Investigation of methods for quantifying sitting postures in cars

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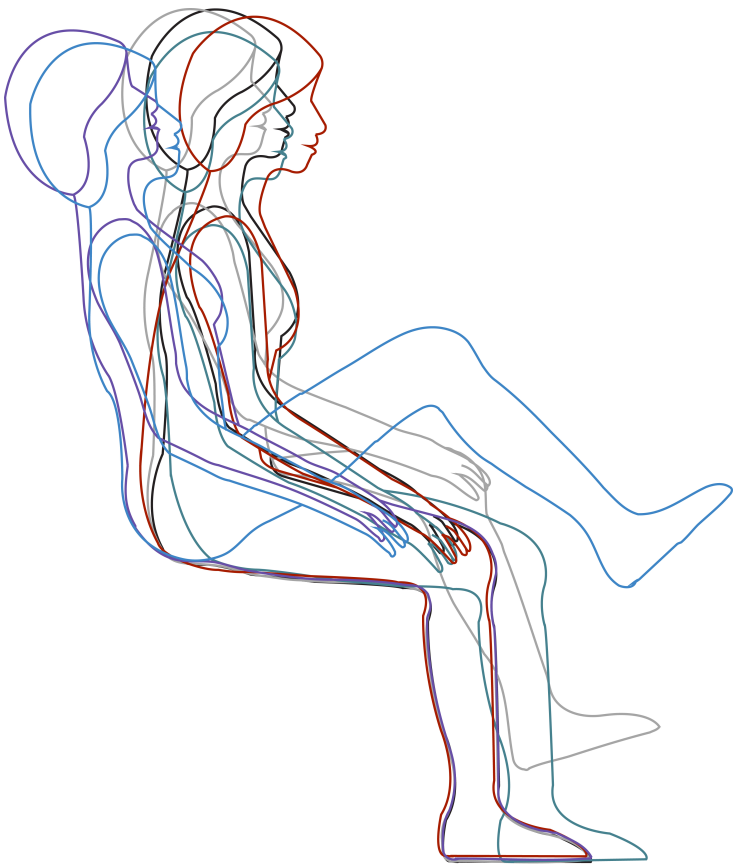
A study focused on pelvic orientation for improved safety assessment

Master thesis

Mathilda Janson and Jessica Wedmark



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Published by Department of Design Sciences Faculty of Engineering LTH, Lund University P.O. Box 118, SE-221 00 Lund, Sweden

Subject: Degree Project in Ergonomics for Engineers (MAMM10), Degree Project in Product Development (MMKM05)
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Abstract

Understanding and being able to quantify sitting postures is a central asset in car safety evaluations. This is due to the fact that passengers can choose a range of different sitting positions. Studying and understanding how passengers choose to sit to obtain some comfort is important for increased safety in futures cars and is particularly challenging facing a heterogeneous population. Data is also needed to improve the accuracy of virtual crash simulations. In addition, more recently the development of autonomous cars has made it important to be able to quantify how passengers choose sit as new behaviors may emerge when there is no responsible driver in the car. The aim of this master thesis has been to find a measuring method that measures the posture of a passenger in a car seat. Focus has been on the orientation of the passenger's pelvis as the interaction of this structure with the lap-belt is a central part of occupant restraint system.

A literature review was conducted to gain knowledge of the ergonomic aspects of this project and to review the different technologies that could be used to quantify passengers' sitting postures. The requirements of the measuring method were defined, different technologies were tested and a few concepts were selected. The concept in focus was a 3D motion capture system developed by Xsens. It was tested in three different experiments on a total of 30 test persons. In the first experiment, the accuracy of the Xsens equipment was verified by comparing it to a recognized method used to measure sitting postures statically in cars. Results showed that the two methods corresponded well. In the second experiment, the possibility of determining the orientation of the passenger's pelvis when knowing the position of the shoulder and the knee was tested. Such a connection would have facilitated the quantification of sitting postures but could not be found. Results showed that the human body is interconnected in a complex way and that it is difficult to draw general conclusions that apply to all body types. In the third experiment, the Xsens equipment was tested during a drive. The equipment performed well in a dynamic environment but a compensation for the movement of the car is needed.

To conclude, a measuring method that measures the posture of a passenger in a car seat was found and evaluated. It can measure the pelvic orientation. It is a precise method if the calibration is carefully done and the sensors stay in place.

Keywords: motion capture system, pelvic orientation, passenger, sitting posture, safety assessement

Sammanfattning

Att förstå och kunna kvantifiera hur passagerare sitter i bilar är en viktig tillgång vid säkerhetsbedömningar. Detta beror på det faktum att passagerare kan välja att sitta i en rad olika sittpositioner. Att studera och förstå hur passagerare väljer att sitta för att uppnå komfort är viktigt för ökad säkerhet i framtidens bilar och är särskilt utmanande med tanke på att människor ser olika ut. Data behövs även för att förbättra noggrannheten i virtuella kraschsimuleringar. Dessutom har utvecklingen av självkörande bilar gjort det viktigt att kunna kvantifiera hur passagerare sitter eftersom nya beteenden kanske kommer att framträda när det inte längre finns någon ansvarig bilförare. Syftet med detta examensarbete har varit att hitta en mätmetod som gör det möjligt att mäta passagerares kroppspositioner i en bilstol. Fokus har legat på passagerarens bäckenbensorientering eftersom dess samspel med bältets höftband är en central del av säkerhetsanordningen.

En litteraturstudie genomfördes för att få kunskap om de ergonomiska aspekterna av detta projekt och för att granska de olika tekniker som skulle kunna användas för att kvantifiera passagerares sittpositioner. Kraven för mätmetoden definierades, olika tekniker testades och några koncept valdes ut. Konceptet i fokus var ett röresleinspelningssystem, även kallat motion capture system, som utvecklats av Xsens. Det testades i tre olika experiment på totalt 30 testpersoner. Under det första experimentet verifierades Xsens-utrustningens noggrannhet genom att jämföra det med en erkänd metod för att mäta statiska sittställningar i bilar. Resultaten visade att de två metoderna stämde väl överens. Under det andra experimentet testades möjligheten att bestämma passagerarens bäckenbensorientering när axelns och knäets positioner var kända. En sådan koppling skulle ha underlättat kvantifieringen av sittställningar men kunde inte hittas. Resultaten visade att den mänskliga kroppen är sammankopplad på ett avancerat sätt som gör det svårt att dra allmänna slutsatser som gäller för alla kroppstyper. Under det tredje experimentet testades Xsens-utrustningen under bilfärd. Systemet fungerade bra i en dynamisk miljö men en kompensation för bilens rörelse behövs.

Sammanfattningsvis, hittades och utvärderades en mätmetod som mäter en passagerares position i en bilstol. Den kan mäta bäckenbenets orientering. Det är en exakt metod om kalibreringen görs noggrant och sensorerna sitter på rätt plats.

Nyckelord: rörelseinspelningssystem, bäckenbensorientering, passagerare, sittpositioner, säkerhetsbedömning

Acknowledgements

This master thesis has been performed during the spring of 2018 at Volvo Cars and it has combined two different master thesis majors at Lund University, Ergonomics and Product Development. There are some people we would like to thank for their help in this project.

Firstly, we thank Katarina Bohman, our supervisor at Volvo Cars, for all her advices, guidance and support during the project. We also thank our supervisors at the department of Design Sciences of the Faculty of Engineering at Lund University, Åsa Ek, Ergonomics and Aerosol Technology, Per Kristav and Per-Erik Andersson, Product Development, for their valuable advises and guidance in this project, especially concerning the writing of the master thesis report.

Secondly, we thank the University of Skövde for lending us the 3D motion capture system from Xsens that was used in this project. We also thank the Volvo Cars Safety Centre workshop for the construction of equipment used during experiments. Moreover, we thank the measurement technicians at Volvo Cars Safety Centre for their measurement help during experiments and all the test persons for their participation.

Thirdly, we thank Matthew P. Reed from the University of Michigan for his expertise and advices regarding the use of a method to measure passengers' sitting postures in a static seat.

Fourthly, we thank the project *Assesement of Passenger Safety in Future Cars*, partly funded by FFI-Strategic Vehicle Research and Innovation, Vinnova, the Swedish Energy Agency, the Swedish Transport Administration and the Swedish vehicle industry for their support and feedback during the process. We also thank the project *Virtual Designer Ergonomics*, partly financed by the KK-foundation, where Volvo Cars collaborates with the University of Skövde, for their support.

Finally, we thank our families and friends for their support during this project.

Lund, May 2018

Mathilda Janson, Jessica Wedmark

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List of acronyms and abbreviations

ASIS Anterior Superior Iliac Spine

ATD Anthropomorphic Test Dummy

BB Bispinous Breadth

BMI Body Mass Index

CAE Computer Aided Engineering

HBM Human Body Models

HJC Hip Joint Centre

PD Pelvic Depth

PSIS Posterior Superior Iliac Spine

TP Test Person

1 Introduction

This chapter is an introduction to the thesis project *Investigation of methods for quantifying sitting postures in cars*. It explains the background, the aim of the project, the delimitations made and the approach used.

1.1. Background

Understanding and being able to quantify sitting postures is a central asset in car safety evaluations. This is due to the fact that passengers can choose a range of different sitting positions. Studying and understanding how passengers choose to sit to obtain some comfort is important for increased safety in futures cars and is particularly challenging facing a population with many different body types and preferences. In the process of quantifying passengers' sitting postures, it has shown to be particularly difficult to determine the orientation of the pelvis and the interaction between the pelvis and the lap-belt. This is mainly due to interference from the car seat and the heterogeneity of the population. Factors such as abdominal fat affect the possibility of achieving accurate measurements. The lap-belt fit is important from a safety perspective as the pelvis is supposed to be the load-bearing structure where the restraining forces are applied during an accident. If the seat belt is worn incorrectly the efficiency of the restraint system can be reduced.

There is also a need to collect data on sitting postures to improve the positioning of Human Body Models (HBMs) which are used during simulations in Computer-Aided Engineering (CAE) environments. These models represent human bodies and they are useful tools with many potential areas of application, noticeably for accurate crash simulations.

Experimental testings are done on Anthropomorphic Test Dummies (ATD) (also called crash dummies) which are physical tools constructed to interact with the restraint systems during a crash in a similar way that a human would. They are used in a controlled environment with standardized positions and strict protocols. Hence, they might be too simplified for the safety assessment in future crash situations. In addition, these represent only a limited part of the population, a method that includes a larger part of the population is needed for safety assessment.

Moreover, in a near future autonomous vehicles will be more common as the automotive industry is moving towards this technique to a greater extent. When all persons in the car become passengers, it is important to examine how different sitting postures affect the safety of the passengers. It is likely that the passengers will choose more relaxed positions during a car ride as a shift of responsibility occurs when this new way of transportation is introduced on the market.

1.2. Project

This thesis project is a part of a bigger project named *Assessment of Passenger Safety in Future Cars* (FFI 2017-01945) associated with SAFER, Vehicle and Traffic Safety Centre at Chalmers in Gothenburg. It is a collaboration between Volvo Cars, Chalmers University of Technology and the automotive safety supplier Autoliv Inc. This research project aims to assess the protection of a heterogenous population of passengers in future vehicles. This master thesis, as part of this larger research group, aims to answer the following question:

How can we quantify sitting postures in a car seat with focus on pelvic orientation during a drive?

