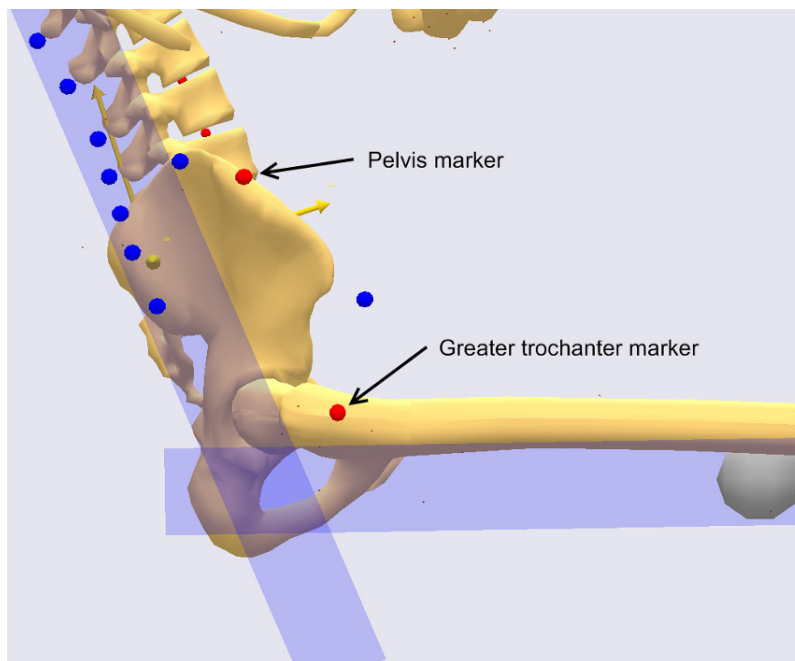


Figure 15 show the pelvis and greater trochanter markers at the AnyBody model

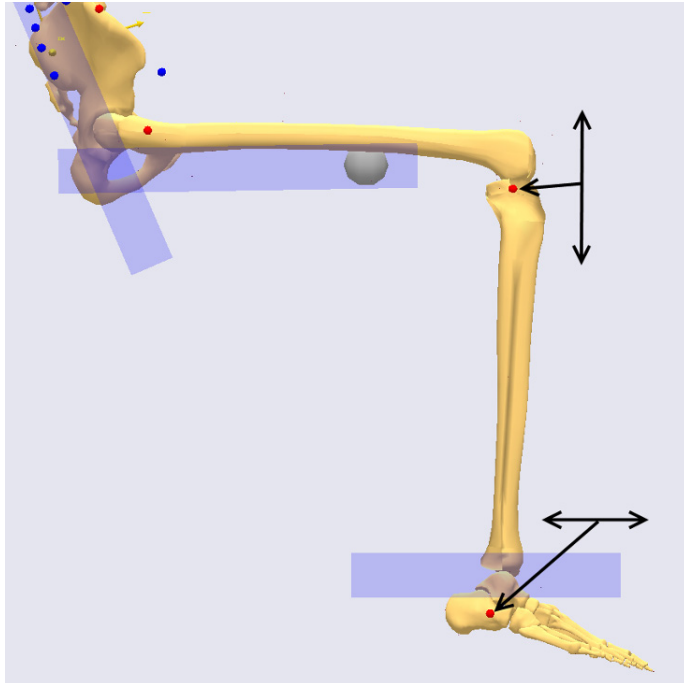


Figure 16 show the leg of the AnyBody model. The marker at the knee is driven in the vertical directions (indicated by the arrow) and the marker at the foot is driven in the horizontal direction, also indicated by the arrow.

### The Thorax posture

The thorax posture or more specifically the angle between the pelvis and the thorax is driven using the marker placed at sternum. The marker at sternum is driven in the anterior/posterior direction and in that way it controls the flexion/extension between the pelvis and the thorax. The thorax lateral bending and rotation is not driven using any markers but constrained to 0.

It was discovered during the modeling work that something was wrong with the position of the CoM of the thorax segment. It is hard to estimate where a CoM for a segment should be. A proper CoM estimate would have to be made MRI scan a person and then segment each part out, assign density to each part. This is a lot of work, but never the less it should be done at some point. Until then a good guess based on the literature will have to do.

The big problem for this model was that it had to use a lot of muscle force to sit in an upright position. To compensate for this the model acted in a strange way. By translating the CoM for the thorax in the posterior direction the muscle activity decreased, at the same time the CoM for the whole human model came closer to the one calculated from the experiment. It was found that moving the thorax CoM 13 cm posterior gave the lowest maximum muscle activity, it also made the whole body CoM within 1 cm from the experimentally obtained CoM for the whole body.

Moving back the thorax CoM 13 cm seems like a lot, at Figure 17 the posture of the model is showed. The two red squares are the backrest bars seen from the side and the gray circle is the thorax CoM after it was translated 13 cm in the posterior direction. That position did not seem right, unless you take the environment into the considerations. Figure 17 show that there was a big gap between the back of the

model and the backrest, which indicates that the model was skinnier at the posterior/anterior direction than the subject was. Since there were no markers at the back of the subject, this is unknown. The problem is that the model is driven in that direction on the marker at the sternum. Therefore it seems fair that if the model is to narrow in and driven from the sternum it should only increase in width in the posterior direction. Taking the position of the backrest bars and the sternum marker into consideration the translated thorax marker seems fair. This is a big assumption that should be investigated through further studies in the future.

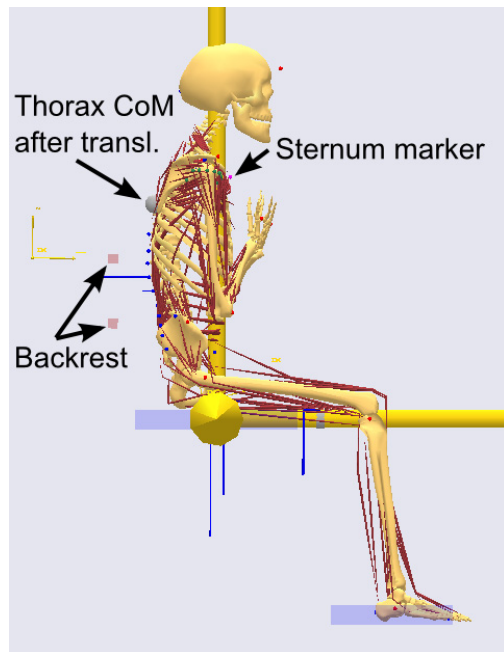


Figure 17 Show how the AnyBody model sit at the chair. The two red dots are the backrest bars that the model is leaning up against.

### The Neck angle

The neck angle is driven by a marker at the forehead of the subject. It is driven in the anterior/posterior direction and in that way driving the neck extension/flexion. The lateral bending and rotation are again constrained to 0.

### The Sternum-clavicular angle

The joint between the sternum and clavicularis is driven with the marker at the shoulder. The shoulder marker is driven in anterior/posterior and in superior/inferior directions and in that way controlling the protraction and elevation of the clavicular bone.

### The shoulder angle

The shoulder angle is driven using the marker at the elbow and the one at the hand. The marker at the elbow is driven in the anterior/posterior direction and in that way controlling the shoulder flexion. The

marker in the hand is also driven in the anterior/posterior direction and in that way controlling the shoulders external rotation.

### **The Elbow angle**

The elbow angle is controlled by the hand driver. The marker at the hand is driven in the superior/inferior direction to drive the elbow angle. As explained in the section above the hand driver is also driven in the anterior/posterior direction however this direction drives the shoulder rotation.





# 3 Results

This chapter will go through the results found while comparing the estimated forces from the AnyBody model and the measured forces from the experiment.

## 3.1 Backrest Height

The first six experiments was done to see how changing the backrest height affected the model, and thereby to see if the AnyBody model was robust towards backrest support at different positions.

The first result was the normal force ( $F_n$ ) as a function of the mean backrest bar height. The plot at Figure 18 show that the trend for both the AnyBody model and the experiment points the same direction. It means that the normal force at the backrests decreases at the height of them increases.

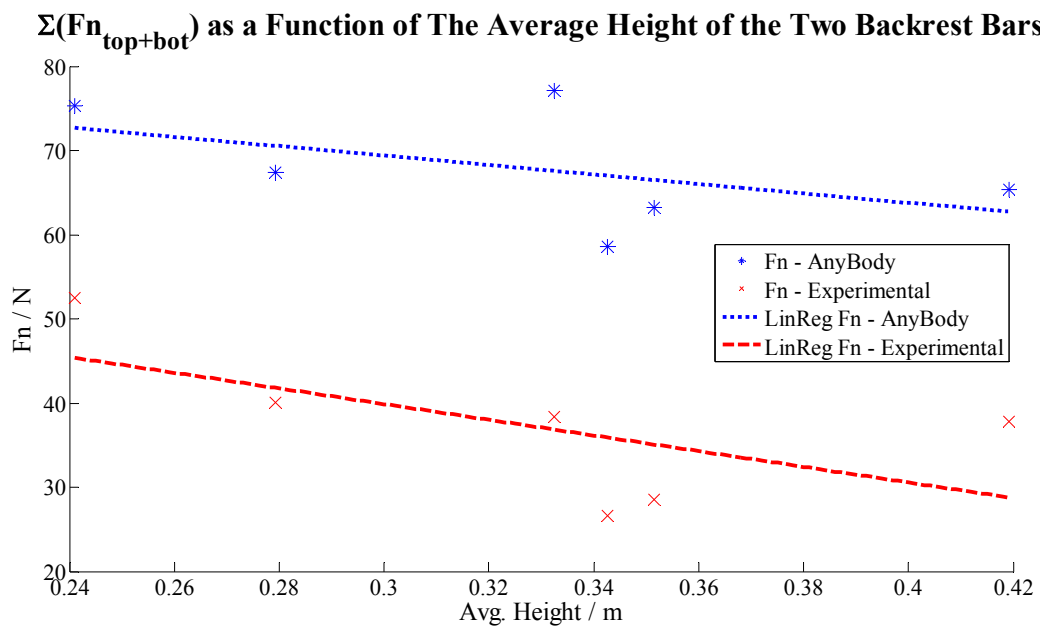


Figure 18 show the summed normal force ( $F_n$ ) as a function of the mean height of the two backrests. The Blue stars represent the AnyBody model and the red crosses represents the experiment

The results at Figure 18 clearly shows a trend, but it also seems like there is an offset between the AnyBody model and the experiment. The offset between the two could be caused by the normal people variation, or just the fact that the AnyBody model weighs 7 kg. more than the subject. The offset of the regression line is one thing, but taking a closer look at the samples, reveals that there are a third factor that influence on the result. Since each sample is matched because the model tries to mimic the experiment, the residual, i.e. the distance from the regression line to the sample is pointing the same

way in all samples. Trying to look into this, Figure 19 show the multiplication factor between the AnyBody model and the experimental results. It looks very close to constant.

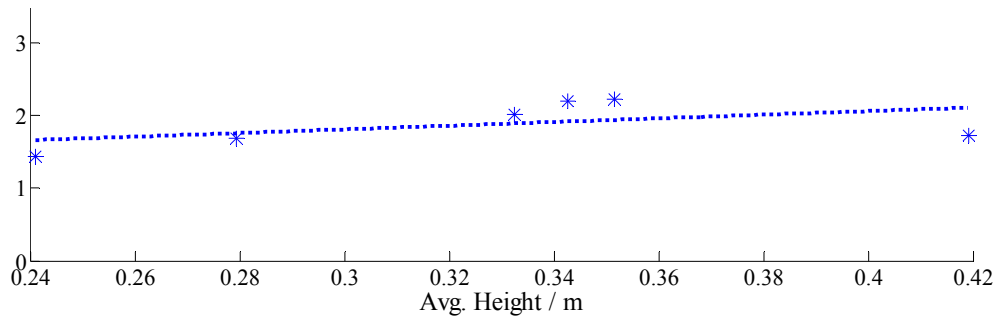


Figure 19 Show the  $F_n - \text{AnyBody} / F_n - \text{Experimental}$  as a function of backrest height. The relationship seems constant which indicates that the difference between the results from the AnyBody model and the experimental are a multiplication factor.

Another closely related result is the shear force on the seat as a function of the backrest height. This result are closely related to the normal force of the backrest but never the less it is more important since it is the shear force at the seat that has been identified as a main risk factor.

#### Shear force ( $F_s$ ) as a Function of The Average Height of the Two Backrest Bars

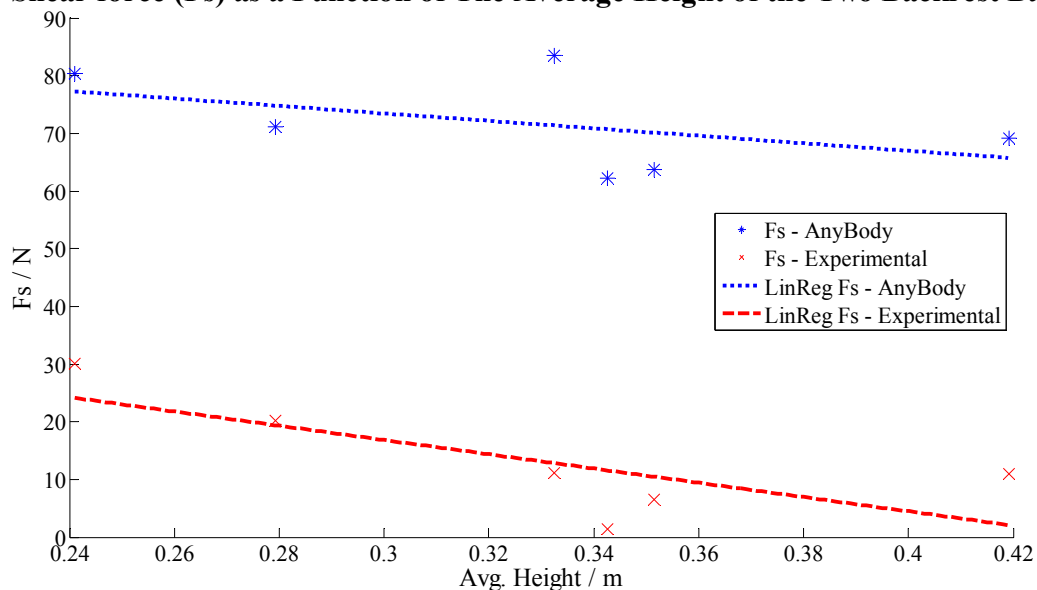


Figure 20 show the shear force at the seat as a function of the mean height of the two backrests. The Blue stars represent the AnyBody model and the red crosses represents the experiment

Another parameter that was investigated was the distance between the two backrests. Between two experiments the only thing that was changed was that the high backrest was raised. The result is plotted at Figure 21 where the summed force from the two backrests were plotted as a function of distance between the two backrest. Since there was only one experiment, we only have two data points. The trend seems like the bigger distance the lower normal force. At the same plot the normal forces applied

to each backrest bar were also plotted, and it can be seen that the AnyBody model estimates 0 N normal force on the lower backrest bar, while the experiment shows that only very low force was applied to the low backrest at the experiment.

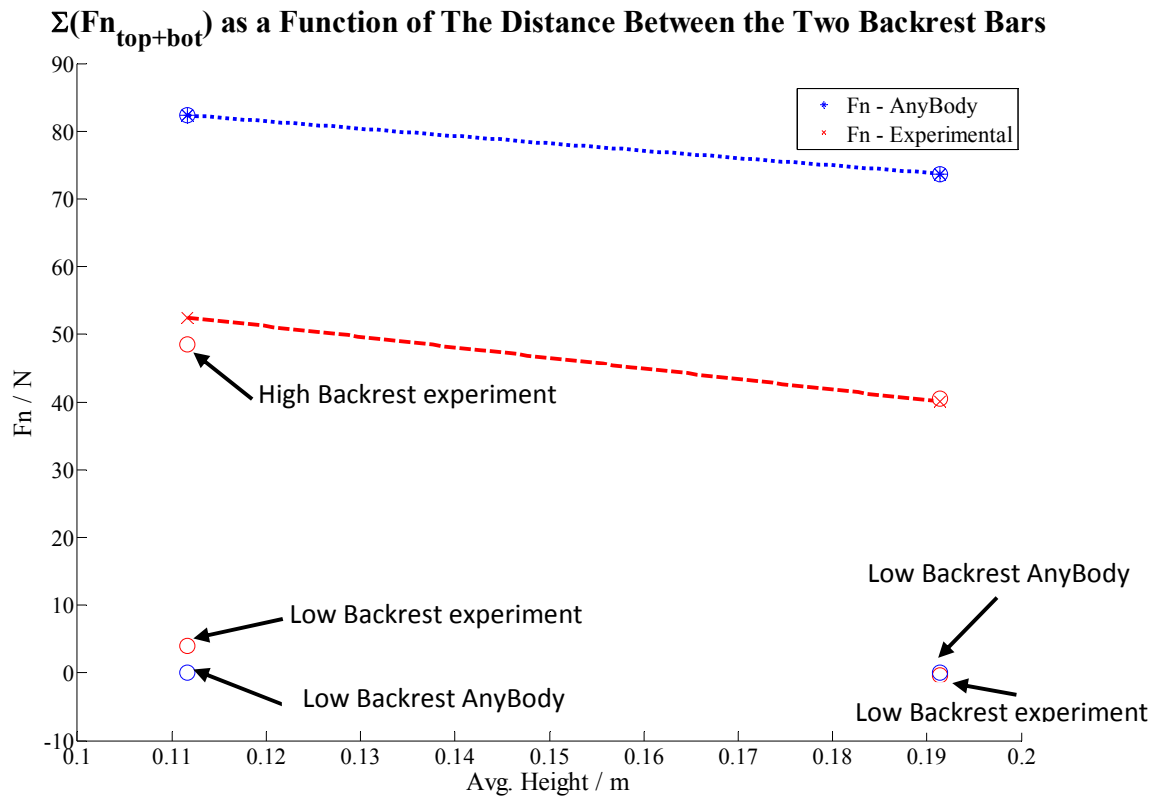


Figure 21 Show the change in normal force at the backrests when the distance between the backrest bars is increased by setting the top backrest bar higher up. The circles represent the normal force for the two backrests while the star and the cross represent the summed normal force at both the backrest.