1.2.1. Aim

The aim is to find a measuring method that measures the posture of a passenger in a car seat, with focus on the orientation of the pelvis. It should be a precise method, applicable in both front and rear seats, that can be used during a drive without affecting the passenger's natural behavior. The measuring method should be easy to use and the data generated should be easy to analyze.

1.2.2. Objectives

The objectives of this master thesis are:

- to evaluate two concepts suggested by Volvo Cars, a 3D motion capture system developed by Xsens and an optimization method developed by Park et al. (2015) to quantify sitting postures of passengers in cars.

  The testing of this equipment should preferably be static in the first experiments in order to evaluate the accuracy of the methods and thereafter (if the techniques seem reliable) dynamic testing should follow. The aim is to be able to quantify sitting postures during a drive which implies a dynamic scenario. A heterogeneous group of test persons (TP) will be recruited to evaluate how the methods work on different bodies.

- to conduct a literature review of the technologies used today to assess passenger sitting postures, focusing on methods that enable the estimation of the orientation of the pelvis. This is done to investigate if there are other fitting solutions that have not been considered at Volvo Cars yet. It could for instance be an emerging technology or a new way of applying an existing technology.

  If a technology seems to fulfill necessary requirements and is not too difficult to get a hold of, the technology will be considered. If so, the technology will be tested through the same procedure as the two concepts suggested by Volvo Cars.

1.2.3. Delimitations

Certain delimitations had to be made due to the time frame, access to laboratory equipment and the well defined starting point in the project. These delimitations with motivations are stated below.

- Only limited research will be conducted to find and evaluate other suitable technologies.
  Volvo Car has, as mentioned above, already two technologies that they wish to evaluate and they will therefore be given priority. Due to a lack of time, limited research will have to be conducted on other technologies.

- Only passenger postures in the front seat of a car will be studied.
  As stated above, the driver is often in focus when assessing sitting postures in vehicles. In this thesis, the passenger's posture is studied as all persons in the car become passengers in autonomous vehicles. The front seat was chosen since it has more settings than the rear seat.

- Tests will be performed in one specific car model.
  The vehicle used was chosen because it is elevated and spacious which makes it easier to access certain anatomical points on a test person for a measurement technician. Moreover, this vehicle features many seat settings which are easy to adjust. In a larger study, different car models would have been used during testing.

- Only adults will be studied.
  Children are not considered in this project because necessary safety measures vary with the age of the child. In this limited project, no valid conclusions could be drawn regarding children.

- The focus will be on the size of the test persons rather than age.
  This is due to the fact that the effects of age on passenger posture in vehicle seats is the focus of another master thesis within the project *Assessment of Passenger Safety in Future Cars*.

1.3. Approach

1.3.1. Structure of the report

The report is structured like the methodology used during the project.

First the **Introduction** to the project was established. The background for the project and aim etc. were clarified. A methodology was chosen to have support during the project and to have predefined activities to implement.

A literature study was conducted to build a foundation of knowledge. The findings are presented in **Theory**. The theory concerns both ergonomics and technologies for capturing body movement. Ergonomics was approached in order to understand how the pelvis is connected to the rest of the skeleton and how these structures can be related to safety and comfort. State of the art technologies were studied in order to see what equipments and techniques might be suitable to this project.

Simultaneously to the literature review, a prestudy was conducted. The aim was to get a clearer insight of the equipment and measuring methods used today and review the limitations. The next step in the **Method** was to investigate one or a few suiting concepts to the measuring method wanted. The activities are inspired from the methodology of Ulrich & Eppinger.

The most important step during the **Method** was the concept testing were a few concepts were tested and data was collected. Three different experiments with different focus were performed. The data was then analyzed. To ensure the concepts' performance one of the experiments was dedicated to verification.

The **Results** address the results from the Prestudy, Concept development, Concept testing and Verification of concept.

During the **Discussion** the different parts of the process were discussed.

Finally, the **Conclusion** of the project was determined.

In the **Appendices** further information about different activities conducted during the master thesis can be seen.

1.3.2. Time plan

In the beginning of the project a time plan was established. It contains the different activities and when they were scheduled to be accomplished, see Figure A.1. During the course of the project, some of the activities were rescheduled, thus the project plan was slightly changed. A revised time plan can be seen in A.2. This shows when the different activities actually were performed.

1.3.3. Author's contributions

The two authors of this master thesis come from different backgrounds. Mathilda Janson has studied Biomedical Engineering with a master specialization within Biomechanics and Rehabilitation whereas Jessica Wedmark has studied Mechanical Engineering with a master specialization within Product Development. These different backgrounds have been a strength throughout the project as the authors have been able to focus on different aspects and thus perform more efficiently.

Mathilda Janson has been responsible for the ergonomic concepts used in the project and Jessica Wedmark has been responsible for the development process in the project. The experiments were thought out and performed together and during data analysis Mathilda Janson was responsible for the calculations performed on the data collected by the Xsens equipment whereas Jessica Wedmark performed the programming used for the method developed by Park et al. (2015). The writing of the report was divided equally and collaboration and support was central throughout the project.

2 Theory

This chapter treats the theoretical knowledge necessary to understand the project and is a part of the Planning phase. It concerns the ergonomic theory and reviews the different technologies considered when attempting to find a suitable solution to the main question:

How can we quantify sitting postures in a car seat with focus on pelvic orientation during a drive?

2.1. Ergonomics

Ergonomics is the science of work: of the people who do it and the ways it is done; the tools and equipment they use, the places they work in, and the psychosocial aspects of the working situation (Pheasant 1986).

In this definition the word "work" takes a broad sense including almost any human activity. Ergonomists generally adopt a user-centered design approach where the worker's tools, skills and efforts are analyzed in order to improve the user's conditions. Ergonomics strives to fit the tasks and the tools to the worker and not vice versa (Pheasant 1986).

In order to design for the user, one has to have knowledge of how the human body functions. In this project, which aims to collect information about passengers' postures with focus on the pelvic orientation during a drive, an overview of the anatomy of the human body will be presented. To fit the project's purpose, focus will lie on the description of the spine and the pelvis.

Just as any other system, the human body is affected by the laws of physics. A human body in a still position is dynamically balanced through the use of muscular forces, creating continuous balancing movements by contraction and relaxation of different muscles (Engström 1996). These concepts are presented under the section called Biomechanics.

Under the same section, the biomechanical interactions between the passenger and the vehicle will be explored. Biomechanics is defined as the study of how stress affects biological matter using the physics laws of mechanics (Engström 1996). This provides information about how safety equipment has been designed to fit the human need in this environment.

However, today there is a gap between how one is supposed to sit to be as safe as possible in a vehicle and how passengers actually sit. Therefore, the fundamentals of sitting will be presented and this will give an insight in how humans tend to sit to obtain some comfort. One should keep in mind that even though it is possible to draw some general conclusions in this matter, it is difficult to generalize when facing a heterogeneous population.

Thereafter, the anthropometric aspects of this project will be explicated. Anthropometry is a branch of ergonomics which focuses on body measurements (such as body size, shape and body strength) and uses this information to adapt the tools and the equipment to the worker (Pheasant 1986). As every human has different anthropometric data it is central to know what body measurements to take into account when developing a new product.

Finally, the conflict between the passengers security and comfort will be evaluated. This is done last as it involves knowledge about the biomechanics of the human body and occupant restraint. It also requires insight in the fundamentals of sitting and anthopometrical aspects.

2.1.1. Anatomy

2.1.1.1 The spine

The spine or the vertebral column, see Figure 2.1, consists of 24 movable bony vertebrae separated by intervertebral discs (indicated in blue in Figure 2.1). The top of the spine supports the skull and the bottom of the spine is tightly linked to the hip bones through the sacrum (Putz & Pabst 2001). The sacrum is the large triangular bone at the base of the vertebral column and above the coccyx (the tailbone). Due to its shape, the parts of vertebral column can be grouped as (Pheasant 1986):

- 7 cervical vertebrae (C1-7),
- 12 thoracic vertebrae (T1-12),
- 5 lumbar vertebrae (L1-5),
- a sacral bone formed by 5 vertebrae (S1-5).

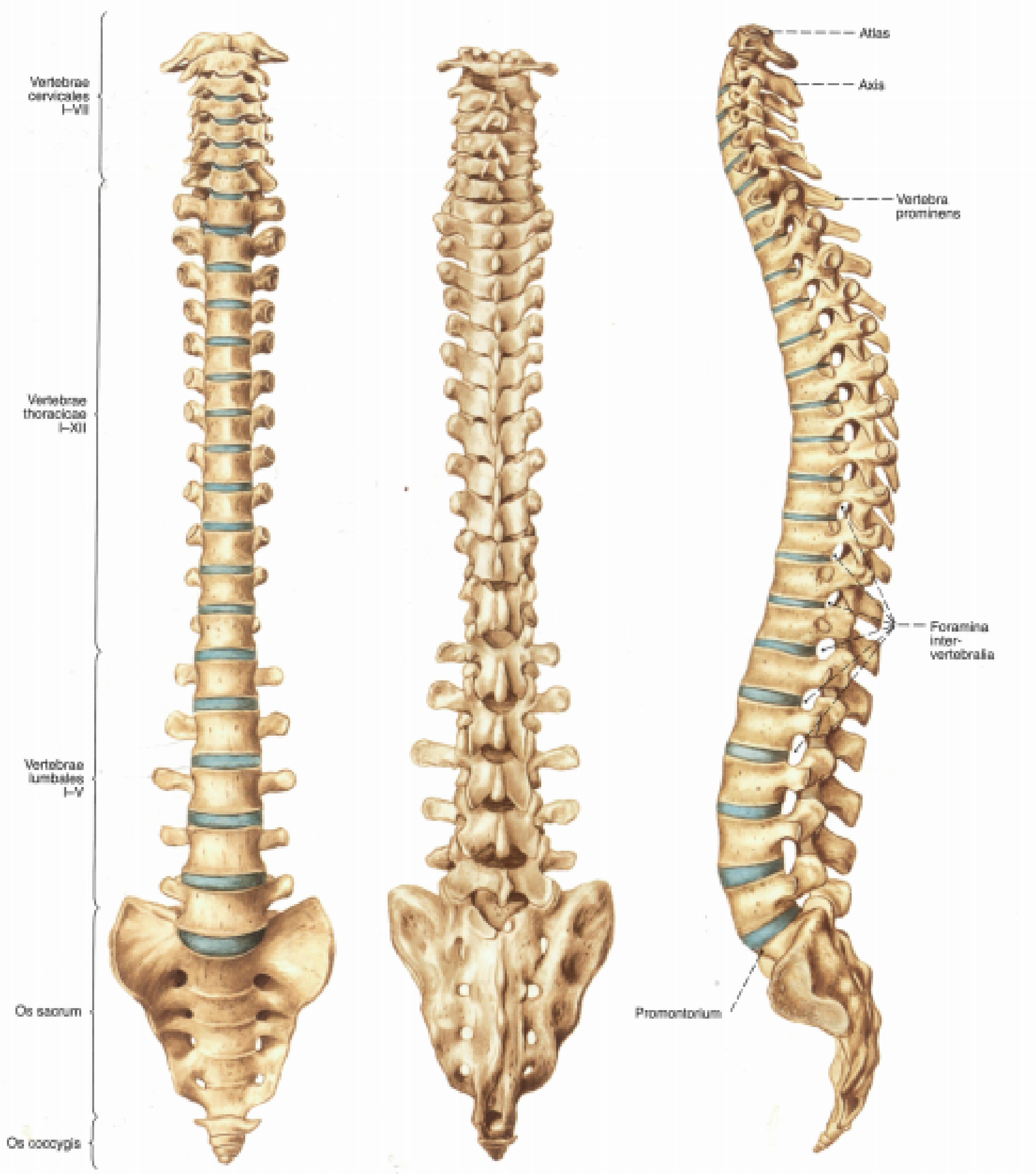

Figure 2.1: Vertebral column; ventral, dorsal and lateral left view (from left to right) (Putz & Pabst 2001)

As shown in Figure 2.1, the cervical region is concave, the thoracic region is convex and the lumbar region is concave. The spine has the shape of a sinous curve where the concave parts are referred to as *lordsis* and the convex parts are known as *kyphosis* (Pheasant 1986).