### 3.2 Relative Angle between Backrest and Seat While Seat is Horizontal

An experiment was done, where the angle between the horizontal seat and the backrest was moved from 90° to 93°. This was done because it was expected to cause a big change because the backrest would move from supporting the subject to carrying some weight for the subject. The shear force at the seat and the normal force at the backrest were plotted at Figure 22 and Figure 23. The two figures show that the AnyBody model predict the change in shear force at the seat and normal force at the backrests the same direction as the experiment showed. The offset is still there and the normal force at the backrest actually increased more in the model than it did at the experimental setup.

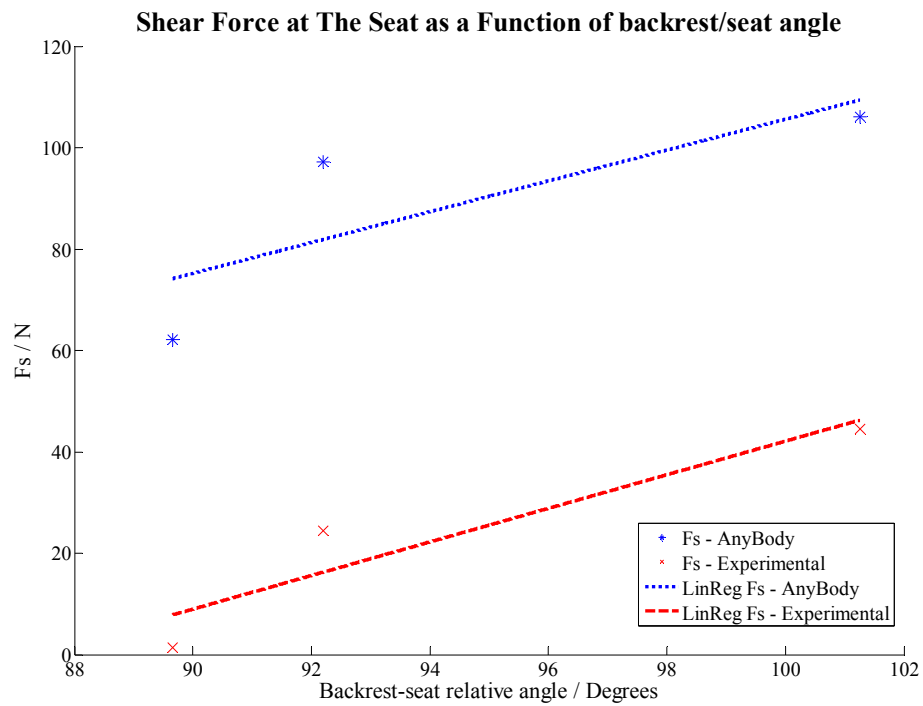


Figure 22 Show the shear force at the seat as a function of the relative angle between the backrest and the seat.

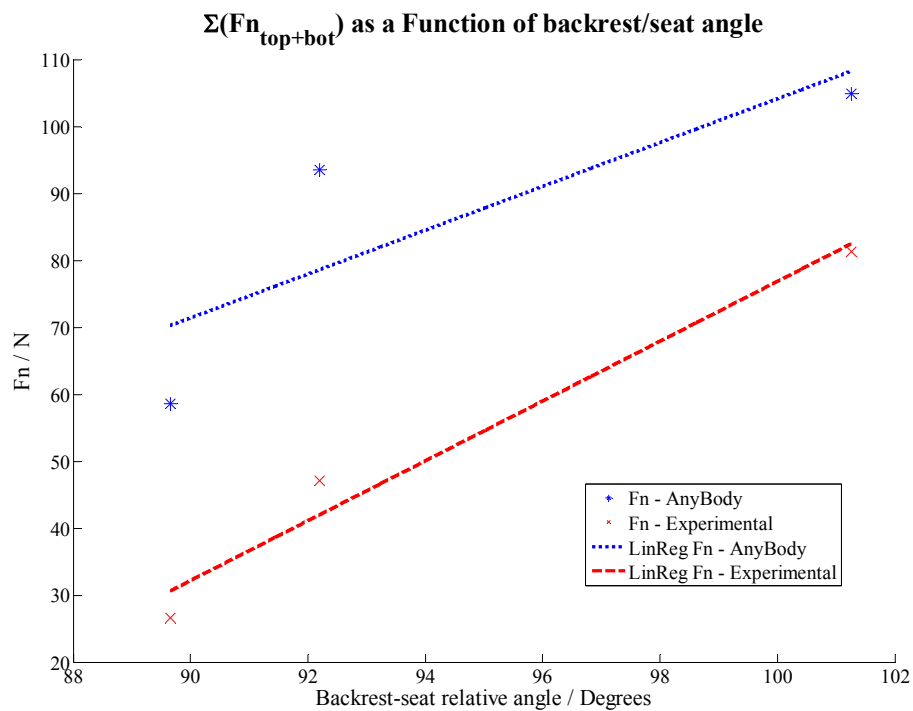


Figure 23 show the summed normal force at the two backrests as a function of the relative angle between the seat and the backrest.

Another measure that was found was the normal force on the seat as a function of the backrest angle. Since the normal force on the footrest was in the same direction these two were added and plotted against the backrest angle at

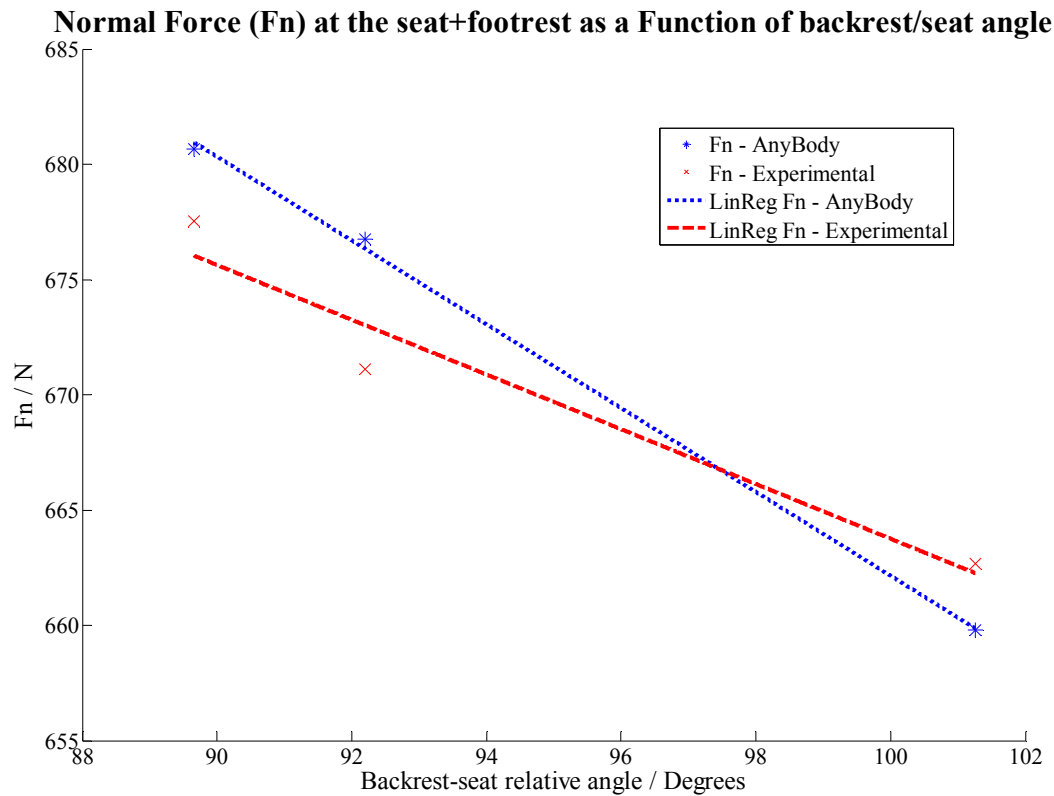


Figure 24 show the normal force at the seat and footrest as a function of the backrest angle relatively to the horizontal seat.

The two graphs at Figure 24 have the same trend, which is that the more the backrest is leaned back, the less weight is on the seat. The two graphs intersect which can't be explained by logic, however the beginning offset between the two graphs is only 5 N counting for less than one percent. The difference is even smaller in the end, therefore the variation in slope can be explained by measuring error and by the fact that the AnyBody model don't have a friction coefficient at the backrest, that can carry weight, but the experiment maybe have a small friction coefficient that actually carried 5 N weight during the experiment.

### 3.3 Seat angle

This experiment is holding everything fixed except for the seat angle. The backrest is leaned back 12°. The first results can be seen at Figure 25 where the graphs show that the trend of the experimentally obtained shear forces and the AnyBody estimated shear forces at the seat are close to equal. There are again a difference in the absolute value, which could be caused by several reasons, one thing to notice is

that the CoM for the model is 3 cm behind the CoM for the subject, which could cause less shear when leaned back and tilted, and more when not tilted but only leaned back.

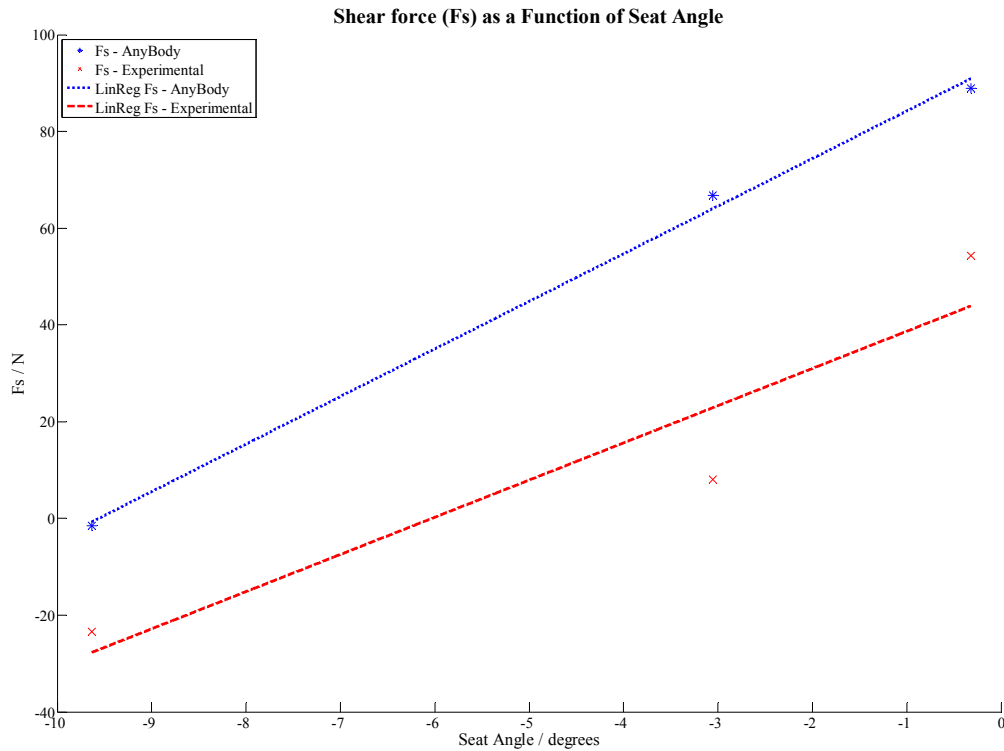


Figure 25 show the shear force at the seat as a function of the seat angle.

Another result less positive was the normal force at the backrest and at the seat+footrest, which was plotted at Figure 26 and Figure 27. The normal force at the backrest which is plotted at Figure 26, which shows at the AnyBody model show a nice trend however the experimentally measured forces does not show any kind of trend.

The normal force at the seat measured experimentally nor shows any trend. The big variations in normal force at the seat were caused by unexpected high shear forces at the backrest which causes the normal force at the seat to decreases.

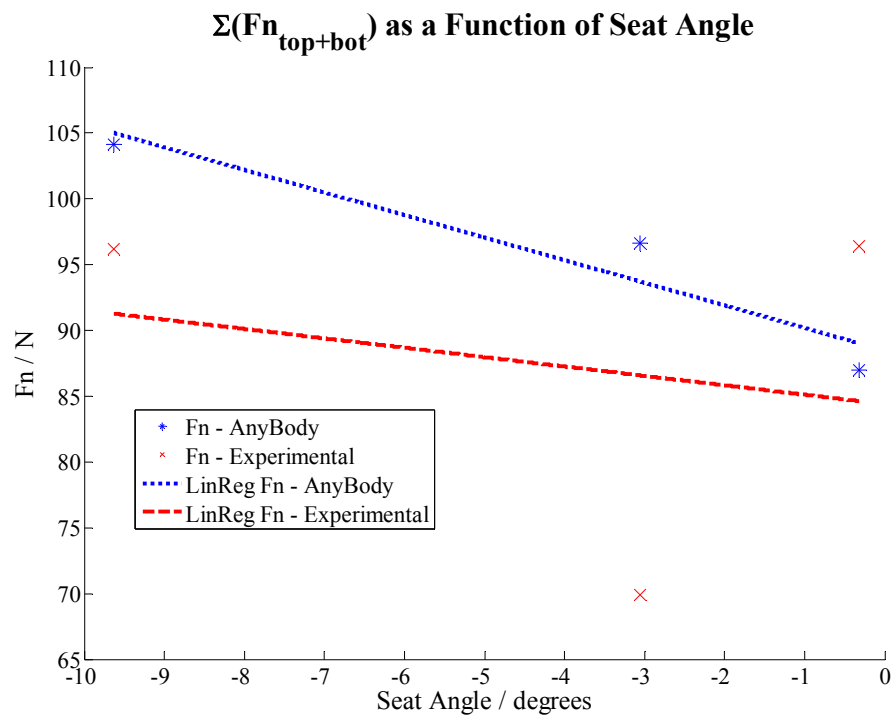


Figure 26 show the normal force at the backrest as a function of the seat angle

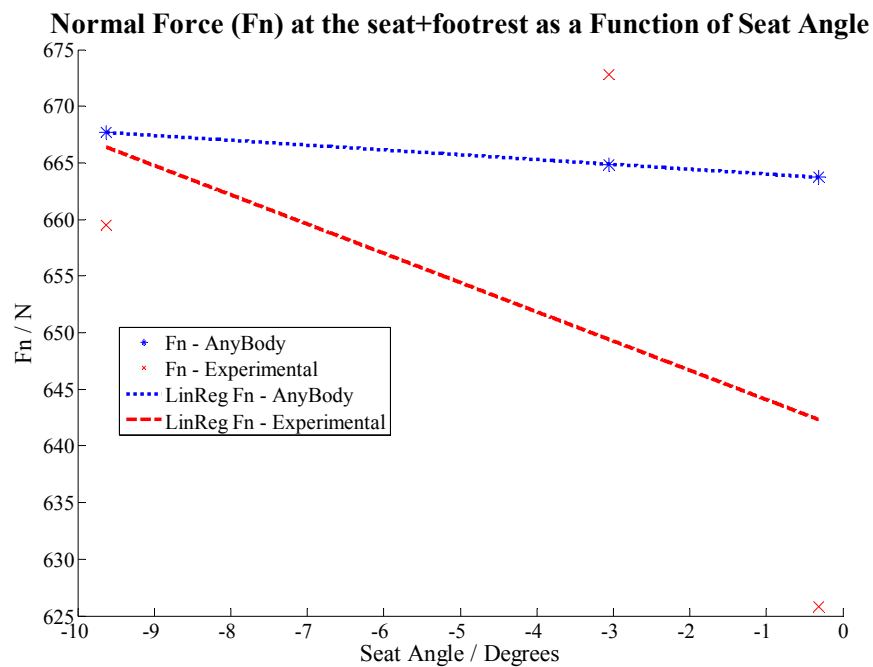


Figure 27 show the normal force at the seat+footrest as a function of the seat angle

### 3.4 Other Results

There were other parameters to look at, parameters that could be identified as important factors for the model. Some of these important parameters could be for instance the position of the CoM for the model compared for the one calculated for the subject. This result is quite interesting since we moved the CoM backwards in order to get the model to relax more and fit into the environment. The result can be seen at Figure 28 where it is obvious that the CoM for the model is a bit more behind the one for the subject. It is not a lot, 1.5 – 3.5 cm, but still it could effect the result, therefore the plot was also made with the CoM for the thorax not moved backward.