2.1.1.2 The pelvis

The pelvis, also called the pelvic girdle, is the bony structure that links together the trunk and the legs of the human body. Its main function is to provide attachment for muscles stabilizing and supporting the trunk and moving the legs and the hips. The pelvic girdle is composed of two hip bones that are attached at the pubic symphysis (anterior view of the body) and at the sacrum (posterior view of the body). The pubic symphysis is a cartilaginous connection formed between the public tubercle of two hip bones, see Figure 2.2 (Latin: *Tuberculum pubicum*) (Putz & Pabst 2001).

Each hip bone is composed of three different types of bones fused in the acetabulum to form a Y-shaped cartilaginous junction, see Figure 2.2 (Latin: *Acetabuli*). The superior widened part of the pelvic bone consists of the Ilium and the lower pelvic bones are the Ischium and the Pubis, see Figure 2.2 (Latin: *Ilium, Ischii and Pubis*). The Ischium forms the posterior distal part of the lower pelvic bone whereas the Pubis forms the anterior medial part of the lower pelvic bone (Putz & Pabst 2001).

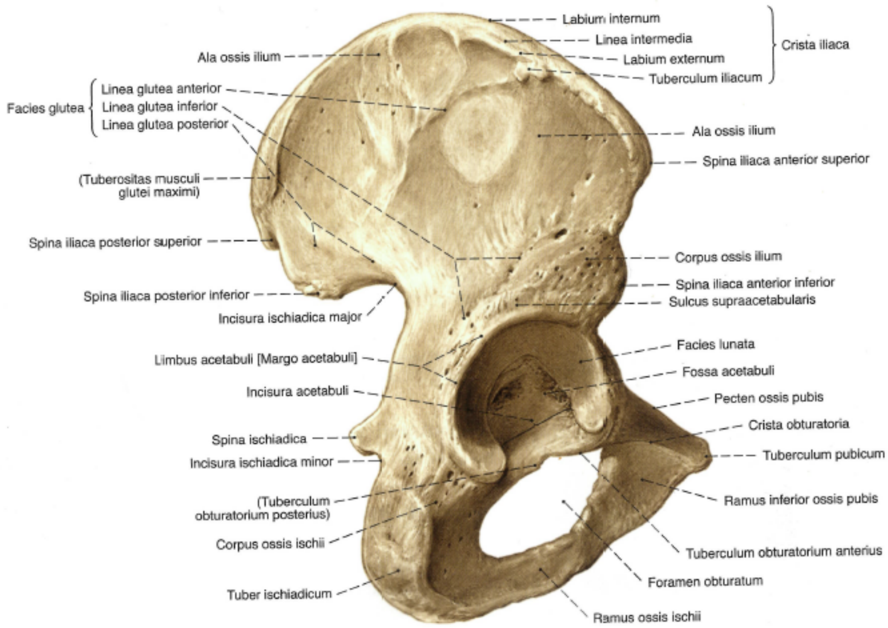

Figure 2.2: Hip bone; dorsolateral view (Putz & Pabst 2001)

The female pelvis has a more oval-shaped inlet than the male pelvis as can be seen when comparing Figure 2.3 to Figure 2.4 (Putz & Pabst 2001).

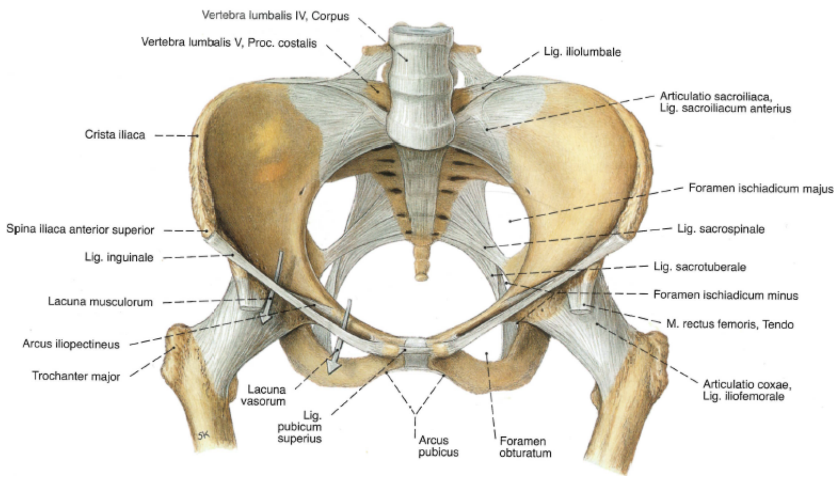

Figure 2.3: Joints of the pelvis and of the lumbosacral region in the female; ventrosuperior view (Putz & Pabst 2001)

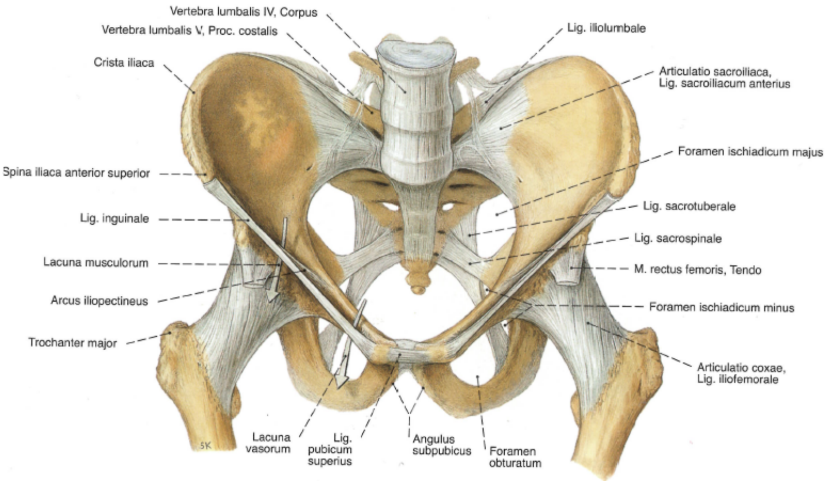

Figure 2.4: Joints of the pelvis and the lumbosacral region, in the male view (Putz & Pabst 2001)

The pelvis has two points that can be found through palpation and are therefore relatively easy to measure:

- Posterior Superior Iliac Spine (PSIS), Figure 2.2 (in the image called *Spina iliaca posterior superior*)
- Anterior Superior Iliac Spine (ASIS), Figure 2.3 and Figure 2.4 (in the image called *Spina iliaca anterior superior*)

Note that when referring to the hip, this implies the pelvic bone and the other surrounding structures (such as muscles, fat etc.).

2.1.2. Biomechanics

2.1.2.1 The human body - Mechanical living system

As previously mentioned, the human body is, just as any other system or object, affected by the laws of physics. To maintain a static posture, the human body must use muscular force to dynamically balance the body. A dead system is balanced entirely by external forces whereas a living system is balanced by both external and internal forces.

The fundamental interior mechanical principals affecting the human body are the following (Engström 1993):

- The feet, the lower and the upper legs influence the pelvis.
  - Depending on how the feet (and the lower legs) are placed on the supporting surface the pelvis are influenced.
  - The position of the pelvis is directly influenced by the tightening och slackening of muscles linking the pelvis to the femur (thighbone).
- The sacrum influences the spine and the skull.

- Due to the connection of the pelvis to the spine through the sacrum, a movement of the pelvis influences the sacrum which has direct impact on L5. A backward flexion, a forward rotation and a sideways tilt of the sacrum result in a spine flexion, a spine extension and a sideways movement of the spine respectively. When the sacrum moves in space, the spine will counterreact in all directions in order to keep balance.
- In order to analyze the position of the head, the position of the sacrum also has to be considered as the spine links together the sacrum and the skull.

2.1.2.2 Mechanics of vehicle crashworthiness and occupant restraint

In this section, the mechanical principals used to keep a passenger as safe as possible during a car drive will be explained. In a vehicle, the safety of a passenger is ensured primarily by:

- the crashworthiness of the vehicle,
- the occupant restraint.

The crashworthiness of the vehicle refers to the implementation of a strong occupant compartment and the design of a crushable front and rear structure. In case of a crash, the occupant compartment will then resist intrusion while the deformation of the front and rear structures will perform work to dissipate the kinetic energy of the crash (Yoganandan et al. 2015). These characteristics primarily depend on the construction of the car, in this study however occupant restraint will be in focus.

Occupant restraint is *the use of lap-shoulder belt, airbags, and other systems to provide ride-down of the vehicle deceleration, containment on the seat, and distribution of forces on the pelvis, shoulder, chest and other designed anatomical structures to decelerate the occupant* (Yoganandan et al. 2015).

To illustrate the essential principles of crash energy management the example of a frontal crash into a large obstacle such as a rigid barrier can be used. The kinetic energy of the vehicle must be managed by the deformation of the vehicle whereas the kinetic energy of the passenger must be handled by the application of forces on the occupant.

In order to maximize the safety of the passenger a restraint system should aim to:

- maximize the time over which restraint forces are applied,
- maximize the distance traveled by the occupant over the ground as restraint forces are applied,
- minimize body deformations,
- apply restraint forces as soon as possible,
- distribute forces over the largest possible area and
- apply restraint forces on bony structures such as the pelvis, the femur, upper thorax, shoulder and head while minimizing the forces applied to the soft tissues (Eppinger 1993).

2.1.2.3 The seat belt

The three point seat belt is the most important occupant restraint equipment of a vehicle. Wearing the seat belt minimizes the risk of death in a car accident by 50% (Trafikverket n.d.). The seat belt is divided in two parts, shoulder-belt that goes diagonally over the occupant's chest and shoulders and the lap-belt that goes over the occupant's pelvis. The shoulder-belt should rest on the shoulder of the occupant as close to the neck as possible and the lap-belt should be worn below the ASIS of the pelvis (Trafikverket n.d.) (Wells et al. 1986).

In case of an accident when wearing the seat belt correctly, the larger forces will be applied on the hard structures of the body (the pelvic girdle, the rib cage and the clavicle) which are much stiffer than soft tissues. The bone can handle greater forces before undergoing permanent deformation (Pal 2016). Moreover, a permanent deformation for a bone implies a bone fracture, which can be treated relatively easily compared to a soft tissue damage.

The seat belt has a good performance in the design position of the vehicle seat where the passenger sits in an upright position. When reclining the backrest, the risk for submarining may increase. Submarining can be described as the situation where the passenger slides under the seat belt in a collision and often leads to severe injuries. The pelvis is then rotated backwards and the larger forces will be applied to the soft tissues of the stomach (Nordhoff 2005), this is illustrated in Figure 2.5. Submarining can also be caused by a slack in the seat belt system and it happens easier for certain body types (Nordhoff 2005) (Reed et al. 2013).

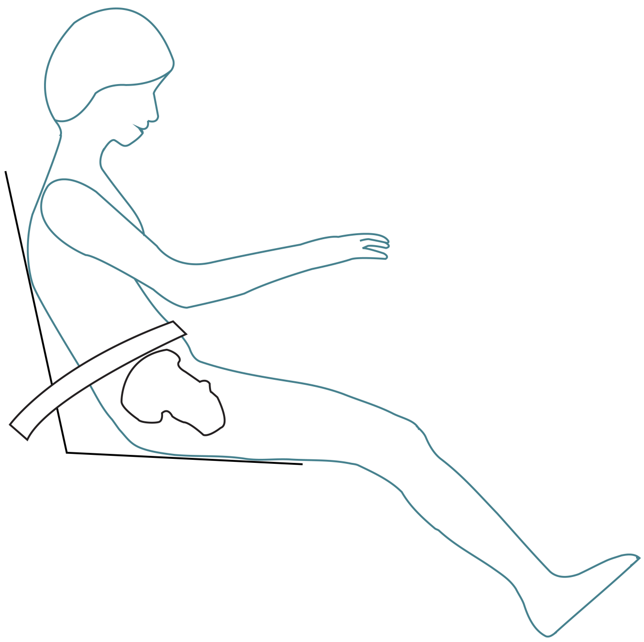

Figure 2.5: An illustation of submarining, the lap-belt has ended up above the pelvis

2.1.3. Fundamentals of sitting

2.1.3.1 Difference between sitting and standing

The human standing position can be compared to a "tower" made up of bones. A good standing posture is generally considered to be achieved when standing erect. People who successfully balance the body in this way tend to walk with more ease than those walking in a more slouched position. In an upright standing position the shoulders are moved backwards and the pelvis is rotated forward whereas in a more slouched position the opposite happens (Engström 1993). In the upright standing position the pelvis is (more or less) in a vertical position. These principals are illustrated in Figure 2.6, were the pelvic can be seen in a vertical position, a backward rotated position and a forward rotated position.

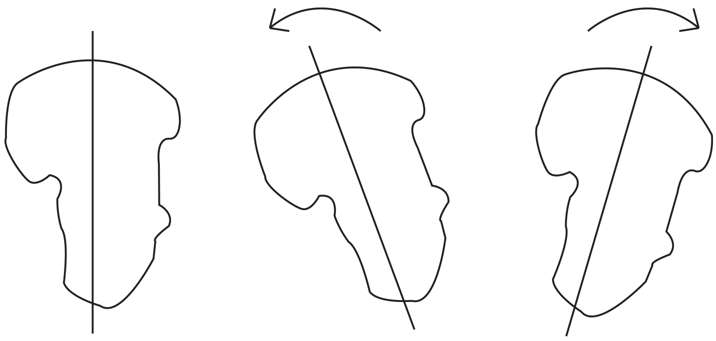

Figure 2.6: The pelvis in a vertical position, a backward rotated position and a forward rotated position (from left to right)

Sitting is in many ways mechanically different from standing, in a neutral upright sitting posture the trunk and thighs as well as the thighs and lower leg form right angles. Most of the weight is then carried by the ischial tuberosity (Latin: *Tuber ischiadicum*), also called the "sitting bones" located in the soft tissue of the buttocks, see Figure 2.2 (Pheasant 1986). When sitting down the pelvis tends to rotate backwards. It is likely that this rotation is due mainly to two factors:

1. The tension created in the hamstrings (muscles on the back of the thighs) when flexing the hip joint to create a right angle between the trunk and the thigh. Unless the subject is very flexible, the pelvis will be rotate backwards to compensate for this (Pheasant 1986).

2. The two hip flexors, Iliopsoas, do not assist the pelvis in keeping a forward rotating position as they do in the upright standing position (Engström 1993).

As a consequence of the pelvis rotating forward when standing up, the back rotates backwards to maintain a mechanically stable upright standing position. Just the opposite happens when sitting down, the pelvis will rotate backwards (as a consequence of the above-mentioned factors) and the spine will rotate forward (Engström 1993). In relaxed sitting, the lumbar spine will flex and the weight of the trunk is then supported by passive structures such as ligaments. In the long run, this causes injuries to the back as the invertebrate discs are heavily deformed. To avoid damage and to maintain a static upright sitting posture, the muscles of the back work to support the weight of the trunk (Pheasant 1986).

2.1.3.2 Factors affecting sitting

The main factors affecting sitting are the following according to (Engström 1993):

- Gravity
  This force pulls all body parts toward the centre of the earth and cooperating with gravity when sitting will affect the body negatively, especially if the subject is seated over a long period of time.

- Centre of mass
  It is natural for the human body to strive to have the lowest centre of mass possible as it increases stability. However long-lasting unfavorable positions can overload muscles and cause injuries. When sitting the centre of mass of the body can be moved by changing the position of the seat unit. This creates a new relationship between gravity and the centre of mass. Therefore it is often the seat unit that determines whether the interaction between the body's parts and the gravity will be positive or negative.

- Time
  Changing postures over a period of time is normal. A more uncomfortable position will result in a more frequent change of position (Engström 1993).

- Mass and body type
  The mass and the body type of the subject affects the pressure against the seat. This also affects the possibility to sit comfortably in a certain position and in a specific seat.

- Area
  The areas of the seat that is in contact with the body (the seat, the backrest, the headrest, the armrest and the space for the feet) affect pressure distribution and thus the passenger's stability and comfort.

- Material
  A bad choice of material can for instance result in a seat that easily becomes too warm or is perceived as rough and therefore creates discomfort. Then it is more likely that the passenger will try to move to be more comfortable.

- Pressure distribution
  The pressure distribution is affected by the mass of the subject, gravity, the area, the shape and the consistency of the seat. The aim is generally to achieve an even distribution of pressure to increase comfort.

- Activity level
  Research performed by Groenesteijn et al. (2012) shows a correlation between the change of position and the activity performed. Subjects working on their computers moved the least over a period of time whereas subjects telephoning or talking moved all their body parts to a greater extent. To conclude, a higher mental activity level, seems to result in a more static posture.

2.1.3.3 Different sitting postures

The previously described upright sitting position where the trunk and thighs as well as the thighs and lower legs form right angles is often described as a "correct" ergonomic sitting posture. However, there is a gap between ergonomic recommendations and reality, as this position is rarely used for longer periods of time. Especially when sitting without back support, one can notice a clear tendency of the back of the subject collapsing after a while. It begins with muscle relaxation in the trunk which leads to flexion of the thoracic vertebrae and a rotation backwards of the pelvis. The tendency of the spine to collapse can be increased by moving the feet forward. The subject then needs greater muscle work to maintain an upright sitting posture (Engström 1993).

When the pelvis is tilted backwards it is difficult to maintain the spine in a straight position. In order not to limit and injure the subject, a good seat should therefore be constructed to decrease the pelvis rotation backwards (Engström 1993).

The following section gives an insight in how we actually sit (Engström 1993). These postures are all applicable to a vehicle environment:

- Sitting on the forward part of the seat
  In this position the muscles of the upper body have to work continuously and the control of the pelvis increases. This makes it easy to balance the trunk and effortless to change between different postures.

- Sliding forward on the seat or ”slouching”
  Slouching is mainly due to the subject's need to increase the stability of the upper body. How much one will slouch is dictated by the backrest. It is sometimes possible to lean against a backrest without the trunk falling forward, but most of the time, it is not the case and to compensate the subject will slouch. It is an adjustment made subconsciously to increase comfort. A slouched position is however not recommended as the invertebrate discs in the lumbar spine become unnecessarily overloaded. This can also contribute to submarining if a car accident occurs.

- Sitting asymmetrically
  It is common to sit asymmetrically. Many tend to cross legs and use an armrest to help balance the body weight. This position is mainly dictated by surroundings and the current activity performed. To sit ”crooked” is not a problem if it is not done for a long period of time.

- Sitting with legs crossed
  Crossing thighs lock the pelvis in a tilted position. There are several ways to cross legs, one common way is to rest the posterior side of the lower leg on the opposite leg's thigh. This pushes the pelvis to a more backward rotated position. The spine is then pushed against the backrest. Another common way is to cross the posterior, hollow part of the knee, over the opposite leg's anterior knee part. This locks the pelvis in a forward rotated position and results in a more extended spine.

  In general, crossing thighs stabilizes the trunk by making it more difficult to flex the spine. When relaxing the trunk while crossing thighs the legs slowly uncross.

- Sitting on one or both legs
  The most common ways to do this:

  – Sitting like a tailor: this rotates the hip joint outwards, forcing the pelvis to rotate backwards.
  – Sitting with both legs under pelvis or on each side of the pelvis: This is a position taken mainly by children as it requires good flexibility in the knee joint. It makes the pelvis tilt forward and extends the trunk.
  – Sitting on one leg while crossing legs: The trunk is easier to extend if using a back support. Without support, the pelvis tilts backwards and sideways towards the flexed and inwardly-roated leg.

- Placing feet higher
  When putting the feet higher, perhaps against the seat in front or on the glove box of a vehicle, the pelvis is stabilized and blocks the spine's flexion forward which decreases the risk of a forward collapse of the spine. The higher the feet are placed, the more the hip flexes and the harder it is to tilt the pelvis forward. Placing one or both feet higher is generally intuitively done to stabilize the upper body.

- Crossing arms
  The arms influence the pelvis indirectly through their connection to the spine. Their weight on the spine reinforce the trunks tendency to collapse. Crossing arms decreases the trunks tendency to collapse forward and increases stability.

It can be added that it is a bigger challenge to change positions when seated and none of the above mentioned positions are ergonomically satisfactory over a longer period of time. An optimal seat allows a frequent change of position so that the body load can be supported by different body parts.
Some of the postures have been illustrated, Sitting on the forward part on the seat and Slouching can be seen in Figure 2.7. Sitting with legs crossed and Placing feet higher can be seen in Figure 2.8. Two other postures relevant for this project is a forward folded collapsed posture and a reclined posture, these can be seen in Figure 2.9.