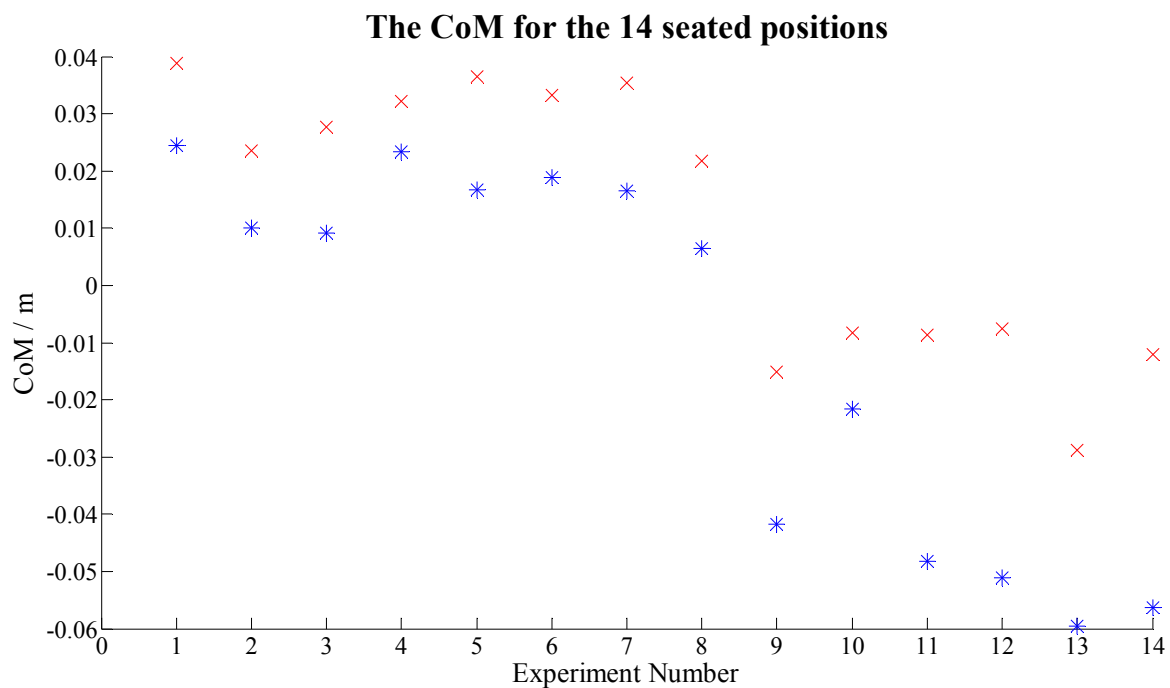


Figure 28 show the CoM for the AnyBody model and the CoM for the subject. The CoM is up the y-axis which represents the sagital position, where 0 is the center of the seat.

Another parameter could be the weight of the model and subject. The weight of the model was defined in the model, therefore this should be constant. The weight of the subject was calculated based on the force measurements and therefore represents the measuring variation. The result is plotted at Figure 29 that show that the AnyBody model had a constant weight and the subjects weight estimated based on the force measurements varies a bit. The mean weight of the subject is 681 N and the standard deviation is 8 N.



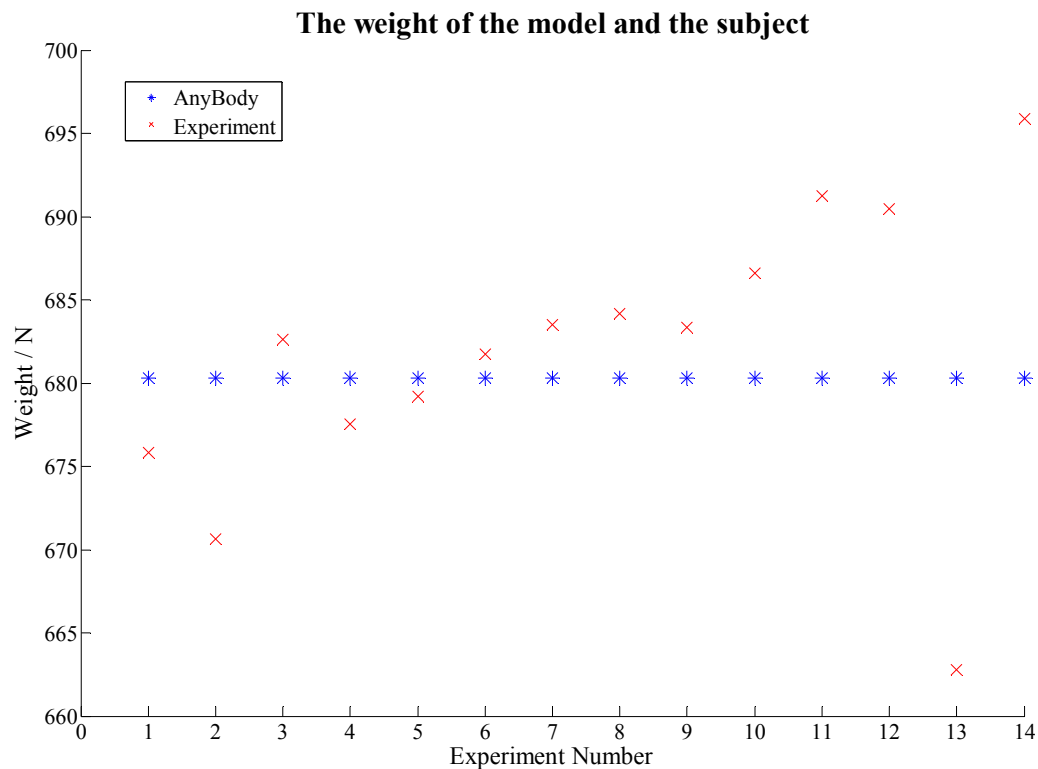


Figure 29 show the weight of the model and the weight of the subject for each of the experimental positions.

Another important factor could be the Maximum muscle activity for each position, calculated from the AnyBody model. The max muscle activity can give a hint if the seated posture is relaxing or hard work. Obviously a seated position should not be hard work; therefore something would be wrong if the maximum muscle activity was too high. The plot is showed at Figure 30 which show that the maximum muscle activity was around 7-10%, which seems reasonably fair.

All the previous results were based on the corrected thorax CoM, that was described in the methods part. By calculating the same results with the old thorax CoM position, the results were close to similar, except for the maximum muscle activity for the model which was at least 7% higher.

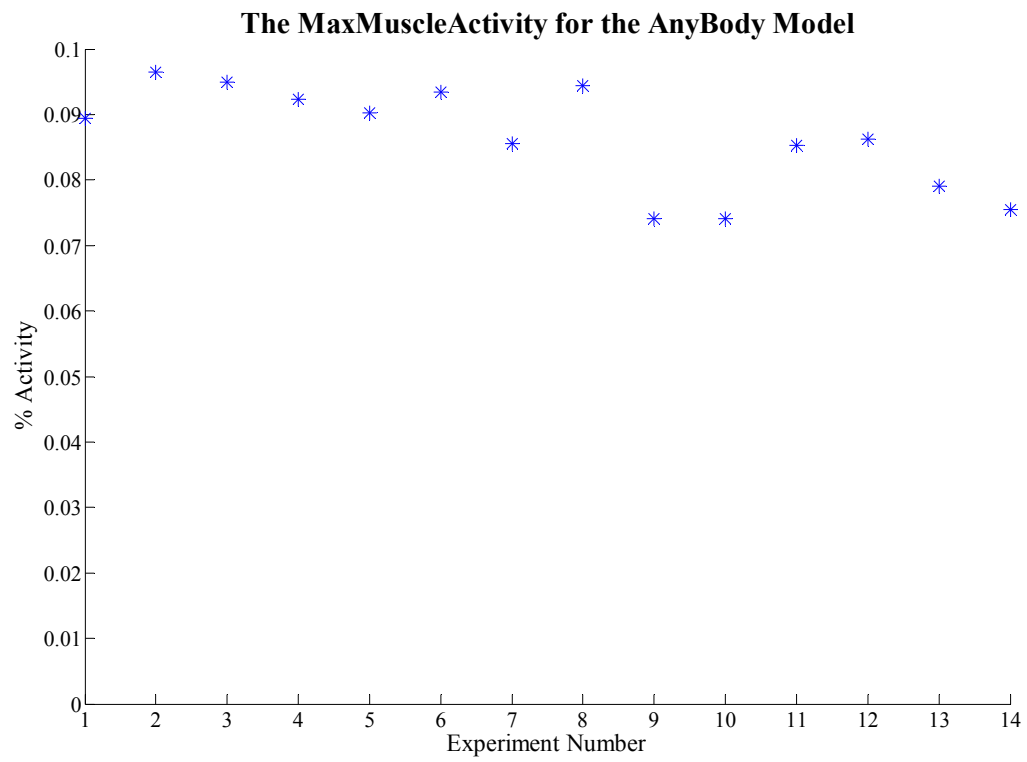


Figure 30 show the max muscle activity from the AnyBody model for each of the experimental positions

# Appendix



# 4 Homepage developing

## 4.1 Background

The Decubitus Project at Aalborg University is a project that involves several people, organizations and companies. To ease the communication between the interested parties and the project group at Aalborg University it was decided to create a homepage. The homepage should serve as a connection between everyone interested in this project; therefore it was a necessity that it was made possible for everyone to write their own input.

## 4.2 Where and How

The homepage is located at Health Science and Technologies UNIX web server at [www.hst.aau.dk/~decubitus/](http://www.hst.aau.dk/~decubitus/). The actual coding syntax is not relevant here but it was created in a text editor using the following languages:

- Hyper Text Markup Language (HTML)
- Cascading Style Sheets (css)
- PHP Hypertext Processor (php)

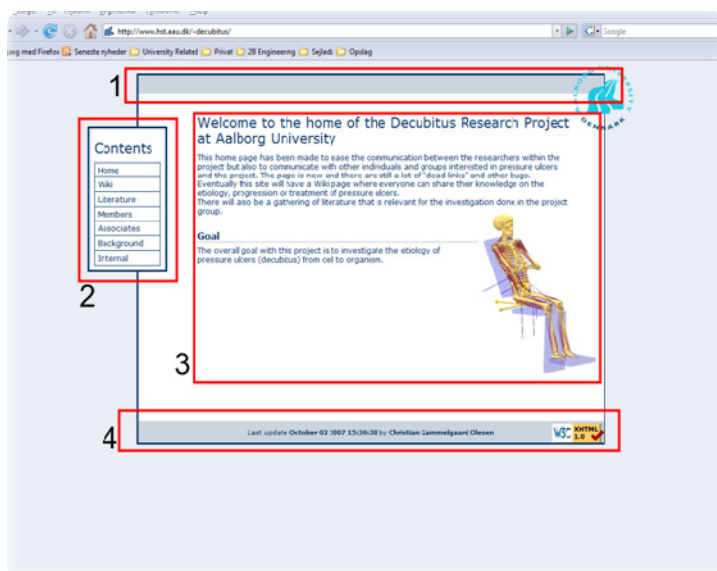


Figure 31 Show a screendump of the main page of the Decubitus web page

It is simple to maintain because of the simple directory structure which was chosen for its simplicity ahead of a more complex MySQL database structure.

The design was kept plain and simple, see

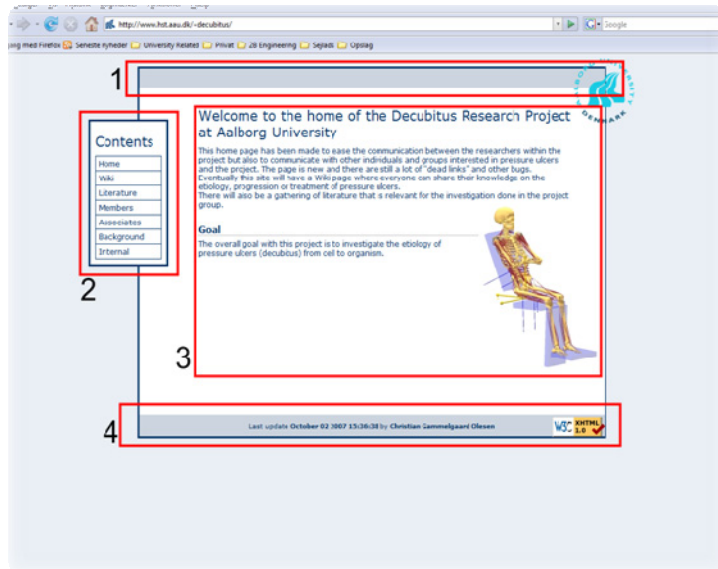


Figure 31. The design that was used was consistent through the whole site which made it easy to navigate. The only place at the site that did not look like the design at

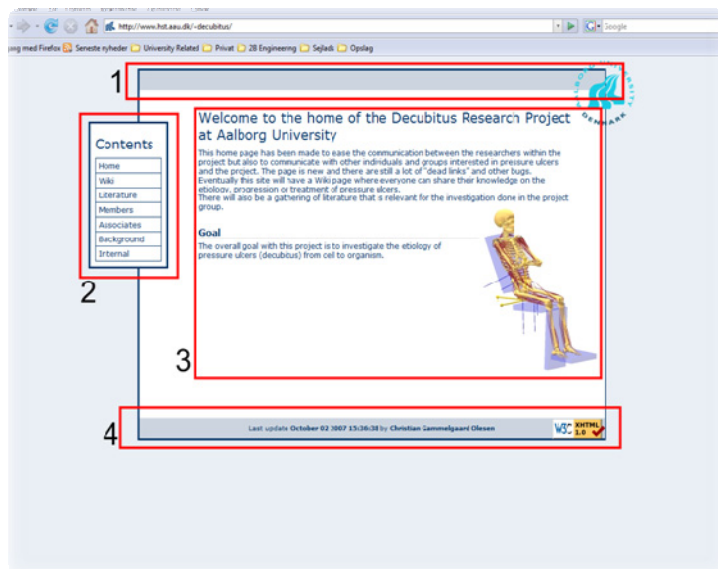
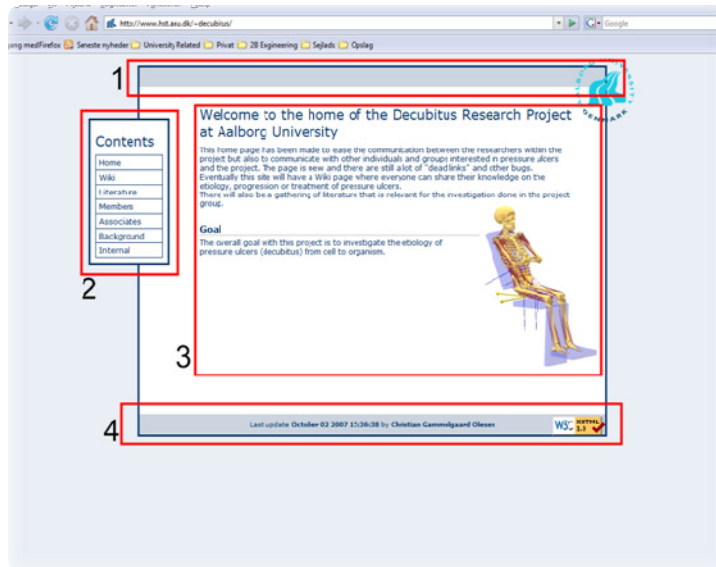


Figure 31 was the “wiki”-part, because this part is a freeware software package that was used.

The design of the page was setup using css and generally a design file was made that described how everything should look and where it should be placed. For instance if one of the links in the menu bar is

clicked on? the browser will look into the directory it is linked to and see if there is an index.\*<sup>2</sup> file. There is an index file in each directory and that index file start by calling the design file that setup object 1 and



2 at

Figure 31 and then the codes that are in the index.\* file will be filled into object 3. The last thing that will happen is that another file is called that setup object 4. So far there is no drop down boxes at the menu, this could very easily be made but there has not really been any demand for this yet. It might be made if more people are going to work at the project at some point.