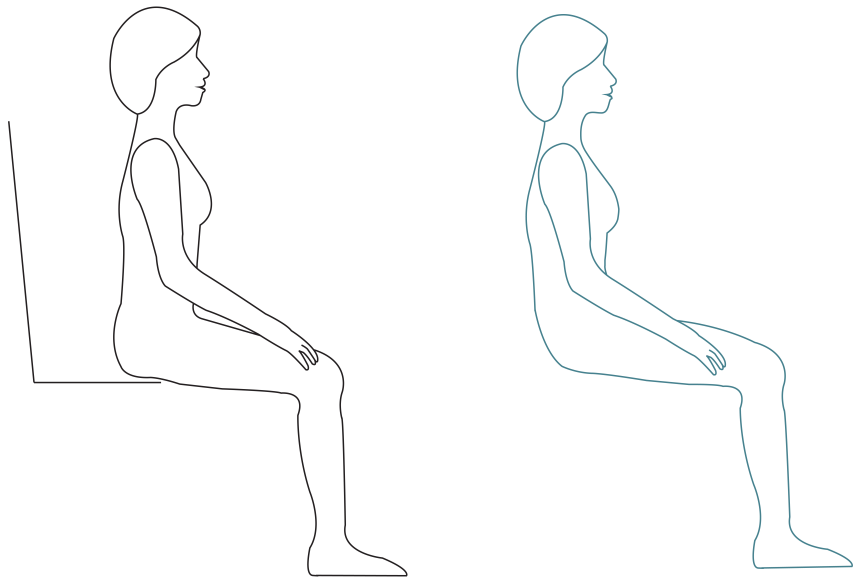

Figure 2.7: The sitting on the forward part on the seat and slouched posture

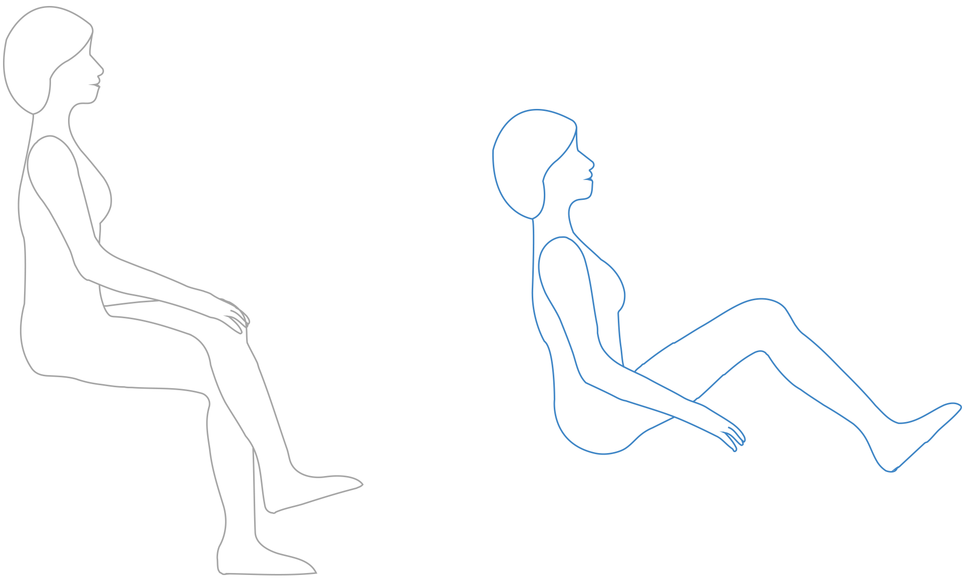

Figure 2.8: The posture with legs crossed or feet placed higher

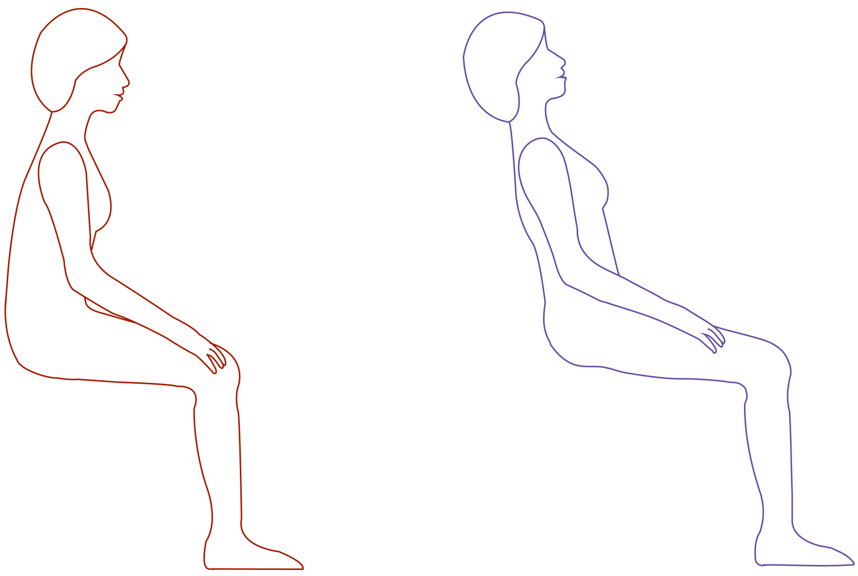

Figure 2.9: The collapsed and reclined posture

2.1.4. Anthropometry

2.1.4.1 Anatomical terms of locations

In this section some anatomical terms of locations are defined in order to make it easier to refer to movements in different anatomical planes or certain parts of the body later in the report.

There are three anatomical planes to define:

- the frontal plane which divides the body into a front and a back part
- the sagittal plane which divides the body into a right and a left part

- the transverse plane which divides the body into an upper and a lower part

Any of these three planes is perpendicular to the two other planes. The planes are illustrated in Figure 2.10.

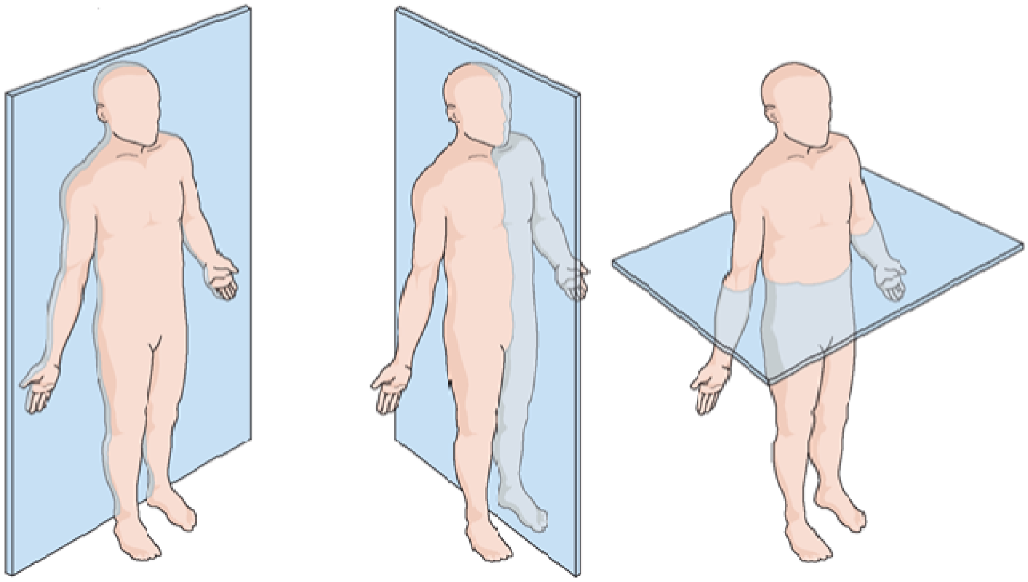

Figure 2.10: The frontal plane, the sagittal plane and the transverse plane (from left to right) (Lateral Edge 2017)

There are eight other terms used to refer to certain locations on the body that have to be defined (Jones 2017):

- Anterior and posterior
  Anterior means front whereas posterior means back. For instance, the ears are posterior to the sternum.
- Superior and inferior
  Superior means higher whereas inferior means lower. For instance, the head is superior to the shoulders.
- Proximal and distal
  Proximal and distal refer to structures that are considered to have a beginning and an end. Proximal means closer to the structure's origin whereas distal means further away from the structure's origin. For instance for the forearm, the elbows is proximal to the wrist.
- Medial and lateral
  Medial means towards the midline (the line dividing the body in two parts when illustrating the sagittal plane in Figure 2.10) whereas distal means away from the midline. For instance, the nose is medial to the ears.

2.1.4.2 Anatomical landmarks

As stated in the introduction, anthropometry is a branch of ergonomics focusing on body measurements (body size, shape and body strength). When having a user-centered design approach, the first intuitive step is to collect data from relevant body measurements from subjects. Thereafter, this data can be used to see the variation of body dimensions within the test group and an analysis of the variables that have to be taken into account in the design process can be made.

When collecting data from subjects, specific anatomical landmarks are used. A landmark is a location that corresponds to the same location for each body shape. For every body segment there are a number of specific body landmarks commonly used in research. In this project, where main focus is on quantify pelvic orientation while sitting in different positions, landmarks on the spine and the pelvis are central. Landmarks on the chest and the legs are also used to get an understanding of how these affect the pelvis and how the whole body functions.

In research conducted by Reed et al. (1999), body landmarks measured on vehicle occupants are presented. Matthew P. Reed is a pioneer when it comes to studying driver's and passenger's positions in vehicles and this article defines the landmarks used in several of his other studies. The body landmark relevant to this project are defined in Table 2.1:

Table 2.1: Body landmarks

Body landmark	Location
C7, T8, T12	Most posterior points of vertebral column (shaped like sinus curve)
Acromion	Most posterior point of the lateral margin of the acromial process of the scapula
Suprasternale	Superior margin of the jugular notch of the manubrium on the midline of the sternum
Substernale	Inferior margin on the midline of the sternum
ASIS	Located through palpation of the midline of anterior thigh surface until the anterior prominence of the iliac spine is reached
PSIS	Located through palpation along the margin of the iliac spine until the most posterior prominence is located, adjacent to the sacrum
Suprapatella	Most prominent part of the knee in sagittal plane

The landmarks presented above in Table 2.1 can be located through palpation. However, there are other body landmarks of interest such as the Hip Joint Centre (HJC) that are harder to access as they are not located near the skin surface. Locating the HJC makes it possible to obtain the hip joint angle which interests many researchers working with the quantification of sitting postures in vehicle seats. The hip joint angle relates the upper part of the body to the lower part of the body. In article published by Park et al. (2015) several methods to calculate the HJC using surrounding body landmarks are compared. Methods based on the an anatomical approach have used the relationship between different pelvic bony landmarks (such as the ASIS) to estimate the HJC. In other approaches, the kinematic linkage between the HJC and the rigid bone structures of the body have been used.

2.1.4.3 A heterogeneous population

When designing a vehicle interior for a heterogeneous population the construction has to take the population-based models of passenger spatial requirements into account. This is central to be able to predict passengers postures in a correct way (Park et al. 2016). There are many aspects to consider when designing for the human body.

Firstly, the body is constantly evolving during a lifetime. In the early years, it happens in an obvious way (length, weight, bone structure etc). During adult life the body continues the evolve (in a less noticeable way), it is then primarily affected by lifestyle choices such as exercise and nutrition and the environment it is exposed to. Later on, as the body ages, a length reduction occurs followed by weight loss (it often happens in this order). The decrease in weight is then mainly due to the waist away of muscles which also leads to decrease of muscular strength (Pheasant 1986). The trunk also tends to collapse, this is especially true for women (Engström 1993). There are also other notable differences between men and women, the bodily proportions and the body fat distributions are different (Pheasant 1986).

Secondly, there are ethnically differences between individuals who originate from different geographic regions. In statistical terms, population of individuals who originate from the same geographic area have certain common physical characteristics which distinguish them from other groups of people. For instance, the average body height of a population or the average height of the lower limbs in comparison the to body height can vary.

Thirdly, there are secular trends that have to be taken into account. A secular trend is an alternation in measurable characteristics of a population of human beings occurring over a period of time. Under the last decades, the human population has grown taller and obesity has become more common in some parts of the world. Body Mass Index (BMI) was developed as an indicator of excessive body fat and is defined as the subject's weight in kilograms divided by the square of the subject's height in meters (kg/m^2). A person with a normal weight for his or her length will have a BMI of between 18,5 and 24,9, a BMI between 25 to 29,5 indicates pre-obesity and a BMI from 30 and above implies obesity. Obesity is most common in North America, Europe and the Middle East (World Health Organization 2018). Another secular trend worth mentioning is that most countries face an aging population today. Consequently, a new group of consumers demanding solutions fitting their needs has emerged (World Health Organization 2014). Lastly, the trend of globalization has an obvious impact on the traditional way of establishing anthropometric trend based on the geographic region individuals originate from.

2.1.5. Safety and comfort

In this section, the human anatomy, knowledge in the area of biomechanics, the fundamentals of sitting and anthropometrical insights are weighed together. This is due to the fact that the comfort of the passenger is an enabler for safety.

Today, the vehicle restraint systems are mostly tested on ATDs, more precisely on ATDs representing the 5th percentile woman, the 50th percentile man and the 95th percentile man. In this ergonomic concept the population is divided into 100 percentage categories ranked from least to greatest with respect to some specific body measurement. The 5th percentile length is a length where 5% of the population is shorter and 95% of the population in taller. The 50th percentile length is the median length of the population and the 95th percentile length is a length where 95% of the population is shorter and 5% is taller. It is very unlikely that a person would be a 5th, 50th or 95th percentile in all body dimensions as the ATDs used today are (Happian-Smith 2001).

The ATDs do not tend be good representations of overweight passengers as they only consist of hard structures and do not take the body shape of an overweight person into account. As previously explained, the three point seat belt is divided in two parts: shoulder-belt that goes diagonally over the occupant's chest and shoulders and the lap-belt that goes over the occupant's pelvis. In the case of an accident the larger forces should be applied on the harder bone structures in order to protect the passenger as much as possible. For an obese passenger, the lap belt will have greater likelihood of interacting with the soft tissues of the stomach instead of the hard bony structures of the pelvis and the person might start to slide under the lap-belt (submarining). Both experimental and simulated studies found that pelvis engagement decreases for obese passengers and that these passengers are at greater risk of submarining (Reed et al. 2013).

As previously stated, an optimal seat is a seat that allows frequent changes of position as no sitting posture is ergonomically satisfactory over a longer period of time (Engström 1993).

Another group to take into consideration is the elderly, as they most commonly have different posture than the ATDs. When aging, the trunk tends to collapse, especially for older women which leads to a changed interaction between the seat belt and the passenger. Older passengers are often less mobile than younger passengers and may therefore have more difficulties changing their posture over time and therefore experience discomfort (Engström 1993).

Comfort is very subjective and therefore it is a concept hard to define (Pennestrì et al. 2005). For instance, some passengers may experience an increased comfort when reclining the back rest of the vehicle seat or when sitting in a slouched position. However, Thorbole (2015) found that in order to avoid submarining, one of the central measures to take was to sit in an upright position. Moreover, Beck et al. (2011) showed that when ATDs of children were placed in a slouched position the submarining was more severe, reclining the seat increased the submarining further.

To conclude, comfort is a central criterion for a modern vehicle as it is less likely that someone will purchase a car they find uncomfortable. Nonetheless, the definition of comfort varies for person to person and no sitting posture is ergonomically satisfactory over a longer period. Passengers therefore tend to vary their posture to experience comfort.

2.2. Technologies for capturing body movement

In order to capture the movement of the human body some equipment have to be used. It is particularly challenging to capture the movement of the pelvis. Thus, the focus was on finding studies that did this. A literature study was conducted and the following keywords were used: pelvis rotation, capture body motion, skeleton motion capture, whiplash x ray, jack software, movement science, biomechanics. The need to be able to track body motion grows and have many applications such as sport, biomechanics, entertainment, virtual reality etc. (Vicon n.d. *a*). The literature showed that some different technologies were recurring and these are presented below. A representative from each category, except one, will be evaluated later in the field of application to which this project relates, namely how it would work in a car environment.

2.2.1. Optical motion and markers

In a study where the correlation between the movement of the centre of mass and the kinematics of the spine, pelvis, and hip joints were examined during body rotation, Wada et al. (2014) used optical motion to capture the body kinematics with markers and cameras. A similar technology appears to be used in another study by Sung (2014). This was a kinematic analysis for shoulder and pelvis coordination during axial trunk rotation in subjects with and without recurrent low back pain. Both these studies had an interest in measuring the pelvic motion and rotation and appear to have captured values on a decimal accuracy. Although neither commented on the accuracy of the equipment.

The technique in the first study uses optical-passive, retroreflective markers that are tracked by infrared cameras. It is also possible to use optical-active markers which uses LED markers connected by wires to the motion capture suit (Vicon n.d.*b*). The motion capture is conducted in a specified area or volume surrounded by a number of high resolution cameras. Each camera has a ring of LED strobe lights along the edge of the lens. The test subject has a number of reflective markers attached to selected body landmarks. When the test subject moves through the specified volume, the light from the strobes reflects back to a light sensitive sensor which gives a signal. The signals are collected and transferred to a software (Tebbutt et al. 2002).

Work is also done trying to optimize how the software connected to the equipment interpreters the data to be able to perform e.g. skeleton tracking. Many skeleton tracking methods based on such systems use a predefined skeleton model, which is scaled once in the initialization step to the individual size of the character to be tracked (Schubert et al. 2016). Some problem occur with this approach and a method that automatically optimizes these bone parameters is developed by Schubert et al. (2016).

In a different study completed by van Geffen et al. (2009), two techniques were combined to track pelvic movement with aim to develop a method that regulates buttock load for wheelchair users. The first technique was reflective markers that were placed on selected pelvis landmarks, ASIS, PSIS and one on the line between each ASIS and PSIS. Pelvic orientation were obtained using an infrared camera motion capturing system. To prevent skin artefacts during pelvis movement, a pelvis mold was shaped around the left and right lateral iliac crest and clamped the ASIS and PSIS for optimal fixation. To prevent problems with pelvis marker visibility since the study was performed in a special chair, an inertial sensor was attached on the mold as an alternative to estimate pelvic orientation.

2.2.2. Inertial sensors

Inertial sensors appears to be another common technology to capture body motion. These sensors are based on inertia and are available as Microelectromechanical systems (MEMS) inertial sensors or larger variants (Xsens n.d.*b*).

The motion characteristics of an object such as the human body can be described by six independent variables. The linear motions along the three perpendicular coordinate axes in the space and three rotational movements, one around each previously mentioned axis. The human vestibular system can simultaneously and accurately detect the six independent variables, which are interpreted by the central and peripheral neural systems to keep body balance and maintain gaze stability. This system has been resembled in engineering counterparts, linear motion and rotational motion are detected by accelerometers and gyroscopes (Zeng & Zhao 2011).

The inertial sensors contains accelerometers, which measures the acceleration using a mass-spring system and gyroscopes which measure angular motion. In addition, magnetometers can be used to prevent the system from drifting. The output data is combined and a Kalman filter weighs the sources of information appropriately with knowledge about the signal characteristics based on their models. This to make the best use of all the data from each of the sensors (Xsens n.d.*a*). The data can often be analyzed in an associated software.

2.2.3. 3D measurement

Different types of 3D measurements is also a potential technique. An example is the equipment used in the Prestudy, the FARO Arm which can measure the coordinates of a given point in space by placing the probe on the point wanted and register it. The data can be exported to e.g. MATLAB or Excel. This method is used in static conditions today in different areas of application. The same company also has a solution called FARO Scanner Freestyle^{3D} X which is a handheld scanner. It uses laser to create high-definition pointclouds and the data can easily be imported into all commonly used software solutions (FARO® n.d.) which then can be analyzed.

Another technology that is similar to the one mentioned above is evaluated by Gao et al. (2015). In this study two kinect sensors were used to accurately capture the the full motion of the body. The two Microsoft Kinect sensors were used to capture both depth and RGB images, this data was then processed with another software and mathematical methods to refine the results.

2.2.4. Inclinometer

An inclinometer, as called a Tilt Sensor, is an instrument that measures the tilt or slope of the instrument with respect to gravity. Digital inclinometers are small, portable and precise. Even though the measured body part must be taken into consideration, very little training is necessary to be able to use this instrument. A limitation of the inclinometer is that it has to be positioned in a very precise location to provide relevant angles in the two planes that it measures.

In a study by Saur et al. (1996), the reliability of measuring lumbar range of motion with an inclinometer was tested. The T12 and S1 vertebrae were used as reference points for positioning the inclinometer. The reference points were identified once using radiologic imaging and another time using only palpation. The conclusion of this study was that the non-invasive method of using an inclinometer gave highly reliable results. In another study, a goniometer and a digital inclinometer are used to measure shoulder mobility. A goniometer is an instrument that is very similar to a protractor with two arms which the angle is measured between. The article showed that the inclinometer and goniometer were interchangeable.

Inclinometers are often included in crash dummies as they enable the positioning of crash dummies is precise positions. This makes it possible to evaluate the impact of a certain initial position during a crash test for instance.

2.2.5. Medical imaging

The last technology which could be relevant is the category medical imaging. The types of medical imaging considered were X-ray, fluoroscopy, Magnetic Resonance Imaging (MRI) and ultrasound. Especially the three first can give a clear image how the body and skeleton are positioned.

Radiography is a diagnostic method used to detect e.g. bone fractures, certain tumors and other abnormal masses, pneumonia etc. using X-rays. X-rays are a form of electromagnetic radiation just like visible light. However X-ray has much shorter wavelength and thus higher energy which can pass through most objects, including the body. Medical X-rays are used to generate images of tissues and structures inside the body (NIBIB n.d. *b*). The images are generated by letting X-rays pass through the body and an X-ray detector and the materials will absorb a different amount of the radiation. The remaining X-ray pattern forms the image (FDA n.d.). Fluoroscopy uses X-rays and a fluorescent screen to obtain real-time images of movement within the body or to view diagnostic processes, such as following the path of an injected or swallowed contrast agent (NIBIB n.d. *b*).

A newer type of X-ray called Digital Motion X-ray (DMX) is an diagnostic equipment used especially after trauma to the spine, such as whiplash. It is similar to fluoroscopy but DMX takes more frames per second. The advantage is that the technique visualizes the movement of the skeleton in real time (Katz 2017).