## 4.3 The Menu

The menu is also build simple with a change in background color when the mouse is moved over it. It links to directories that are underneath the main directory which makes it easy and intuitively to link to a certain place in site for instance linking directly to the “Background” page will have the URL: [www.hst.aau.dk/~decubitus/background](http://www.hst.aau.dk/~decubitus/background) not like when a site is made with MySQL database structure you often see URL’s using “?php/hash=DhJEld” which makes no intuitively sense and are just annoying when typing is necessary.

Most of the content of the menu speaks for itself except a few things.

**Literature** was created as a page where all the literature references that we dig up during the project can be located. The index file takes a html file as input and that html file can be generated by reworks which is an online reference manager tool.

**The members page** was made as a page where contact information can be found on the people that are closely involved with the project.

<sup>2</sup> \* is a general term for “something” and that “something” is here htm, html, asp, php or similar

**Associates** is a contact page for the parties that contribute to the project in some way.

**Background** contains the background for the project

**Internal** is a password protected using a htaccess password protection. Behind the password a set of full text papers are located for use in the project group.

**Wiki** leads to a “wiki-page” that works like any other wiki-site. It gives people the possibility to write whatever they want and link between it. It gives everyone interested in the project the possibility to contribute with their knowledge.

## 4.4 Conclusion

The webpage was build and it works as intended. It is very simple to maintain with a very low level of skills in html, and the html syntax is very simple, much like LaTeX that all engineering students know. Have a look yourself at [www.hst.aau.dk/~decubitus](http://www.hst.aau.dk/~decubitus)



## 5 Able-bodied Vs. Paraplegic subjects

This project has an end goal which is to investigate the internal stresses subjected to the soft tissues in the buttocks. Since the seated AnyBody model will be only validated with respect to able-bodied subjects, assumptions has to be made to generate load data from the model that imitates a paraplegic subject.

The assumptions will be to change the model so it will sit like a paraplegic subject; therefore the literature has been investigated on differences on seating posture between able-bodied and paraplegic subjects.

Shirado, O. et al (2004)[21] did a study where the sitting posture of spinal cord injured (SCI) subjects and able-bodied subjects were compared with respect to their posture. They saw that SCI subjects had a backward rotated pelvis and therefore a decreased lumbar lordosis. When the pelvis is tilted as they describe it would give a higher shear load on the seat because of the loading angle being closer to horizontal and therefore more load is translated to shear instead of normal. See Figure 32 for an illustration of the pelvic tilt in SCI patients.

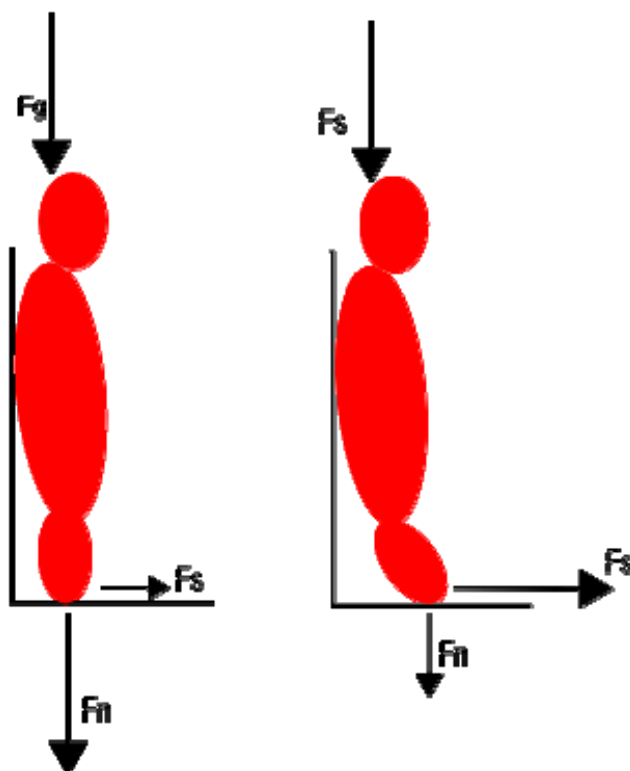


Figure 32 show the differences in pelvic angle. The left sketch is a normal person with an upright pelvis and the right drawing illustrates a SCI patient with a tilted pelvis.

This pelvic tilt agrees with the findings of Hobson, D.A. (1992)[14] that find greater shear load applied to the seat by SCI patients than able-bodied persons.

This indicates that it is reasonable to assume that SCI in general have a more tilted pelvis than able-bodied subjects and therefore a relationship between pelvic angle and shear/normal force under the seat would be relevant.

## 6 Force Measurements (Worst case estimate)

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The task of building a wheel chair with load cells mounted for measuring the reaction and shear forces obviously includes working with load cells and therefore the available load cells and force plates from the lab had to be examined to see if they could be used for the purpose. The following list is a list of load cells available.

2 x AMTI FS6 250

2 x AMTI FS6 500

3x AMTI force plate

So the question is how big loads will be applied in worst case at the different load bearing parts of the chair? We will start by defining the parts of a chair that will be subjected to a load.

Seat

Backrest

Footrest

Armrest?

This adds up to at least three locations where we need to measure forces. The seat, backrest and footrest.

### 6.1 Worst case

We could say that worst case would be a subject on 120 kg.

#### 6.1.1 The Seat

Obviously the seat is subjected to a major load in  $F_z$  while subjects sit on it. The  $F_x$  and  $F_y$  are subjected to a shear force which should be limited compared to the vertical  $F_z$ . The chair will be exposed to static sitting and of course a loading phase where the subjects sit down on the chair. During the loading phase the subject could accidentally apply significant loads to the edge of the seat which would apply a significant  $M_{x/y}$ .

Minimum requirements to the  $F_z$  would be the full body weight plus the actual seat, let's say an extra 20 kg which end up at 140 kg plus a safety margin at 30%,  $F_{z,min} = 1800 \text{ N}$

Minimum requirements of  $M_{x/y}$  would be that the load cell/force plate could withstand a moment that could in worst case be generated based on the full load of the subject at the edge of the seat. Let's say 120 kg at the end of 30 cm.  $M_{x/y,min} = 350 \text{ NM}$ .

Now the big question is if we have load cells that can withstand those loads or we should aim for building in a force plate as a seat. The biggest load cell we have is the AMTI FS6 500 which have a  $F_{z,max} = 2200 \text{ N}$  and a  $M_{x/y,max} = 56 \text{ NM}$ . Since the load cell cannot withstand the moments that can be applied we will have to use a force plate as seat.

## 6.2 The Backrest

The backrest should be variable regarding the angle and therefore the load that will be applied to the backrest is variable and all maximum forces/moments of the load cells should be considered.

$F_z$  will be subjected to the highest load if the backrest is lowered to horizontal, where the load will come from the backrest itself plus the upper body of the subject. Let's say 80 kg + 20 kg of backrest plus a safety margin at 30% and it all ends up with a  $F_{z,min} = 1300 \text{ N}$

$F_{x/y}$  i.e. the shear loads will be limited at the backrest and these will not have to be taken into consideration.

$M_{x/y}$  are hard to estimate because they depend on where the load cell is placed. The load cells have  $M_{max}$  that is very low and therefore this is a critical consideration. The solution could be to mount two load cells on the backrest depending on if we can find a practical solution.

## 6.3 The Footrest

The foot rest shouldn't be subjected to large loads while the subject is sitting in the chair, but the easiest thing would be to place the footrest at a force plate built into the floor in the laboratory.

### 6.3.1 The Armrests

The armrest shouldn't be subjected to loads bigger than 5% of the body weight of the subject, but extensive loads can be subjected to them if the patient tries to change posture by using the armrest, therefore some kind of protective mechanism could be built into the armrest, so the load cell only holds the weight while measuring on the subject, not while the subject is entering the chair.

## 7 Recording kinematic and force data

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To be able to set the seated AnyBody model in the same position as the subject that the model is trying to mimic, it is important to know the posture of the subject. It is only the “static” posture we are interested in, since it is not a dynamic experiment, joint axis and other dynamic measures are not relevant. However a few anthropometric measures and joint angles will be needed to drive the AnyBody model. Therefore kinematic recordings were made during the force measurements, to determine the position of the person sitting in the wheelchair in 3d.

To determine positions in 3d it is necessary to use more than one camera. The 3d spatial position can be determined using more than one camera. To describe the relationship between the 2d coordinates on the cameras and the 3d position in the lab coordinate system a direct linear transformation (DLT) is often used. [20] for  $n$  cameras the relationship between the coordinates of the marker on camera  $j$ , ( $j=1,...,n$ ) and the coordinates of this marker in 3d is determined by:

$$x_{ij} = \frac{a_{1j}x_i + a_{2j}y_i + a_{3j}z_i + a_{4j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1}$$
$$y_{ij} = \frac{a_{5j}x_i + a_{6j}y_i + a_{7j}z_i + a_{8j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1}$$

Where for a given marker  $i$ :

$x_{ij}$  = x coordinate of marker  $i$  on camera  $j$

$y_{ij}$  = y coordinate of marker  $i$  on camera  $j$

$x_i$  is the x-coordinate of marker  $i$  in the 3d space.

$y_i$  is the y-coordinate of marker  $i$  in the 3d space.

$z_i$  is the z-coordinate of marker  $i$  in the 3d space.

$a_{kj}$  are the transformation coefficients based on a calibration. The coefficient  $k$  for the transformation of marker  $i$ . The coefficient can be determined by calibrating with  $N$  points with known coordinates. At least six calibration points i.e. 12 equations is needed to solve for the 11 coefficients. If the system is over determined then a least square technique can be used to fit coordinates. [20] Each camera has two equations and the DLT-method provides more equations than unknowns for the position of a marker  $i$  as long as at least two cameras can see the marker. When more than one camera can see the marker the determination of a marker coordinate does not have a unique solution.

The experiment that will be conducted in this study will be conducted using eight cameras connected to a computer. Qualisys tracking manager will be used to record the positions of the markers. A trigger will be connected to start the recording at the same time as when the force measurements are started.

## 8 Thoughts on what to measure and why?

To validate the seated model from the public AnyBody repository it will be necessary to conduct experiments with subjects and then try to model that specific subject and compare the results.

Since the model should be validated towards using it for generating data to apply on a FEM to get a better understanding of pressure ulcers, it would be a good idea to validate the model with respect to SCI patients because they also get pressure ulcers.

I believe it will be hard to do the experiments on SCI patients, because you cannot compare SCI patients. They all sit differently and they need various types of support, which they would get with their own wheelchair that is fitted to them by a therapist. I simply find it too complicated to get the prototype wheelchair with the force plates and load cells to fit a SCI patient plus we don't have the expertise to do so. If we did have the expertise it would be a subjective matter if the patient was sitting right or wrong. In the end we will end up with results similar to every other experiment in the literature that tried to compare the way able-bodied subjects sit with the way SCI patients sit. Shirado, O et al [21] showed that SCI patients have a rotated pelvis compared to able-bodied.

It is therefore suggested that only able-bodied subjects will be included in the experiment. The able-bodied subjects can sit in different postures with respect to their pelvis. The therapeutic view on the problem is focused on the pelvis rotation. If the model is validated data could be generated using another pelvic angle.

### 8.1.1 Pros and Cons

The pros and cons for doing experiments with and without SCI patients is listed here:

Only able-bodied subjects		Able-bodied subjects and SCI patients	
Pros	Cons	Pros	Cons
Subject cooperation is eased	Do not get the model validated for SCI patients	Measure the difference in able-bodied and SCI patients	Subjective assessment of sitting posture
No Ethical Approval?			Hard to find the right subjects
			Hard to compare subjects with lesions in different locations

Everything sums up to the fact that if we conduct an experiment with able-bodied subjects and SCI patients we might get a difference, but is this difference true? And can we explain it?





# 9 Literature study

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## 9.1 Purpose

This chapter documents the search for literature and specifies which criteria were used to exclude and include journal papers. There are several areas related to pressure sores that need to be investigated before it is possible to specify how this project will get us a step closer to understanding how pressure sores develop.

## 9.2 Search strategy

The search strategy was to identify the search terms and use the NCBI PubMed search engine to find relevant literature. When the abstracts were read and a few key papers were identified the bibliography from the key papers were inspected and the relevant papers were then found this way.

The search strategy had to be applied three times because there were three main areas that had to be investigated. The three areas were:

- Experimental sitting related to pressure sores
- Computational models of the buttock area
- Cell response to stresses caused by sitting

The first area to investigate was the area concerning the experimental sitting related to pressure sores. The search came up with ~200 hits. The titles were looked through and abstracts for the relevant ones were read and 22 full text papers were read and their bibliographies were investigated to make sure that no important papers were missed. A few literature review papers were also investigated, where the most recent one was from 2005:

[Decubitus ulcers: A review of the literature \[54\]](#)

[4]

The procedure was carried out for the other two areas as well.

## 9.3 Experimental sitting related to pressure sores

The most relevant papers in the area related measuring pressure, normal and shear forces on the skin and during sitting are summarized in this section.

[Support Force Measured of Midsized Men in Seated Positions \[1\]](#)

[24]

The paper is about building a chair with load cells for designing car seats and the objective of the study was to measure human loads for 12 seated positions divided into three back rest inclinations with four levels of articulation. The three back rest inclinations were 20, 24 and 28 degrees behind vertical and the articulations were named slouched, neutral, erect and supererect. The neutral was when the two back panels were aligned. The forces measured were normal and shear. Two variables were tested, the "body recline" and the "torso articulation". The body recline was defined as the inclination of thorax and pelvis support rearwards of vertical. The thorax articulation was defined as the pelvic and thoracic support moved in equal and opposed direction. They used a Qualisys motion capture system to measure the positions of the recline bar of the chair and the pelvic and thoracic support. The experiment was conducted on 23 men about the size of the 50<sup>th</sup> percentile male. The results reported are complete and very thorough, in total a very good study with a very well described protocol. This paper will be a key paper in the process of building a chair with load cells and it could even be used to conduct a pilot validation of an AnyBody Model.

### **Seat Support Surface Optimization Using Force Feedback [2]**

[25]

This paper is based on the assumption that lower peak pressure in special areas will help on not developing pressure ulcers. A chair with pistons and force feedback was build and they optimize it to keep low peak pressure in certain areas. Not an obvious reference but they do have a good introduction.

### **Effect of Seat Inclination on Seated Pressure of Individuals With Spinal Cord Injury [3]**

[12]

The paper is describing an experiment where "squeezing" of wheelchair frames is evaluated. Squeezing is done to make sure users don't slip out of the chair. They change the inclination angle of the seat and backrest and measure the pressure under the buttock. It is not a key paper for the project but it could be used in a discussion regarding the seat angle. They change the seat angle and measure pressure, but not shear. They use only paraplegic patients.

### **Quantitative Evaluation of Long Sitting in Paraplegic Patients with Spinal Cord Injury [4]**

[21]

This paper describes a comparison study on how paraplegic and able-bodied people sit with respect to pelvis angle and movement of COG. They had 24 subjects sitting on a flat surface. They describe a difference in pelvic angle from able-bodied to paraplegic patients.

### **Shear Stress Measured on Beds and Wheelchairs[5]**

[18]

This paper describes a couple of interesting experiments. They develop a shear stress measurement electrode for soft tissue. They test it and use it to measure shear stress in wheelchairs with different postures and in hospital beds with different postures. They measure highest shear stress in the areas where the highest pressure happens. They conclude that local shear stresses are highly affected by the body movements.

### **Sitting forces and wheelchair mechanics [7]**

[17]

This paper describes a study where a force plate was mounted in the seat of a wheel chair and the purpose of the experiment was to investigate normal and shear forces on the seat when people lean back and raise the seat to normal position again. They found interesting results that could be usable and definitely should be considered in the project and the measuring protocol. They saw that the normal and shear force are greater when the subject change recline angle from almost laying down and back to zero, it seems like there is a kind of “hysteresis”. In the forces.

### **Thirty-minute continuous sitting force measurement with different support surfaces in the spinal cord injured and able-bodied [8]**

[15]

This paper describes an experimental setup similar to the one in “**Sitting forces and wheelchair mechanics**” but this time they do a 30 min experiment with able-bodied, paraplegic and quadriplegic subjects. They sat on Jay and ROHO cushions. They measured normal and shear forces in the seat and arm rest. Their main result was that armrest relief force from the buttock in both paraplegic and quadriplegic subjects.

### **Body Build and Its Relationship to Pressure Distribution in the Seated Wheelchair Patient [9]**

[26]

This paper investigates the relationship between pressure distribution and body builds and seat. They have four different kinds of cushions and they divide their subjects into three groups; thin, normal and obese. They find that thin subjects have higher peak pressure than the others and more often peak pressure around bony locations.