MRI uses powerful magnets which produce a strong magnetic field that forces protons in the body to align with that field. When a radiofrequency current is then pulsed through the patient, the protons are stimulated, and spin out of equilibrium, straining against the pull of the magnetic field. When the radiofrequency field is turned off, the MRI sensors are able to detect the energy released as the protons realign with the magnetic field. The time it takes for the protons to realign with the magnetic field, as well as the amount of energy released, changes depending on the environment and the chemical nature of the molecules. It is then able to tell the difference between various types of tissues based on these magnetic properties (NIBIB n.d. *a*).

In an article called *Investigation of Whole Spine Alignment Patterns in Automotive Seated Posture Using Upright Open MRI Systems* MRI is used for investigate the whole spinal alignment patterns in an automotive seated posture (Sato et al. 2016). The technique gives a clear image of how the spine is aligned although it is not able to perform dynamic testing with this equipment.

Ultrasound is a technology which uses sound waves to produces pictures of the inside of the body. Ultrasound imaging involves the use of a small transducer (probe) and ultrasound gel placed directly on the skin. High-frequency sound waves are transmitted from the probe through the gel into the body. The transducer collects the sounds that bounce back and a computer then uses those sound waves to create an image. Because ultrasound images are captured in real-time, they can show the structure and movement of the body's internal organs (RadiologyInfo n.d.).

3 Method - An overview

This chapter gives an overview of the different activities conducted during the project. This is done to give the reader an easier understanding of the work performed, which is described in detail in the next chapter.

3.1. Methodology

The methodology used during this project origins from *Product Design and Development* by Ulrich and Eppinger. Usually, this methodology is associated with developing physical products but in this project it was applied on the concept development of a measuring method.

The reasons for choosing to work according to a methodology are stated below Ulrich & Eppinger (2012, chapter 1):

Firstly, the activities within the methodology make the decision process explicit. It allows rationale decision making and reduces the risk of moving forward with an unsupported decision.

Secondly, the activities act as checklists of the key steps in a development activity and they ensure that important issues are not forgotten.

Thirdly, structured activities are largely self-documenting. In the process of executing the activities, the team creates a record of the decision-making process for future reference.

Although the authors state that the activities are not intended to be applied blindly. They are a starting point for continuous improvement. Teams should adapt and modify the approach to meet their own needs (Ulrich & Eppinger 2012, chapter 1).

The project follows the two first phases in the Ulrich and Eppinger methodology, Planning and Concept development (Ulrich & Eppinger 2012, chapter 2) see Figure 3.1.

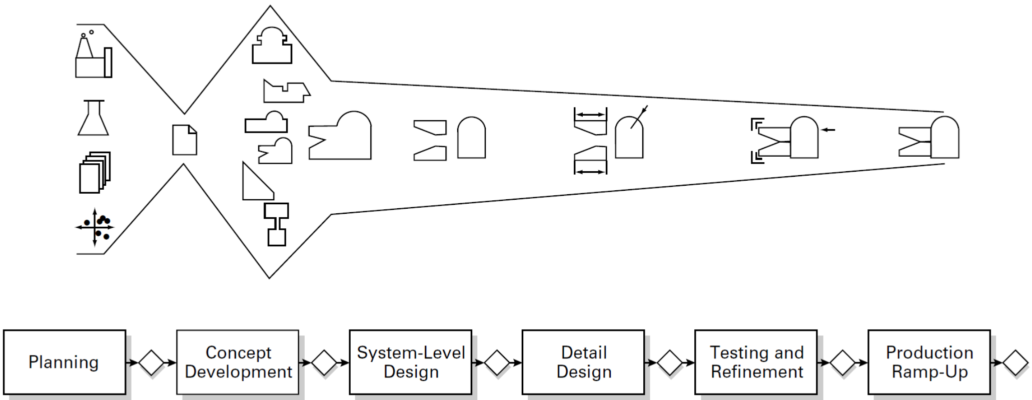

Figure 3.1: The generic product development process (Ulrich & Eppinger 2012)

The steps were slightly modified to fit the project and testing the concepts was of high importance. Thus, the focus in the Concept development phase was put on testing and data collection.

The Planning phase was supposed to give knowledge about the background of the problem, assess new technologies and give a solid foundation to help define the problem.

In the Concept development phase user needs and specifications were established, possible concepts were investigated and suitable concepts were tested and analyzed.

3.2. The activities conducted during the project

In the following list all the activities conducted during the project are described briefly to get an overview and context. The items correspond to the heading in next chapter.

- **Prestudy**. A prestudy was conducted to see how safety assessment is done today and what limitations are present with the current methods.
- **Concept development**. During the Concept development activities were carried through with objective to find a suitable concept for the measuring method wanted. A concept could be some equipment or a way of working.
  - **Identifying needs**. Firstly, the needs and requirements of the measuring method were clarified through the following steps:
    - **Gather raw data from users**. Opinions and input regarding the measuring method were collected through e.g. workshops.
    - **Interpret raw data to user needs**. The different opinions were interpreted to user needs.
    - **Organize needs**. The user needs were organized in four categories and after relative importance.
  - **Establish target specifications**. The user needs were reinterpreted to get a clearer view of what the measuring method should do.
    - **List of metrics**. A list of metrics was made.
  - **Concept generation**. During these activities different concepts for the measuring method were produced.

        - **Generation of concepts**. The approach for generating concepts are presented.
        - **Produced concepts**. The produced concepts for the measuring method are presented here.
    - **Concept selection**. A concept selection was made.
        - **Demo**. To get a clearer sense of how the different concepts worked, these were tested.
        - **Concept screening**. A screening was made to remove non suitable concepts.
        - **Concept scoring**. To get a higher resolution the concepts were scored.

- **Concept testing**. The most suitable concepts were tested.
    - **Prepare laboratory work**. The experiments were prepared, e.g. plan the experiments, find test persons etc.
    - **Laboratory work**. The three experiments were conducted.
        - **Experiment 1**. This experiment was focused on verification of the measuring method.
        - **Experiment 2**. This experiment focused on determining the orientation of a test person's pelvis when knowing the position of the shoulder and the knee. It also focused on evaluating how passengers choose to sit.
        - **Experiment 3**. This experiment was a dynamic testing session.

- **Verification of concept**. The approach for the verification is presented here.

- **Analysis**. The collected data was processed.
    - **Experiment 1**. The angles and segments from the verification were analyzed. The settings for the equipment's software were examined. The pelvic angles were obtained from the equipment and compared with the results from the verification.
    - **Experiment 2**. The relevant angles were calculated and compared with the pelvic angle values from the equipment. As well as different movements of body parts.
    - **Experiment 3**. The data collection was reviewed and compared with notes.

4 Method - A complete description

This chapter will address the different activities conducted during the project in detail.

4.1. Prestudy

In order to get deeper understanding of present measuring methods used for safety assessment and their limitations a prestudy was conducted. The team got their first insight in how measurement technicians work with experimental crash simulations and restraint system evaluation.

As previously mentioned, the current safety assessment tools have their limitations. The ATDs tend to have a higher stiffness than the human body in order to be more sustainable and to have the right kinematic properties when exposed to high g forces. This results in a limited area of use as the ATDs can not be positioned in extreme postures. The ATDs are only representative for a few selected body types. They are often based on the male body which excludes a large part of the population. However, the HBMs which are virtual models of human bodies, have tools which enables morphing which is currently developed and researched. These tools enables to reshape the HBMs to represent a more heterogeneous population. But as mentioned, more data is needed to position the HBMs in a humanlike way to assure the goodness of fit between the model and the reality.

This prestudy aimed to show the different behaviors of the human body and the ATD when reclining the seat. As ATDs are stiff and designed for an upright position, they behave differently than humans when reclining the seat. Two volunteers were recruited for this study and the ATDs used were THOR 50th percentile male and HIII 5th percentile woman. The experiment was carried out in the front passenger seat of an XC90. The backrest of the car seat was tilted back from the upright design position to +35° from vertical for the ATDs and to +40° from vertical for the test persons. In both cases, an increment of +5° between each measurement set was used. Measurements were done on a selected number of landmarks, see Table 4.1.

Table 4.1: Body landmarks measured in the Prestudy

Body landmarks measured on volunteers
1. Ear (right)
2. Shoulder (right)
3. Upper sternum
4. Lower sternum
5. ASIS upper right
6. ASIS upper left
7. ASIS lower right
8. ASIS lower left
9. Knee (right)
10. Lap belt right
11. Lap belt left
12. Shoulder belt

To get a clearer view on the different points measured, see Figure 4.1 - 4.2.

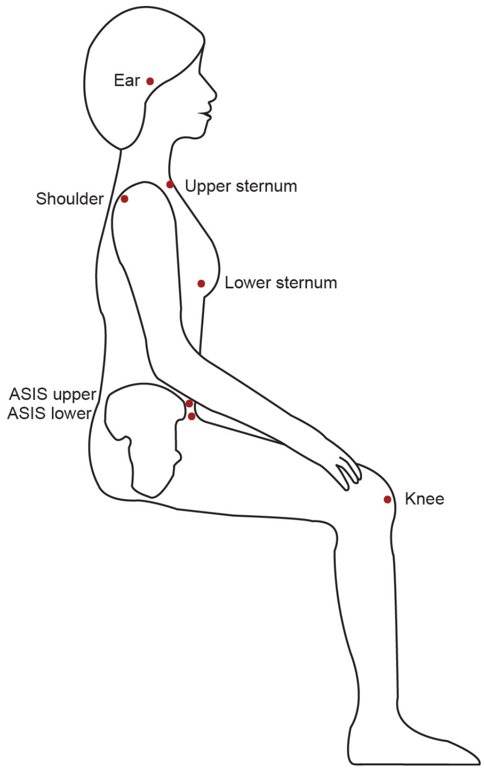

Figure 4.1: The body landmarks measured in the Prestudy

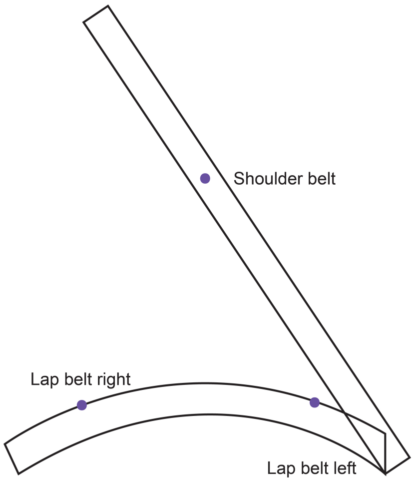

Figure 4.2: The points on the seat belt measured in the Prestudy

The upper ASIS landmarks are the hardest to distinguish. The ASIS lower landmarks were selected approximately three centimeters from ASIS upper at the same y-coordinate in direction towards the thigh, see Figure 4.1.

The data from the two volunteers was compared to data from the ATDs in order to notice if there were significant differences. Careful attention was payed to the position of the pelvis during the measurement sets. Photographs of the test persons were taken as well. The data was compiled in Excel and graphs and angles were plotted and calculated respectively. Especially the angle formed by the upper and lower ASIS was examined and compared to the angle formed by the shoulder and the knee.