### **Comparative effect of posture on pressure and shear at the body-seat interface [10]**

[14]

This paper describes an experiment done on normal and SCI subjects. Each subject was seated in nine different ways and the pressure and shear force were measured. The method described in the paper is a bit unclear but they do show interesting shear results for different postures. Interesting setups: They set the foot rest to a height where it holds 10% of the bodyweight. They found a body position with hardly any global shear. They also found that SCI patients have significant higher pressure than normal people and changing posture did not change the peak pressure much. They also found that the peak pressure gradient was much greater in disabled people than normal which suggests that there are shear stresses you cannot measure externally.

### **Shear vs Pressure as Causative Factors in Skin Blood Flow Occlusion [11]**

[27]

This paper describes a study where an instrument was developed to measure pressure, shear and arterial blood flow. They do experiments where they apply pressure and measure the blood flow and

apply shear and measure blood flow and then apply both pressure and shear and measure blood flow. They find that pressure was twice as effective as shear for causing blood occlusion but pressure and shear together was particularly effective. So maybe it would be wrong to look at one factor without the other one.

#### **Skin Stress and Blood Flow in Sitting Paraplegic Patients [12]**

[16]

This paper describes a study conducted with normal, paraplegic and geriatric patients. Their results are not very useful but they have a very good discussion where they mention all the different theories there are on how pressure and shear acts together in developing decubitus.

#### **The effect of shear forces externally applied to skin surface on underlying tissues [13]**

[28]

They describe the theory for estimating biomechanical measures in tissue and build an indenter for measuring the blood flow, Pressure and shear force. They also show that blood occlusion is a mix of shear and pressure.

#### **Influence of Shear on Skin Oxygen Tension [15]**

[29]

They measured shear and pressure on a local point and measured the skin oxygen tension. They basically showed that for a local point if you apply pressure you lower the oxygen tension and if you apply shear and pressure it takes less pressure to lower the oxygen tension.

#### **In vivo (CT scan) comparison of vertical shear in human tissue caused by various support surfaces [44]**

[8]

This study is trying to estimate shear stress and strain by loaded and unloaded buttock ct-scans. They did an experiment laying down on different cushions and calculated the shear stress and strain and saw which mattress that subjected the soft tissue to less shear stress and strain.

#### **Impact of Sitting Time on Seat-Interface Pressure and on Pressure Mapping With Multiple Sclerosis Patients [24]**

[30]

This paper describes an experiment where sclerosis patients and able-body subjects were seated in a chair with a pressure mat. The pressure distribution was then measured over time and they found that normal subjects pressure distribution change the first 4 min and sclerosis patients change the first 8 min after they were seated.

#### **Pressure distribution under the ischium of normal subjects [37]**

[31]

This study describes a pressure distribution measurement system based on pneumatics. They measure pressure distribution under the buttocks of five subjects. It is more a developing paper than a experimental study paper.

**The false premise in measuring body-support interface pressures for preventing serious pressure ulcers [43]**

[32]

This paper is a great support for our current work. It describes a experiment done where they used a ischial bone from a human and a bovine gluteus and measured the stresses and correlated those to the interface pressure measured and showed that there were no correlation.

**Periodically relieving ischial sitting load to decrease the risk of pressure ulcers [48]**

[33]

This paper describes an experiment where two different ways of relieving pressure from the wheelchair user. They either have to do a push up or get lifted up, or the rear end of the seat get removed. They clame that relieving the pressure the load on the buttocks get smaller.

**Three-dimensional tissue deformation in subcutaneous tissues overlying bony prominences may help to explain external load transfer to the interstitium [51]**

[34]

This paper describes an experiment were load was applied the back of a pig. They were trying to explain load transfer. They saw creep in the tissue. Not very relevant for our study.

**The relationship between pressure ulcer incidence and buttock-seat cushion interface pressure in at-risk elderly wheelchair users [52]**

[35]

This paper describes an observational study where interface pressure was measured when they were seated in the wheelchair and then followed them to see if they developed pressure ulcers. They saw that high pressure were more likely to develop pressure ulcers.

**The recovery characteristics of soft tissue following repeated loading [35]**

[36]

This paper assumes that transcutaneous gas tension causes pressure ulcers. They tested normal subjects and debilitated subjects and they saw that some debilitated subjects was slower at recover from the loading. They applied pressure and measured the gas tension using an indenter at the sacrum. They also did a pressure measurement sitting in a wheelchair on a air cushion with air bellows that could individually be deflated. They put a pressure measurement array on one of the bellows under the iscium.

**Differential Response of Skin and Muscle in the Experimental Production of Pressure Sores [36]**

[37]

This paper describes an experiment on a set of rats, where a pressure ulcer were induced and afterwards the pressure ulcers were covered up randomly with a muscle tissue to see if it was a good load relieving tissue. Their main conclusion is that it is not a good weight bearing tissue.

## 9.4 Computational models of the buttock area

### **In vivo (CT scan) comparison of vertical shear in human tissue caused by various support surfaces [44]**

[8]

This study describes a computational model that is rather complex model assuming poroelasticity in the soft tissue at the buttocks. They look at the change in shear stress, tissue compaction and porepressure over time.

### **Mechanical compression-induced pressure sores in rat hindlimb: muscle stiffness, histology and computational models [16]**

[6]

This paper is a major paper about material properties in the soft tissues and how to model pressure sores. Mostly laying down and pressure sores around the hip, feet, head.

### **Three-dimensional computer model of the human buttocks, in vivo [19]**

[9]

This Paper describes a 3D FEM that are patient specific and used for cushion design. They list all their material properties and the assumptions that were made.

### **A subject-specific FEM model for evaluating buttock tissue response under sitting load [20]**

[38]

This paper describes a simple setup with an ultrasound/pressure probe. They apply pressure to a subject buttocks and look at the deformation. They create a specific FEM based on their measurements.

### **The etiology of pressure ulcers: skin deep or muscle bound? [23]**

[10]

This paper describes a hypothesis that question the etiology of pressure sores. They explain a reasoning behind that pressure sores actually comes from the muscles. They have simple finite element models that show that stress is higher in the muscle tissue.

### **Can loaded interface characteristics influence strain distributions in muscle adjacent to bony prominences? [25]**

[39]

This paper describes a study where a FEM was used to show that pressure distribution measurements maybe shouldn't be used to evaluate the stresses caused by sitting. They find shear strain near the bony

prominence and fat layer. So even with a low interface pressure the stresses can be high around the bones.

#### **Assessment of mechanical conditions in sub-dermal tissues during sitting: a combined experimental-MRI and finite element approach [40]**

[11]

This paper describes a study on measuring stresses in the buttocks. They used a reverse engineering approach. They had healthy subjects sitting in an open MRI scanner with load on and without load on their buttocks. They created a subject specific FEM of each subject and used the displacement they found from the two scans as a boundary condition. They did not sit them in any specific way and they did not measure on paraplegic patients.

#### **Risk factors for a pressure-related deep tissue injury: a theoretical model [42]**

[3]

This paper describes a FEM approach where a simple theoretical model was created. They used Hertz contact theory. They only applied vertical force from the ischial tuberosity to the gluteus maximus. Both were theoretical shaped.

#### **Evaluation of a new sitting concept designed for prevention of pressure ulcer on the buttock using finite element analysis [46]**

[40]

This paper describes a validation of a sitting concept where they remove the rear end of the seat in a wheelchair. From my point of view I am not sure that you actually can sit a paraplegic patient in that chair and if you can, I think that the shear is much worse than the pressure you relief from. The thigh are more exposed to the load.

#### **Finite Element Analysis of Undermining of Pressure Ulcer with a Simple Cylinder Model [47]**

[7]

This paper describes a FEM that are very simple. The body is a cylinder and there are only two types of materials, soft and hard. They model how the stress changes as a function of undermined tissue. When necrotic tissue spreads out under the skin the stress due to pressure changes.

#### **A mixture approach to the mechanics of skin [45]**

[41]

This paper presents a set of equations that describes the material properties of the human skin. They use an approach that models a mixture of solids and fluids.

#### **In Vivo Muscle Stiffening Under Bone Compression Promotes Deep Pressure Sores [55]**

[5]

This paper is rather extensive. They do an experiment with 42 rats. They measure the muscle stiffness during compression and see that it is larger. They then apply these characteristics to a FEM model of the human buttocks and see that the muscles are subjected to more and more stress.

#### **Modeling the body/chair interaction – an integrative experimental – numerical approach [77]**

[42]

This paper describes a simple FEM where deformations are applied from contact measurements from when a subjects sits down in a chair. The approach seems kind of strange.

#### **Seat-Interface Pressure on Various Thicknesses of Foam Wheelchair Cushions: A Finite Modeling Approach [78]**

[43]

This paper start with an experimental setup. A subject sits on a pressure distribution mat and a cushion. They change cushion thickness and measure the pressure. The pressure distribution was applied to a very simple FEM of the buttocks. And the shear stress and max interior stress was plottet as a function of the cushion thickness.

## **9.5 Cell response to stresses caused by sitting**

[10]

The most relevant papers describing how the different mechanical stresses affects the cell behavior.

#### **Compression-induced deep tissue injury examined with magnetic resonance imaging and histology [18]**

[44]

This paper describes a study on rats where pressure was induced on muscles in the leg, they were relieved from pressure and dissected and histological samples were taken 1,4 and 20 hours after they were relieved from pressure. They saw big changes and necrotic tissue. Interesting experiment but not very relevant for this project.

#### **Compressive deformation and damage of muscle cell subpopulations in a model system [41]**

[45]

This paper describes a muscle cell study where they subject the different types of cells to different strains. They found that one type of cell were more sensitive to strain. The elongated myotubes were more susceptible to damage.

#### **Temporal differences in the influence of ischemic factors and deformation on the metabolism of engineered skeletal muscle [17]**

[46]



This paper describes a study made on engineered muscle tissue that they subject to starving of nutrients and no oxygen and compress and they see that there are an increased cell death.

#### **Quantifying pressure sore-related muscle damage using high-resolution MRI [58]**

[47]

This paper describes an experiment where five rats were MRI scanned after load was applied to a muscle. They could see the muscle damage at the MRI scans and therefore they suggest that MRI scans are used instead of histology. Note that they used a 4.7T scanner and small coils with a diameter of 16mm.

## **9.6 Pressure Sore in General**

The most relevant papers describing stats, prevalences, incidences, scales and other related subjects.

#### **Medical complications during acute rehabilitation following spinal cord injury--current experience of the Model Systems [30]**

[48]

This paper studied how big a problem pressure ulcers are. They found that in a group of 1600+ SCI patients 23.7% had a problem with pressure ulcers during their rehabilitation period.

#### **A new pressure ulcer risk assessment scale for individuals with spinal cord injury [31]**

[49]

This paper describes the development of a new scale for assessing the pressure sore risk factor. They studied 219 subjects over 2 years.

#### **The biomechanics of sitting acquired pressure ulcer in patients with spinal cord injury or lesions [50]**

[2]

This paper is a review paper of the current understanding of sitting acquired deep tissue ulcers. They point out that deeper tissue is more vulnerable to pressure. They also say that material properties change when tissue die. Gefen goes through how loading affects the tissue over time. Patients with muscle atrophy have changed geometry.



# 10 Biomechanics Theory and Modelling

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Because of the fact that the literature published in the pressure ulcer area deals with different types of mechanical loading it was found necessary to study the different types of mechanical loading to gain a better understanding of these. The combined effect of pressure, pressure gradient, force and shear force from a mechanical point-of-view were investigated. This has been described in a number of standard text books. Therefore this worksheet will take a more applied approach where a few simple computational models will be used as examples. The whole chapter is written based on [50]

## 10.1.1 Force

Force is defined by Newton's second law  $F = ma$ , where "m" is mass and "a" is acceleration so basically force is defined as the action that causes a body of mass "m" to accelerate. The SI-unit of force is N,

Newton which is a derived unit from the base SI units,  $kg \frac{m}{s^2}$ .

Generally speaking about normal forces acting on a chair seat because someone is sitting on it, you are referring to the force caused by the gravitational acceleration on the mass of the subject sitting on the chair.

A subject sitting on a chair the mass and the gravitational acceleration will cause a vertical force on the chair. This gravitation on the human body is given uniquely by the body weight. However the way the force is transferred from body to seat can be changed by for example by sitting on other cushions, by change of the interface area between the chair and the body, or by change of the location of the support points offered by the chair.

Force can be measured using a force platform or a load cell. A force platform is usually built by four load cells that are placed in the corners of a plate and from those it is possible to calculate center of force, moments and vertical-horizontal forces.

## 10.1.2 Pressure

Pressure is defined as the force per area acting perpendicularly on a surface. It is formulated as

$p = \frac{F}{A}$  or  $p = \frac{dF}{dA}$  where "p" is the pressure and "F" is the normal force acting on the area "A". The SI

unit used for pressure is Pa, Pascal. Pascal is also a derived unit from the base SI units,  $\frac{N}{m^2}$ .

When talking about pressure related to sitting in a chair the interface between the buttock tissue and the chair seat is in focus. The vertical force that the chair is subjected to by the body weight can be

described in higher detail by the pressure distribution underneath the buttocks. The pressure distribution is measured by for instance a pressure mat equipped with a lot of small pressure sensors that react to vertical force on the surface. As it comes out clearly, pressure is linked to force but takes the area into account. When sitting on a chair the force is decided based on our body weight, but the pressure also takes area into account. Therefore it is often the pressure or peak pressure that is measured and it can be controlled by for example making subjects sit on a cushion that increases the weight-bearing area and therefore lowers the pressure.

### 10.1.3 Stress

Stress is in many ways similar to pressure, but seen from a more material physics point-of-view. Stress is also measured in load per area and it is formulated as  $\sigma = \frac{dP}{dA}$ , where “dP” is the load for acting on a small cross-sectional area defined by “dA”. The stress,  $\sigma$  is as indicated also measured in Pascal, Pa and it is measured positive in tensile stress and negative in compressive stress. There are other kinds of stress that also relate to material mechanics, for instance shear stress. This section will concentrate on normal stress in for instance a cube with a load on top. This can be illustrated by the example where you have a cube with the dimension 1x1x1 meter and apply a uniform load of 1000 N on the top.

$$\sigma = \frac{P}{A} = \frac{1000N}{1m^2} = 1000Pa$$

So the stress that the cube is being subjected to is 1000 Pa. This was a simple calculation where the problem was a simple cube with a uniform load, compared to a more complex problem with complicated structures and varying loads as you would have if trying to calculate stresses on the buttocks of a seating person. The Finite Element Method (FEM) can be used when solving more complex problems. The simple problem from before has been solved as a FEM model using ANSYS. The model was a 2-D model of a cube 1x1x1 m. The material is linear isotropic elastic with a Young’s modulus of 30MPa and a Poisson’s ratio of 0<sup>3</sup>. The square is constrained at the bottom in all directions i.e. in all degrees of freedom (DOF). At **Error! Reference source not found.** the load is applied on the top of the square as a pressure of 1 kPa, i.e. 1 kN on the 1m<sup>2</sup> surface. **Error! Reference source not found.** illustrates the result seen from the side, where the two values in the purple circle “SMX” and “SMN” are the minimum and maximum stress values in the y-direction. Both values are 1000 which agrees with the calculation done above. **Error! Reference source not found.** shows the result for the same geometry as **Error! Reference source not found.** but with half the load applied to half the area. The load is applied to the right side of the square. This solution is far more complex as indicated at **Error! Reference source not found.**. For instance there are stresses in the cube from 242 to -1240 Pa.

---

<sup>3</sup> A measure of compressibility that will be explained in a later section



Figure 33 show a solution in ANSYS to a square constrained in the bottom line and a pressure applied on the top.

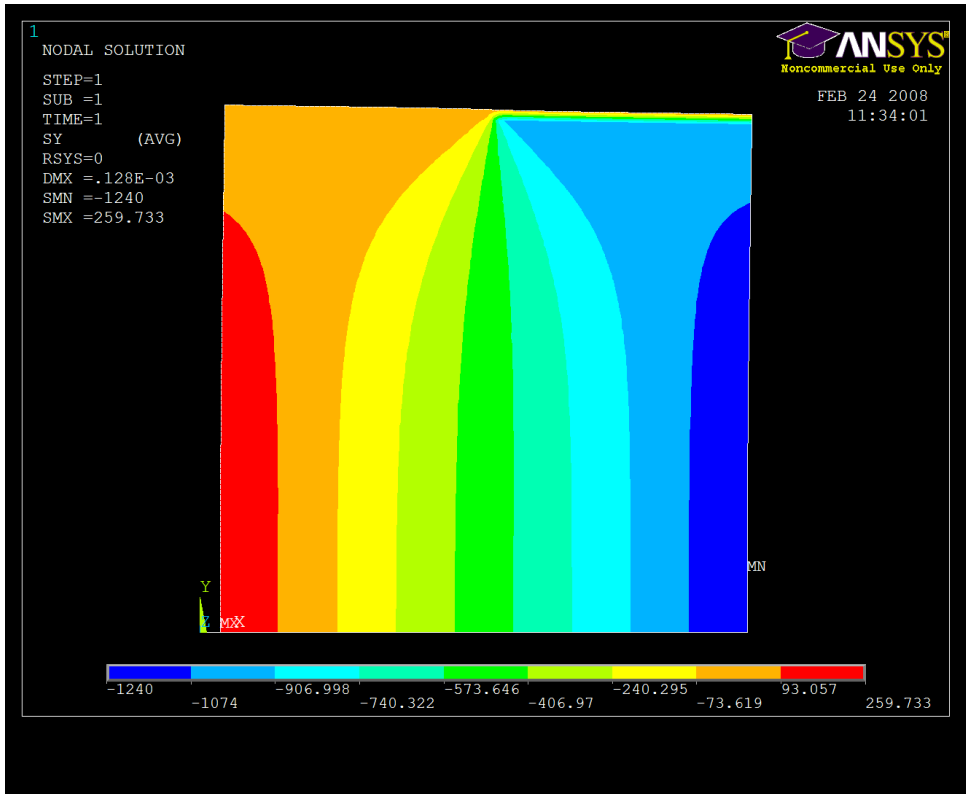


Figure 34 show how the stresses distribute in a square where only half of it is loaded.

### 10.1.4 Strain

Deformation in a material subjected to a specific load causes stress. The deformation is also named strain, which is a relative measure of deformation and is defined as deformation per unit length. Strain is normally denoted by the Greek letter epsilon,  $\epsilon$  and written as:

$$\epsilon = \frac{\delta}{L}$$

Where  $\delta$  is the deformation and “L” is the initial length and obviously the strain is unit less. The strain can also be used to estimate the force that is applied to an object if the stiffness and compressibility is known; this will be explained in the section about modulus.

### 10.1.5 Shear

Shear force is a force acting parallel to a surface and often it causes shear stress inside the material, just like the normal force causes stress in a material. If a shear force is causing deformation it is called shear strain. Shear stress is calculated from:

$$\tau_{avg} = \frac{P}{A}$$

Where  $\tau$  is the average shear stress and “P” is the load applied parallel to a surface and “A” is the area. Shear stress cannot be considered to be uniform and therefore the shear stress value calculated from is an average value for the shear stress, to illustrate how non uniform the shear stress is in a very simple example we again use the same cube as earlier but this time we constrain the bottom surface and then apply 1000N parallel to the top surface, and the result is illustrated as a contour plot at **Error! Reference source not found.** The calculation of the average shear stress looks like this:

$$\tau_{avg} = \frac{P}{A} = \frac{1000N}{1m^2} = 1000Pa$$

It is obvious that the distribution of shear stresses inside an object subjected to shear forces is complex. The range of shear stress that is calculated in the FEM is from -170 – 1620Pa. Shear stress is also present, even when applying normal forces, this will be explained later in this section.

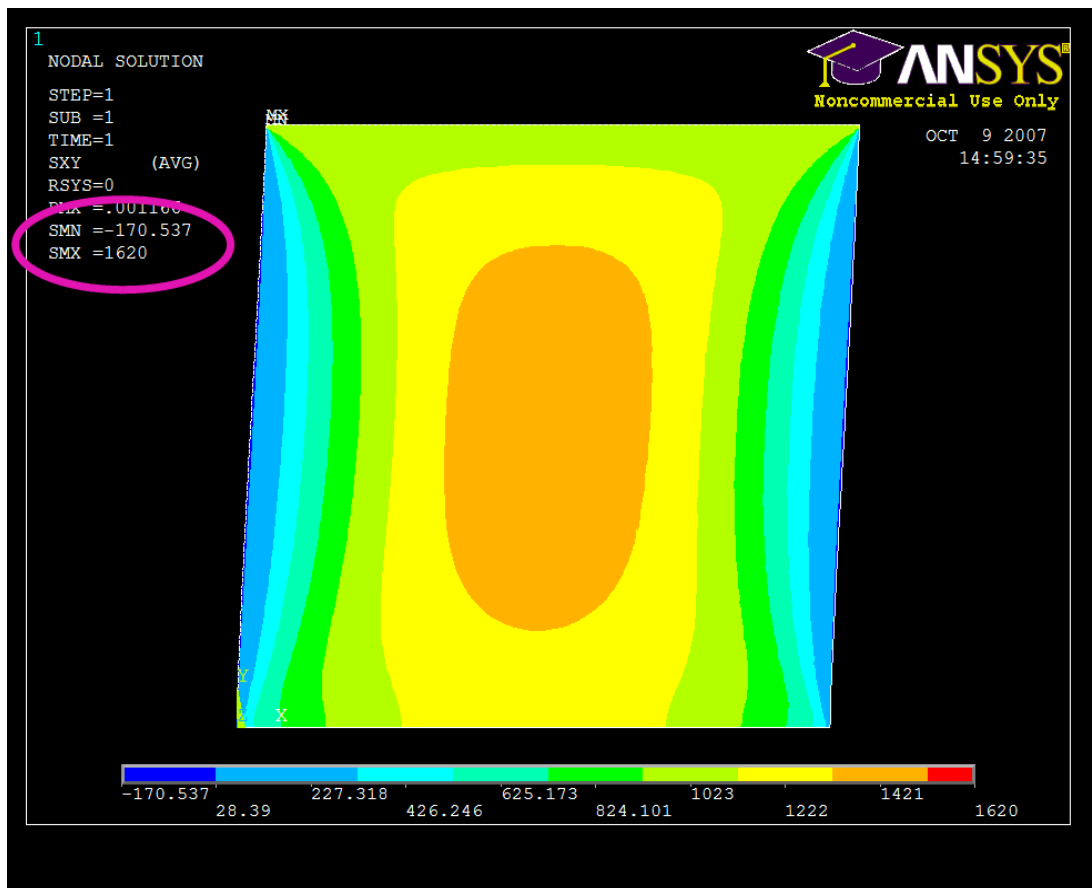


Figure 35 show the shear stress contour plot of a model that have been subjected to 1000N shear force

### 10.1.6 Modulus

Modulus of elasticity is a measure of stiffness and is also called Young's modulus. Young's modulus is a material property that all materials have. The higher modulus value the stiffer and they are and thereby harder to deform. Hooke's law describes the relations between stress, strain and modulus. Hooke's law is written as:

$$\sigma = E\varepsilon$$

Where "E" is the modulus of elasticity,  $\varepsilon$  is the strain and  $\sigma$  the stress. This law gives the possibility of calculating the stress inside an object if the deformation, i.e. strain and modulus of elasticity is known. To give an example we can use the cube we used earlier. The cube is still 1x1x1 m and it is constrained at the bottom. We give the material that the cube is made of a Young's modulus of 3 MPa and a Poisson's ratio at 0. Then a displacement of 10% strain was applied on the top of the cube. The calculations look like this:

$$\sigma = E\varepsilon = 3\text{MPa} \cdot 0.1 = 0.3\text{MPa}$$

$$\Updownarrow$$

$$F = \sigma A = 0.3\text{MPa} \cdot 1\text{m}^2 = 300\text{kN}$$

This means that it takes 300kN to compress a cube of the size of one m<sup>3</sup> and  $E = 3\text{MPa}$  10%. This calculation can be modeled just the same as previously done using a FEM model. The result is showed at **Error! Reference source not found.** where inside the purple circle the min and max stress in Pascal is showed and correspond exactly with the result we calculated above.





Figure 36 show the stress that the cube is subjected to due to the deformation of 10 % strain

The elastic modulus of a material can also be more complex, as some materials are not linear for example they become more and more stiff the more they are stretched.

### 10.1.7 Poisson's ratio

When a material is stretched in one direction it has a tendency to get thinner in the other two directions, Poisson's ratio is a measure of this tendency. Poisson's ratio is calculated by this formula:

$$\nu = -\frac{\text{lateral strain}}{\text{axial strain}} = \frac{\epsilon_y}{\epsilon_x}$$

Poisson's ratio is a material property that is defined by the specific material. The FEM models used so far have all been with a Poisson's ration set to zero because it makes things easier to look at and the previous models were trying to illustrate a specific stress due to some specific loading. Most materials have Poisson ratios in the interval 0-0.5. A Poisson's ratio of zero means that if you compress or stretch the material it doesn't change thickness, which is rare, but cork has a Poisson ratio very close to zero. Steel has a Poisson's ratio around 0.3 and rubber around 0.5, which basically means that rubber is

incompressible (at least for small deformations). So how is Poisson's ratio for the soft tissue in the human buttocks? Well the answer to that is presumably complex, but since the soft tissues mostly consist of water and water is incompressible, a good guess would be close to 0.5. If we take the model from **Error! Reference source not found.** and set the Poisson's ratio of the material to 0.5 and apply the same load we would get the result showed at **Error! Reference source not found.** where there is something going on in the bottom corners, this is due to the displacement constraint of the bottom surface. It is also clear that the solution is not as simple as it is in **Error! Reference source not found.**, which is due to the incompressible material used in this experiment, the stress in most of the material seems to be less than in the experiment from **Error! Reference source not found.**, this is due to the fact that the stress is calculated as the load/area ratio and because of the incompressibility the cross sectional area of the cube becomes bigger when it is compressed.

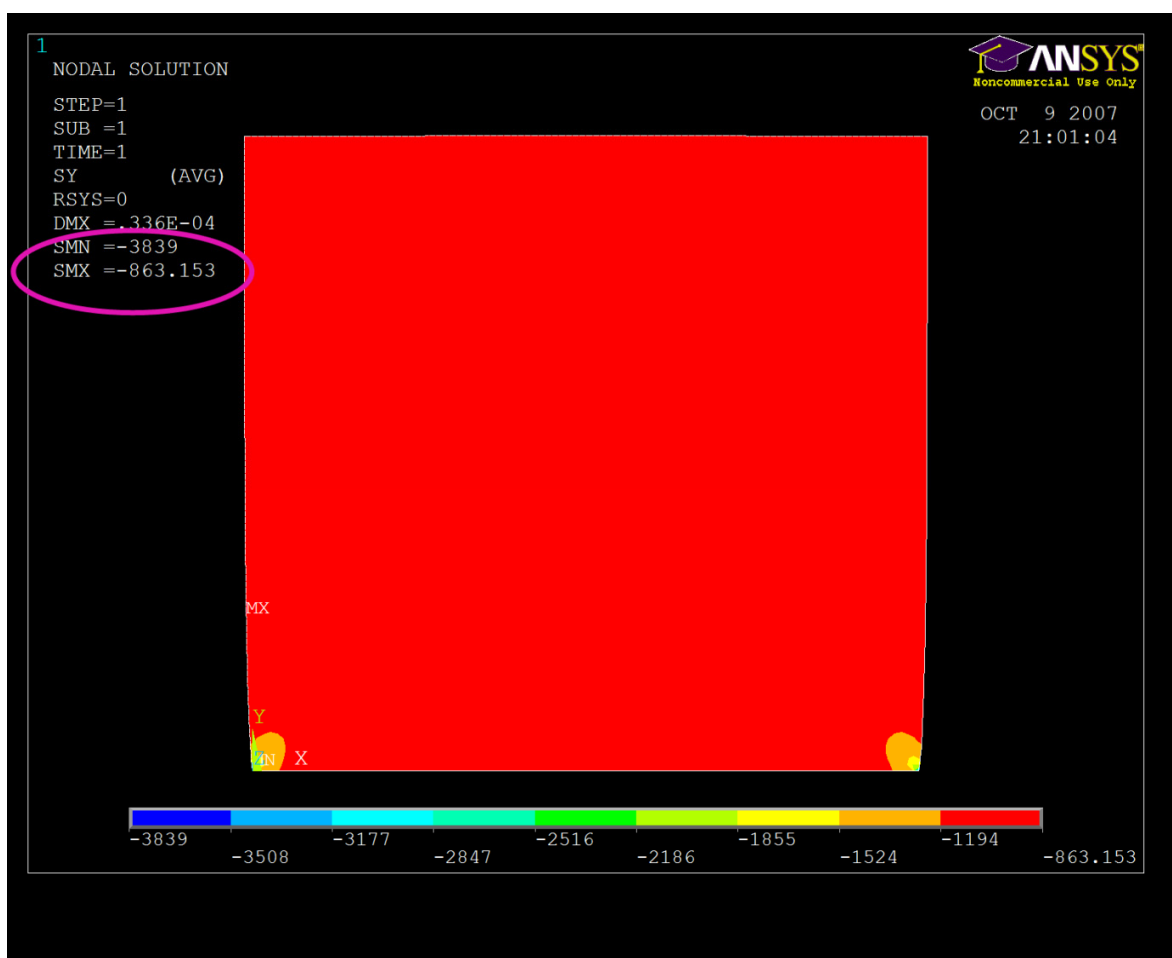


Figure 37 show the result from the same experiment as figure 1, but with an incompressible material

### 10.1.8 Principal Stresses

Considering the stresses in a material point and expressed in a given coordinate system, this coordinate system can be rotated until the shear stresses are zero. If the shear stress is zero for a plane which

indicates that the stress is in the normal direction. For instance hydrostatic pressure causes no shear stress because the stress is always normal to the plane.

The three dimensional Cauchy stress tensor is defined as:

$$\sigma_{ij} = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}$$

Where the tensor is symmetric because of the fact that the plane zy is the same as yz, at least for steady state problems.

The coordinate system that the tensor is defined in, which is illustrated at Mohr's circle that can be seen at **Error! Reference source not found.** where the circle is drawn for plane stress. The circle illustrates the shear stress as a function of normal stress and rotating around the circle illustrates rotating the coordinate system for the stress tensor.

The circle show that there always can be found a way to rotate the coordinate system that removes the shear stresses. By choosing the coordinate system to be equal to the principal axes the equations describing the stress applied to a point becomes relatively simple and there will be no shear stress.

C is the average normal stress,  $\sigma_{ave}$ . The point A is the maximum principal stress,  $\sigma_1$  and B is the minimum principal stress,  $\sigma_2$ . The point X is defined as  $(\sigma_x, -\tau_{xy})$  and Y is  $(\sigma_y, \tau_{xy})$ . The circle can be followed around and the maximum shear stress can be found equal to  $R_m$ . The angle  $2\theta_p$  is the angle between the normal stress and the maximum principal stress, i.e. the angle that if the coordinate system was rotated  $2\theta_p$  there would be no shear stress.

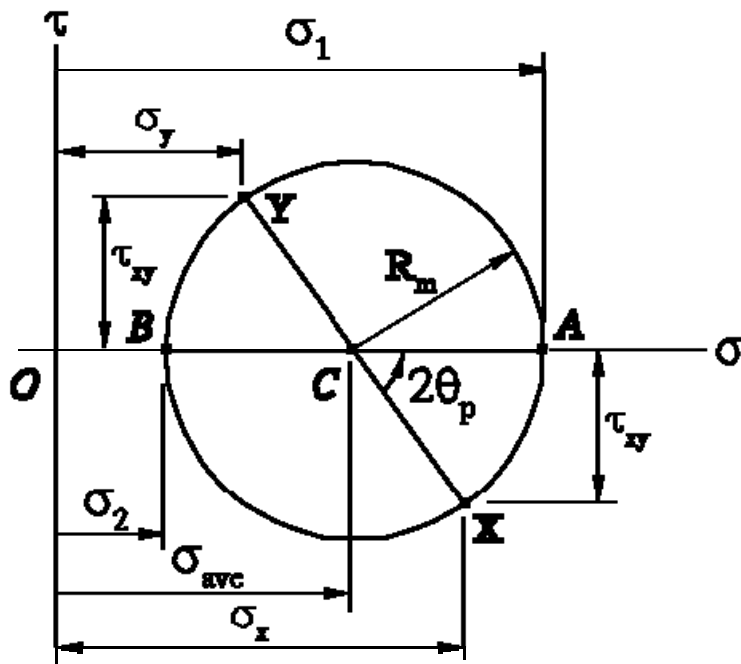


Figure 38 illustrate Mohr's circle for plane stress.

Mohr's circle is a rather clever circle that has been very useful when trying to find the maximum component of normal stress or shear stress. This could be used to for example to estimate structures of brittle and ductile materials respectively.

To illustrate the point **Error! Reference source not found.** show a model of the same cube as used earlier, but here the cube is constrained in the bottom and force is applied to the top. The contour plot at shows shear stress in the  $xy$ -plane caused by the axial force only, for comparison Figure 40 show the same experiment but the compressive stress is plotted.

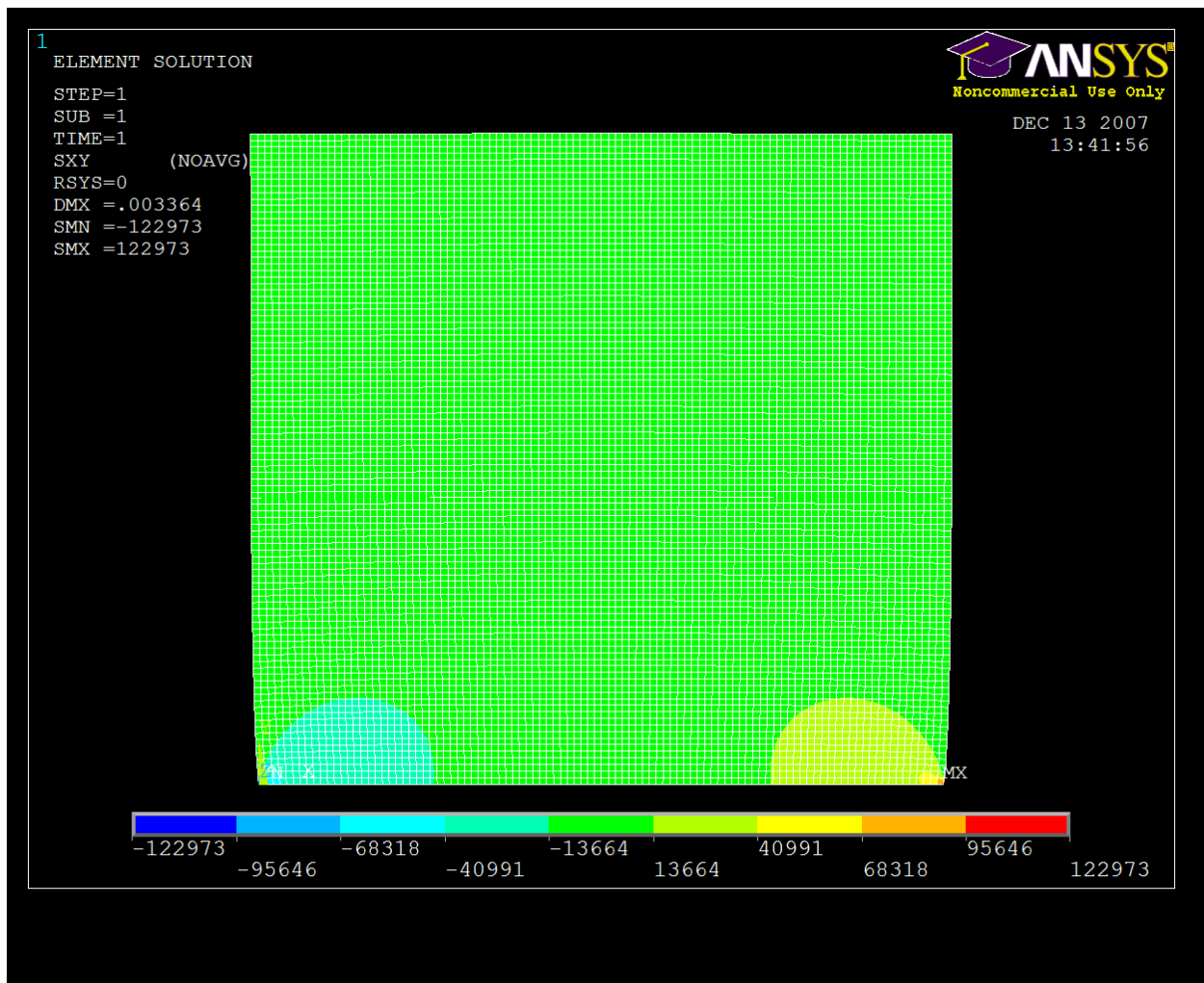


Figure 39 is the same cupe as used previously with a load applied to the top surface. The plot is the shear stress in the xy-plane.

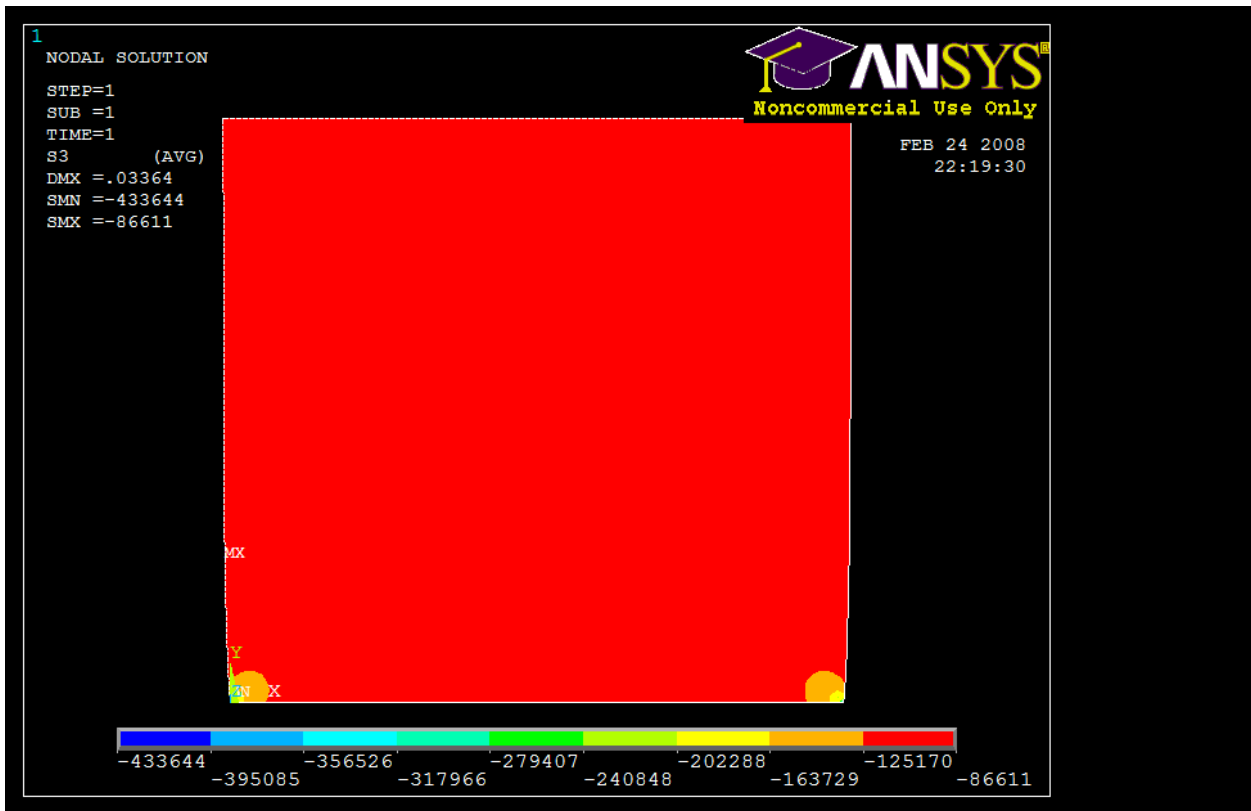


Figure 40 show the 3. principal stress for the same experiment as Error! Reference source not found.

### 10.1.9 Von Mises

When looking at model results from FEM models as the ones in the examples above stresses are plotted as contour plots but for example **Error! Reference source not found.** where the stress is seen in the y-direction, what about the other directions? To illustrate this **Error! Reference source not found.** is the same setup but the contour plot show the stress in the x-direction, which doesn't really look like the one in the y-direction.

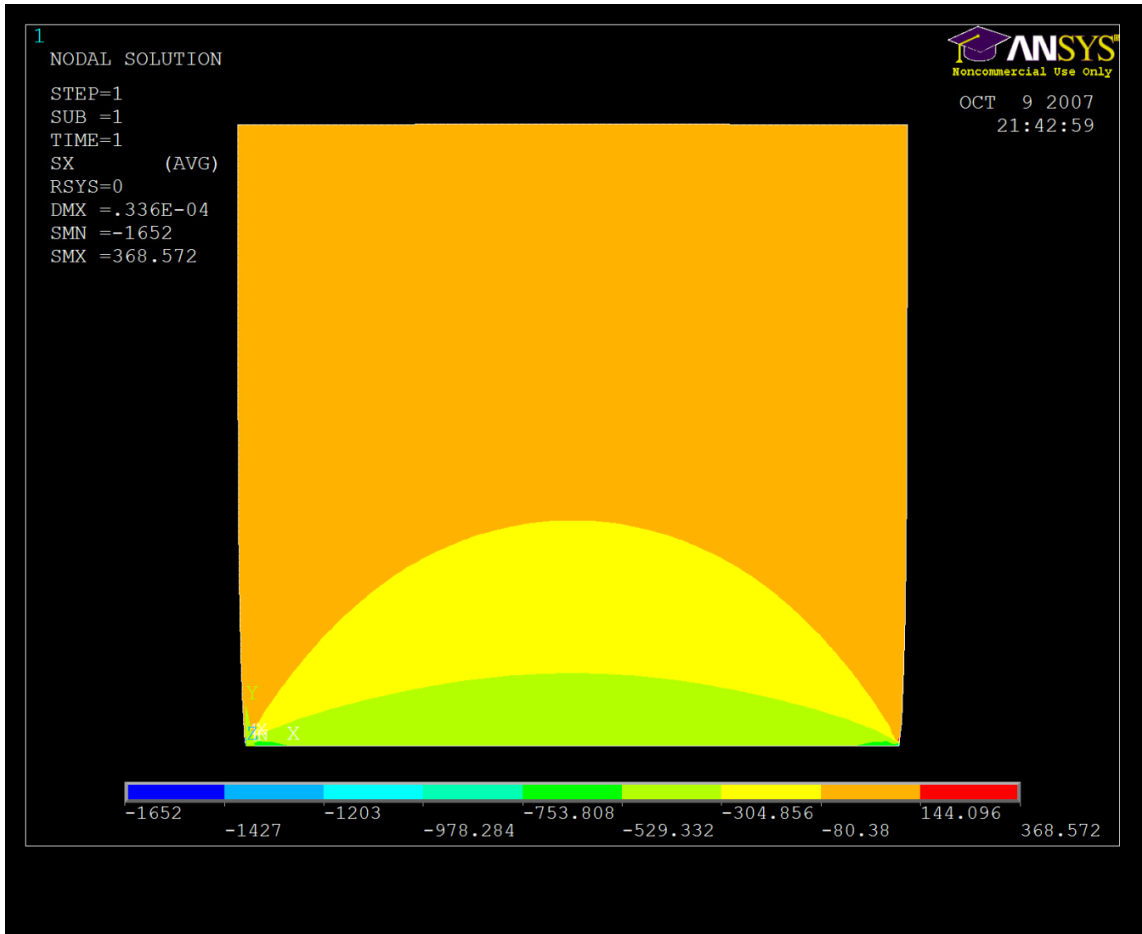


Figure 41 illustrates the same result as figure 5, but the stress seen in the x-direction instead for the y-direction

Instead of a stress measure in a single axis the Von Mises stress,  $\sigma_v$  can be used. Von Mises stress is a stress measure on the overall magnitude of the stress in the object. It can be calculated from the principal stresses or from the normal and shear stresses in an object. If the principal stresses are known they can be used to calculate  $\sigma_v$  by:

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Where  $\sigma_1, \sigma_2, \sigma_3$  are the principal stresses. In an arbitrary Cartesian coordinate system it can be calculated as:

$$\sigma_v = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}{2}}$$

Where the  $\tau$  values are the shear stresses in the three planes. The Von Mises stress is a yield criterion that describes the distortion energy in a given material, i.e. the energy associated with the change in shape in the material. As seen in the equation above the shear stresses are multiplied with 3, compared

to the normal stresses, indicating that those are more important in the criterion. Also noting that if the Von Mises stress is calculated on hydrostatic pressure it would come out as zero.

It is important in pressure ulcer research because so many papers have been published saying the shear stress is important for the pressure ulcer etiology. Von Mises stress is mainly used for ductile material because those are the ones that fail under shear stresses compared to more brittle materials that fail from normal stress. Human tissue seems to have more in common with a ductile material than a brittle one.



# 11 Matlab Scripts

This appendix chapter documents the MatLab scripts that were developed during the project period. The MatLab scripts were used for post processing of the kinematic data measured with the Qualisys motion capture system, and to process the force data measured from the force plates and load cells.

## 11.1 Kinematic post processing

The kinematic data measured using the Qualisys motion capture system were first processed using the Qualisys software where the markers were identified and named. The markers at the chair was named A-L. and the markers placed at the subject were named for example “kneeR” for the marker at the right knee. The naming of the markers has to follow the naming convention showed at Figure 42.

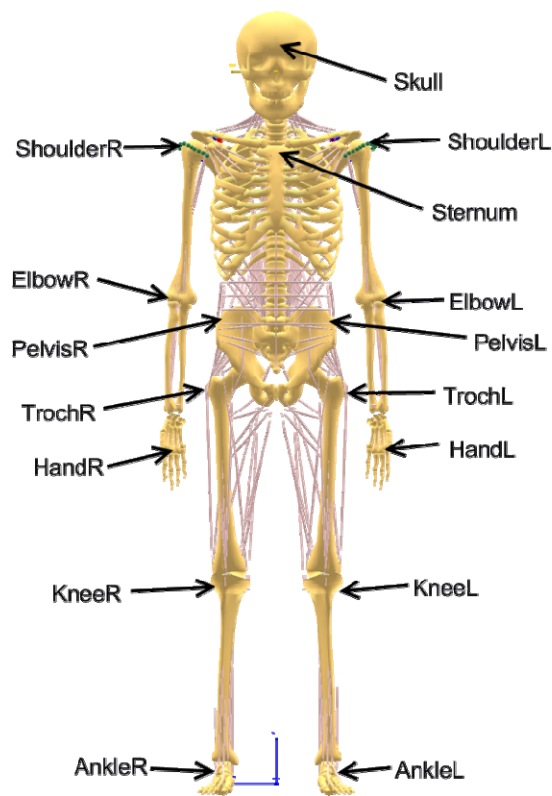


Figure 42 show the marker name convention for the markers placed at the subject to measure how the subject sits.

The markers at the chair should be used by the AnyBody system to position the seat in the right position with respect to gravity and angles and lengths between the different parts of the chair. An origin should also be calculated as the position illustrated at fig xx. It is defined as the intersection of the extension of the vector between the two backrest bars at the right side and the plane of the seat.

The markers placed at the subject was then defined as the vector from the calculated origin to the marker.

### 11.1.1 Qtm2anybody

The main script file is called qtm2anybody indicating that it converts the data from the qtm software into a format that the AnyBody model reads. The qtm is a \*.tsv file which is a tab separated values. The file is read and the header lines are read in order to figure out how much data there is in the file and what each coordinate set represents. The coordinates found in the \*.tsv file are used for calculating the values needed for the AnyBody model and they are written into an input file as AnyVar and AnyVec values.

```
function [Data]=qtm2anybody(filename)

if ~exist('filename', 'var') || isempty(filename)
    [filename, pathname] = uigetfile('*', 'Pick a file');
    filename = fullfile(pathname, filename);
end

%% Find number of samples
fid=fopen(filename, 'r');
Nmarker=textscan(fid, '%s%s', 'headerlines', 2, 'delimiter', '\b\t');
fclose(fid);
Nmarker=str2num(cell2mat(Nmarker{1,2}(1)));
strvar='';
for i=1:Nmarker
    strvar=strcat(strvar, '%s%s%s');
end

%% Find what markers that are in the file and put the mean marker values in
%% a cell together with the marker name
fid=fopen(filename, 'r');
markers=textscan(fid, strvar, 'headerlines', 9, 'delimiter', '\b\t');

fclose(fid);

t=0;
for i=1:length(markers)
    A(:,i)=str2num(cell2mat(markers{1,i}(2:201,1)));
end
Amean=mean(A);
for i=2:Nmarker+1

    markeravg(i-1,1)=markers{1,i}(1,:);
    markeravg(i-1,2)=num2cell(Amean(1,i-1+t));
    markeravg(i-1,3)=num2cell(Amean(1,i+t));
    markeravg(i-1,4)=num2cell(Amean(1,i+1+t));
    Amean(i-1,1:3)=Amean(1,i-1+t:i-1+t+2);
    t=t+2;
end
Amean=Amean(1:Nmarker,1:3)/1000;
%Data.markers=markeravg;
```

```

%% Create vectors on the chair

FE=[Amean(5,1)-Amean(6,1); Amean(5,2)-Amean(6,2);Amean(5,3)-
Amean(6,3)];%%BackrestLeft
BA=[Amean(1,1)-Amean(2,1); Amean(1,2)-Amean(2,2);Amean(1,3)-
Amean(2,3)];%%BackrestRight
FB=[Amean(2,1)-Amean(6,1); Amean(2,2)-Amean(6,2);Amean(2,3)-Amean(6,3)];
DC=[Amean(4,1)-Amean(3,1); Amean(4,2)-Amean(3,2);Amean(4,3)-
Amean(3,3)];%%SeatRight
HG=[Amean(8,1)-Amean(7,1); Amean(8,2)-Amean(7,2);Amean(8,3)-
Amean(7,3)];%%SeatLeft
CG=[Amean(3,1)-Amean(7,1); Amean(3,2)-Amean(7,2);Amean(3,3)-Amean(7,3)];
IJ=[Amean(9,1)-Amean(10,1); Amean(9,2)-Amean(10,2);Amean(9,3)-Amean(10,3)];
KL=[Amean(11,1)-Amean(12,1); Amean(11,2)-Amean(12,2);Amean(11,3)-Amean(12,3)];
IK=[Amean(9,1)-Amean(11,1); Amean(9,2)-Amean(11,2);Amean(9,3)-Amean(11,3)];
%% Calc Seat Angles
z=[0; 0; 1];

seatRange=acosd(dotProd(z,DC)/(vecLen(z)*veclen(DC)));
seatLangle=acosd(dotProd(z,HG)/(vecLen(z)*veclen(HG)));
Data.angles.seat=-90+(seatRange+seatLangle)/2;

SeatNormVecR=scalProd(DC,CG);
SeatNormVecL=scalProd(HG,CG);
meanSeatNormVec=(SeatNormVecL+SeatNormVecR)/2;

%% Calc relative backrest angle

BackNormVecR=scalProd(BA,FB);
BackNormVecL=scalProd(FE,FB);
meanBackNormVec=(BackNormVecL+BackNormVecR)/2;
seatLangle=acosd(dotProd(BackNormVecL,BackNormVecR)/(vecLen(BackNormVecL)*veclen(BackNormVecR)));
Data.angles.RelBackRestAngle=(acosd(dotProd(meanBackNormVec,
meanSeatNormVec)/(vecLen(meanBackNormVec)*veclen(meanSeatNormVec))));

%% Find Origin
ScalarR=estimateOrigin(Amean(4,:),Amean(3,:),Amean(2,:),Amean(1,:))
ScalarL=estimateOrigin(Amean(8,:),Amean(7,:),Amean(6,:),Amean(5,:))
meanScalar=(ScalarL+ScalarR)/2;
Data.Origin=transp(Amean(3,1:3))+(meanScalar*DC)

%% SeatLength

Data.Dist.Seat=(vecLen(Data.Origin-transp(Amean(4,1:3))))

%% Seat vs. footrest
Data.Dist.heightSeatFootrest=((Amean(4,3)-Amean(9,3))+(Amean(8,3)-
Amean(11,3)))/2
Data.Dist.xDistFootRest=((Amean(9,2)-Amean(4,2))+(Amean(11,2)-Amean(8,2)))/2
%% Height Backrest
Data.Dist.heightLowBackrestBar=(vecLen(Amean(2,1:3)-
Amean(3,1:3))+vecLen(Amean(6,1:3)-Amean(7,1:3)))/2
Data.Dist.BackrestBarDist=(vecLen(BA)+vecLen(FE))/2
Upperheight=Data.Dist.heightLowBackrestBar+Data.Dist.BackrestBarDist;

```

```

%% Dimensions
%Seat
Data.Dist.SeatLength=(vecLen(Data.Origin-transp(Amean(4,1:3))));
Data.Dist.SeatWidth=vecLen(CG);
%Backrest
Data.Dist.BackRestWidthLower=vecLen(FB);
Data.Dist.BackRestWidthUpper=vecLen(Amean(1,1:3)-Amean(5,1:3));
%Footrest
Data.Dist.FootrestWidth=vecLen(IK);
Data.Dist.FootrestLength=(vecLen(IJ)+vecLen(KL))/2;

%% Calculate the marker pos. from the origin
for i=1:Nmarker
    switch cell2mat(markeravg(i,1))
        case 'skull'
            Data.pos.skull=(transp(Amean(i,1:3))-Data.Origin);
        case 'sternum'
            Data.pos.sternum=(transp(Amean(i,1:3))-Data.Origin);
        case 'shoulderR'
            Data.pos.shoulderR=(transp(Amean(i,1:3))-Data.Origin);
        case 'shoulderL'
            Data.pos.shoulderL=(transp(Amean(i,1:3))-Data.Origin);
        case 'elbowR'
            Data.pos.elbowR=(transp(Amean(i,1:3))-Data.Origin);
        case 'elbowL'
            Data.pos.elbowL=(transp(Amean(i,1:3))-Data.Origin);
        case 'handR'
            Data.pos.handR=(transp(Amean(i,1:3))-Data.Origin);
        case 'handL'
            Data.pos.handL=(transp(Amean(i,1:3))-Data.Origin);
        case 'pelvisR'
            Data.pos.pelvisR=(transp(Amean(i,1:3))-Data.Origin);
        case 'pelvisL'
            Data.pos.pelvisL=(transp(Amean(i,1:3))-Data.Origin);
        case 'trochR'
            Data.pos.trochR=(transp(Amean(i,1:3))-Data.Origin);
        case 'trochL'
            Data.pos.trochL=(transp(Amean(i,1:3))-Data.Origin);
        case 'kneeR'
            Data.pos.kneeR=(transp(Amean(i,1:3))-Data.Origin);
        case 'kneeL'
            Data.pos.kneeL=(transp(Amean(i,1:3))-Data.Origin);
        case 'ankleR'
            Data.pos.ankleR=(transp(Amean(i,1:3))-Data.Origin);
        case 'ankleL'
            Data.pos.ankleL=(transp(Amean(i,1:3))-Data.Origin);
    end
end

%% Write the values that are needed in the AnyBody file
fid =
fopen('C:\Users\cgammel\Documents\uni\10.semester\AnyBody\Repository.6.5\ARep\
AalborgExperimental\SeatedHumanShear - Chr\Input.txt', 'w');
%Dimensions

```

```

%Seat
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'SeatLength=', Data.Dist.SeatLength, ';');
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'SeatWidth=', Data.Dist.SeatWidth, ';');
%Backrest
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'BackrestLowerWidth=',
Data.Dist.BackRestWidthLower, ';');
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'BackrestUpperWidth=',
Data.Dist.BackRestWidthUpper, ';');
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'BackrestHeightLower=',
Data.Dist.heightLowBackrestBar, ';');
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'BackrestHeightUpper=', Upperheight, ';');
%Footrest
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'FootrestWidth=',
Data.Dist.FootrestWidth, ';');
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'FootrestLength=',
Data.Dist.FootrestLength, ';');
%Dist
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'FootRestSeatLinY=',
Data.Dist.heightSeatFootrest, ';');
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'FootRestSeatLinX=',
Data.Dist.xDistFootRest, ';');
%Angles
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'SeatGlobalRotZPos=',
Data.angles.seat, ';');
fprintf(fid, '%s %s %f%s\n', 'AnyVar', 'SeatBackRestRotZPos=',
Data.angles.RelBackRestAngle, ';');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'Origin={', Data.Origin, '};');
%positions
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'skull={',
Data.pos.skull, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'sternum={',
Data.pos.sternum, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'shoulderR={',
Data.pos.shoulderR, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'shoulderL={',
Data.pos.shoulderL, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'elbowR={',
Data.pos.elbowR, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'elbowL={',
Data.pos.elbowL, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'handR={',
Data.pos.handR, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'handL={',
Data.pos.handL, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'pelvisR={',
Data.pos.pelvisR, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'pelvisL={',
Data.pos.pelvisL, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'trochR={',
Data.pos.trochR, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'trochL={',
Data.pos.trochL, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'kneeR={',
Data.pos.kneeR, '};');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'kneeL={',
Data.pos.kneeL, '};');

```

```
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'ankleR={',
Data.pos.ankleR, '});');
fprintf(fid, '%s %s %f, %f, %f%s\n', 'AnyFloat', 'ankleL={',
Data.pos.ankleL, '});');
fclose(fid)
```

### 11.1.2 Additional scripts

To ease the main script a bit a few additional functions were made because some of the operations had to be used more than once, for example calculating the dot product between two vectors or the scalar product to calculate a angle between two vectors. Also calculating the vector length had to be used several times, why it was scripted. The additional functions can be found here:

#### vecLen – Calculates the vector length

```
function [lengthVec] = vecLen(a)
if length(a)==3
    lengthVec=sqrt(a(1)^2+a(3)^2+a(2)^2);
elseif length(a)==2
    lengthVec=sqrt(a(1)^2+a(2)^2);

end
```

#### scalProd – Calculates the scalar product

```
function [normVec]=scalProd(a,b)
normVec=[(a(2)*b(3)-a(3)*b(2)), (a(3)*b(1)-a(1)*b(3)), (a(1)*b(2)-a(2)*b(1))]
```

#### estimateOrigin – Estimates the origin

```
function [scalar] = estimateOrigin(A1,A2,A3,A4)
%This function takes four positions as input, A1, A2 and A3 A4 which are the
%marker at the right side of the chair, the right side of the seat and
%backrest.

%% Calculations
b=abs(A3(3))-abs(A2(3));
a=abs(A3(2))-abs(A2(2));
c=vecLen((A3-A2));
e=vecLen((A1-A2));
d=vecLen((A3-A1));
D=acosd(dotProd((A1-A2),((A2-A3))/(vecLen((A2-A3))*vecLen((A1-A2)))));
El=acosd(dotProd((A3-A2),((A4-A3))/(vecLen((A2-A3))*vecLen((A4-A3)))));
F=180-D-El;
el=sind(El)*(c/sind(F));
scalar=el/e
```

#### dotProd – Calculates the dot product

```
function [aDOTb] = dotProd(a,b)
aDOTb=a(1)*b(1)+a(2)*b(2)+a(3)*b(3)
```

## 11.2 Force Post Processing

The forces measured at the chair were recorded by Mr.Kick. The output from the force plates and load cells were voltages at the 36 different channels. Each force plate or load cell had a sensitivity matrix that had a multiplication factor to calculate the force from the voltage. The matrix also included crosstalk between the different channels.

The script was called calcForce and can be seen at 11.2.1. Basically it loads the calibration matrixes and the file saved by Mr.Kick that holds all the data. In the beginning of the script the gain and excitation voltage were declared for each of the force plates / load cells.

The force was calculated by the formula:

$$F_f(\text{load}) = V_{f_{out}} / (V_{f_{exc}} S_f G_f 1e^{-6})$$

Where the  $F_f$  is the force,  $V_{f_{out}}$  is the output voltage from the amplifier,  $S_f$  is the sensitivity matrix for the force plate and  $G_f$  is the gain.

### 11.2.1 calcForce

```
function [data]=calcForce(filename)

load(filename)
load('calMat.mat')
Forces=mean(dat1001)

%% Declaration of the different forceplates/loadcells

%BRT loadcell 4755
brtGain=1000;
brtVb=10;

%BLT loadcell 4756
bltGain=1000;
bltVb=10;

%BRB load cell 3850
brbGain=1000;
brbVb=10;

%BLB loadcell 3851
blbGain=1000;
blbVb=10;

%seat forceplate
seatGain=4000;
seatVb=10;

for i=1:length(Forces(:,1))
    %BRT
```

```

        data.rawForce.brtF(i,:)=transp((Forces(i,1:6)/BRT4755)/(brtGain*brtVb*10^-
6));

        %BLT
data.rawForce.blbF(i,:)=transp((Forces(i,7:12)/BLT4756)/(bltGain*bltVb*10^-
6));

        %BRB
data.rawForce.brbF(i,:)=transp((Forces(i,13:18)/BRB3850)/(brbGain*brbVb*10^-
6));

        %BLB
data.rawForce.blbF(i,:)=transp((Forces(i,19:24)/BLB3851)/(blbGain*blbVb*10^-
6));

        %seat
data.seatF(i,:)=transp((Forces(i,25:30)/Seat3964)/(seatGain*seatVb*10^-
6));

end

data.backRestTop=data.rawForce.brtF+data.rawForce.blbF;
data.backRestBot=data.rawForce.brbF+data.rawForce.blbF;

```

## 11.3 Generating the Input File for AnyBody

The input file for AnyBody had to include all the motion data, on top of that the force data had to be calculated for the same posture, so it could be compared with the output from the AnyBody model.

The CalcTotal file takes motion and force data as input and calculate everything that is necessary for comparing to the anybody output.

### 11.3.1 CalcTotal

```

[filename, pathname] = uigetfile('NisExp\Preprocessed\*', 'Pick a TSV Motion
file');
filenameM = fullfile(pathname, filename);

[filename, pathname] = uigetfile('NisExp\Preprocessed\*', 'Pick a TSV Force
file');
filenameF = fullfile(pathname, filename);

[filename, pathname] = uigetfile('NisExp\NISForce\*', 'Pick a MrKick Force
file');

```



```

filenameF2 = fullfile(pathname, filename);

motion=qtm2anybody(filenameM);
forceFoot=qtmForce2Mat(filenameF);
Force=calcForce(filenameF2);

%% Calc COP Seat
SeatZ0=0.038;
SeatX0=-.002;
SeatY0=-.00042;

seatCOPX=((Force.seatF(1,5)+(SeatZ0*Force.seatF(1,1)))/Force.seatF(1,3))*(-1);
seatCOPY=((Force.seatF(1,4)-(SeatZ0*Force.seatF(1,2)))/Force.seatF(1,3));

gravityForceSeat=(Force.seatF(1,2)*sind(motion.angles.seat))+(Force.seatF(1,3)*cosd(motion.angles.seat));
HorizontalForceSeat=abs((Force.seatF(1,2)*cosd(motion.angles.seat))+(Force.seatF(1,3)*sind(motion.angles.seat)));

%% Calc COP Footrest
footZ0=0.036;
footX0=-.001;
footY0=-.00012;

footCOPX=((forceFoot.FootForce(1,5)+(footZ0*forceFoot.FootForce(1,1)))/forceFoot.FootForce(1,3))*(-1);
footCOPY=((forceFoot.FootForce(1,4)-(footZ0*forceFoot.FootForce(1,2)))/forceFoot.FootForce(1,3));

gravityForceFoot=forceFoot.FootForce(1,3)
horizontalForceFoot=abs(forceFoot.FootForce(1,2))*(-1)
%% calc COP Backrestbar
backrestTopZ0=(210-63.5+53.3)/1000;
backrestBotZ0=(210-63.5+36)/1000;

backRestTopGravityForce=(Force.backRestTop(1,4)/backrestTopZ0)*cosd(motion.angles.seat-motion.angles.RelBackRestAngle+90)+(Force.backRestTop(1,3))*cosd(motion.angles.seat-motion.angles.RelBackRestAngle+180);
backRestBotGravityForce=(Force.backRestBot(1,4)/backrestBotZ0)*cosd(motion.angles.seat-motion.angles.RelBackRestAngle+90)+(Force.backRestBot(1,3))*cosd(motion.angles.seat-motion.angles.RelBackRestAngle+180);
backrestTopHorizontal=abs((Force.backRestTop(1,4)/backrestTopZ0)*sind(motion.angles.seat-motion.angles.RelBackRestAngle+90)+(Force.backRestTop(1,3))*sind(motion.angles.seat-motion.angles.RelBackRestAngle+180));
backrestBotHorizontal=abs((Force.backRestBot(1,4)/backrestBotZ0)*sind(motion.angles.seat-motion.angles.RelBackRestAngle+90)+(Force.backRestBot(1,3))*sind(motion.angles.seat-motion.angles.RelBackRestAngle+180));

```

```

%% Calculate global Center
%The direction vertical
zeroZ=abs((motion.Origin(3,1)-motion.Pos.D(1,3))/2)+motion.Origin(3,1)
seatY=(cosd(motion.angles.seat)*(-SeatZ0))*HorizontalForceSeat;
footY=((((motion.Pos.I(1,3)+motion.Pos.K(1,3))/2)-zeroZ)-
footZ0)*horizontalForceFoot;
backrestBotY=(motion.Pos.B(1,3)-zeroZ)*backrestBotHorizontal;
backrestTopY=(motion.Pos.A(1,3)-zeroZ)*backrestTopHorizontal;

%The horizontal
zeroY=-(abs(transp(motion.Origin)-motion.Pos.C)/2)
seatZ=(zeroY(1,2)+SeatY0+seatCOPY)*gravityForceSeat;
footZ=((((motion.Pos.D(1,2)-transp(motion.Origin(2,1)))/2)-((motion.Pos.I(1,2)-
motion.Pos.J(1,2))/2)-footCOPY)*gravityForceFoot
backrestTopZ=(motion.Pos.A(1,2)-((motion.Pos.D(1,2)-
transp(motion.Origin(2,1)))/2))*abs(backRestTopGravityForce)
backrestBotZ=(motion.Pos.B(1,2)-((motion.Pos.D(1,2)-
transp(motion.Origin(2,1)))/2))*abs(backRestBotGravityForce)
GlobalCenterZ=(seatY+footY+backrestBotY+backrestTopY)/(abs(HorizontalForceSeat
)+abs(horizontalForceFoot)+abs(backrestTopHorizontal)+abs(backrestBotHorizonta
l));
GlobalCenterY=(seatZ+footZ+backrestBotZ+backrestTopZ)/(abs(gravityForceSeat)+a
bs(gravityForceFoot)+abs(backRestTopGravityForce)+abs(backRestBotGravityForce)
);

```

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---

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