4.2. Concept development

This section treats the activities used during the different steps which were carried out during the Concept development phase. The intended concepts are presented and a concept selection was conducted. Since different measuring methods were investigated in this project, the concepts are often equipments and ways of using them. The Concept development phase were based on knowledge retrieved from the literature study and the Prestudy.

4.2.1. Identifying needs

The goals of this step were to ensure that the product, or in this case measuring method, was focused on user needs. The needs are not connected to a specific concept but should be independent to the direction chosen (Ulrich & Eppinger 2012, chapter 5).

There are different activities to go through to establish the needs according to Ulrich & Eppinger (2012, chapter 5):

1. Gather raw data from intended users of the measuring method
2. Interpret the raw data in terms of user needs
3. Organize the needs into a hierarchy of primary, secondary and (if necessary) tertiary needs

4. Establish the relative importance of the needs
5. Reflect on the results and the process

Below the process for identifying needs in this project is described.

4.2.1.1 Gather raw data from users

The approach for gathering raw data for users needs were different types of workshops and discussions as well as observing the current methods used in today's safety assessment.

First, the Prestudy was conducted and it clarified the limitations that exist today. The requests regarding the properties of a alternative measuring method were noted. The project team participated in two workshops held by members in the project group working with the project *Assessment of Passenger Safety in Future Cars*. Each participant in those workshops had their own areas of expertise e.g. ergonomics, biomechanics, HBMs etc. Discussions were held around the project and valuable information and comments were gathered. Discussions were held as well with selected persons who could broaden the view in a certain field and also give deeper knowledge about different areas. The method used to document the interaction with the intended users were notes. The project members altered to be the primary notetaker which allowed the other member to concentrate on the questioning. This is recommended by Ulrich & Eppinger (2012). The notes were reviewed right after the sessions to share information and insights between the team members.

4.2.1.2 Interpret raw data to users needs

The gathered statements from the raw data collection had to be converted into user needs. In order to do this the following guidelines were used (Ulrich & Eppinger 2012, chapter 5):

- Express the need in terms of *what* the product has to do, not in terms of how it might do it
- Express the need as specifically as the raw data
- Use positive, not negative, phrasing (if possible)
- Express the need as an attribute of the product
- Avoid the words *must* and *should*

4.2.1.3 Organize needs

To get a clearer overview of the needs a more organized structure was made. In this project, the project team chose to divide the needs into four categories: *method, equipment and environment, data* and *output.*

In order to establish the relative importance of the needs a form was created and distributed to some selected people who had a good insight into what the measuring method should deliver. They were asked to rank the relative importance of a need on a scale 1-5 where 1 meant that the need is not important and 5 meant that the need is very important. In addition, they were asked to add suggestions if they thought something was missing. Seven persons filled in the form. From these forms the needs were divided in three categories: *very important, important* and *slightly important.* The form can be found in Appendix C.2 as Figure C.1.

4.2.2. Establishing target specifications

This step was meant to answer e.g. the question: How could the relatively subjective user needs be translated into precise targets for the remaining development process?
User needs are helpful for developing a clear sense of the issues of interest to users but they provide little specific guidance about how to design and engineer the product, or in this case measuring method. The specifications should spell out in precise, measurable detail what the measuring method has to do. A specification consists of a metric and a value. For example, "average time to assemble" is a metric, while "less than 75 seconds" is the value of this metric (Ulrich & Eppinger 2012, chapter 6).
The different activities are (Ulrich & Eppinger 2012, chapter 6):

1. Prepare the list of metrics
2. Collect competitive benchmarking information
3. Set ideal and marginally acceptable target values
4. Reflect on the results and the process

Since it wasn't a physical product that was developed rather a measuring method it was not as useful and intuitive to develop specifications. The measuring method developed includes both hardware/equipment, software and a way of performing the test.

4.2.2.1 List of metrics

It was still considered useful to convert the needs to metrics. This was to describe how the measuring method would work and what it should provide.

4.2.3. Concept generation

This step was meant to answer e.g. the questions:
What existing solution concepts, if any, could be successfully adapted for this application?
What new concepts might satisfy the established needs and specifications? The authors suggest a five-step method to generate concepts (Ulrich & Eppinger 2012, chapter 7):

1. Clarify the problem. Understand the problem and decompose it into simpler subproblems.
2. Search externally. Gather information from lead users, experts, patents, published literature, and related products.
3. Search internally. Use individual and group methods to retrieve and adapt the knowledge of the team.
4. Explore systematically. Use classification trees and combination tables to organize the thinking of the team and to synthesize solution fragments.
5. Reflect on the solutions and the process. Identify opportunities for improvement in subsequent iterations or future projects.

Below the concept generation in this project is described.

4.2.3.1 Generation of concepts

In order to produce relevant concepts it was important to clarify the problem and divide it into smaller parts. Most of this work was done during the Prestudy and the workshops held in the beginning of the project.

The project team proceeded to conduct a literature study to find suitable technologies and studies similar to what was supposed to be achieved in this project. The theory about how the pelvis is constructed and functioning was investigated as well as the ergonomic and biomechanical aspects. This to be able to assess the potential of different solutions related to the human body.

In addition, an internal search was performed to investigate if promising technologies were available at Volvo Cars. Useful information from parties with different expertise were collected.

The findings were then organized and suitable solutions were further investigated.

4.2.3.2 Produced concepts

Below are the considered concepts of the measuring method for this project. Some concepts are complete systems with both hardware and software while some concepts are more an idea or part of a larger system.

Qualisys Miqus is an optical motion capture system which work much like described in 2.2.1. The concept is a whole system and includes a suitable number of cameras, passive markers and a software called QTM. The passive markers are placed on points one desires to capture and in the software a kinematic model of the points can be created. The data can be exported to several softwares and programs (Qualysis n.d.).

Xsens MVN Awinda and MVN Analyze is a motion capture system based on inertial sensors. The system includes the hardware MVN Awinda which is 17 sensors that are placed on predefined locations. These collect data and based on certain body measurements a live model of the test person's body is created. Data can be collected during a chosen time span and exported to several softwares and programs (Xsens 2017).

3D scanning, the technology in mind is especially FARO Freestyle or Kinect. Both uses IR-light to scan the environment and in this way build a representation of the 3D environment as previously mentioned.

IES 1402 Dual Axis Tilt Sensor is an inclinometer currently used in the ATDs at Volvo Cars. It is used to accuratly position the ATDs before performing a crash test (Humanetics 2017). It shows the angle relative to a chosen reference plan in two axes.

Medical imaging techniques might give clear results in the sense of seeing how the pelvis and spine move. Especially the technology called DMX.

Shoulder-knee is a concept that was tested during the Prestudy. It is based on the hypothesis that the pelvis moves in relation to how the shoulder and the knee move. The idea is that the angle of the pelvis and the angle between the shoulder and the knee are approximately the same.

If this is correct then it would be sufficient to track the movement of the shoulder and knee with e.g. video cameras.

4.2.4. Concept selection

Concept selection was the step where one or a few concepts were chosen to continue with. There are different methods to perform a concept selection. Those relevant in this project were:

- Prototype and test: The organization builds and tests prototypes of each concept, making a selection based upon test data.
- Decision matrices: The team rates each concept against prespecified selection criteria, which may be weighted.

Decision matrices are further described by the authors. The first stage is called concept screening and the second stage is called concept scoring. Each is supported by a decision matrix that is used by the team to rate, rank, and select the best concept(s). Both activities follow the same layout:

1. Prepare the selection matrix
2. Rate the concepts
3. Rank the concepts
4. Combine and improve the concepts
5. Select one or many concepts
6. Reflect on the results and the process

Concept screening uses a reference concept and the other concepts are rated against this using the following system, + for “better than”, 0 for “same as”, – for “worse than”, in order to identify some concepts for further consideration.
Concept scoring is used when increased resolution is needed to differentiate among the concepts. In this stage, the project team weighed the relative importance of the user needs and focused on more refined comparisons with respect to each need. The concept scores were determined by the weighted sum of the ratings (Ulrich & Eppinger 2012, chapter 8).

4.2.4.1 Demo

In order to get a deeper understanding of how the different concepts worked, the project team performed tests/demos with those concepts that were available for the team to test. The aim was to acquire knowledge of how well the different concepts would perform in the intended test environment.

Qualisys Miqus was tested at Qualisys facilities in Gothenburg. A mockup was set up with two cameras of the model *Miqus* and an office chair to simulate a vehicle seat. The cameras were placed in a position that could correspond to the location in a car with respect to distances and angles. The cameras used could capture about 60 x 40°. The test person was equipped with five markers placed on relevant points. The cameras were connected to a computer and were adjusted to capture the relevant view of the test person in the two camera angles. The iris diaphragm and sharpness were adjusted. The equipment was calibrated using a kit of appropriate size containing a wand and an L-frame, to define the size and orientation of the captured volume. A couple of measuring sessions were done where the test person was positioned in the office chair and the back rest was reclined in a smooth motion. The data was reviewed and some features in the software were shown. The general impression was that it was a system with high precision and flexibility regarding placing the markers. It seems to be able to fit in a car environment. Aspects to think about were that a power source must be available. The set up and calibration are relatively time consuming and requires high accuracy. Since the goal was to capture the movement of the hip, a third camera might have to be used in order to maintain a clear line of sight. The cameras must be stationary in relation to each other.

Xsens MVN Awinda and MVN Analyze were demonstrated at Volvo Cars facilities by two persons from the University of Skövde. One of the members of the project team acted as volunteer. First the sensors were started and placed with straps on predefined places on the body. The sensors were visible live in the software and different features were shown. Different body measurements were taken to adapt the manikin which represent the test person. The information was saved and the manikin appeared in a 3D space. To get reasonable results, the sensors had to be calibrated and this was done with a procedure where the test person stands in a certain pose, then walks a few meters, turns and returns to the first pose. After that the manikin represented the test person who could start moving around. The manikin followed the test person live and recordings could be done as well. The recordings give both a video of the events and information about position, orientation, acceleration etc. for different body segments and joints. This information can be displayed in both graphs and the exact values can be downloaded. It appeared that the manikin followed the test person well and gave relevant values of the body segments reviewed. The procedure seemed to be quite intuitive. Aspects to think about were the placement of the sensors and the importance of them staying in the same place. The values (position, orientation e.g.) of the different body segments e.g. the pelvis is a mean value estimated from the measurements of the sensors. This equipment may be difficult to use during a drive as the manikin rotates in relation to the earth's midpoint and not the car. Preferably, the car should be the reference point.

FARO Scanner was used during the Prestudy to scan the position of the ATDs in a car seat with two different seat back angles. This version of scanner was connected to the FARO Arm but the technique is similar to FARO Freestyle in terms of the output. The scanner was moved a small distance (about 10 - 20 cm) from the object scanned. The scanner was moved around the object to capture the whole object. A 3D point cloud was created and could be reviewed. This type of scanning is a static method whereas e.g. Kinect is a dynamic version. Both give a representation of the surface of the body. Since an important goal was to capture the movement of the hip, it would be essential to maintain a clear line of sight.

IES 1402 Dual Axis Tilt Sensor was tested simply by placing the sensor on a suitable location, in this case from ASIS and down vertically aligned. The sensor was connected to a computer and the software associated with the sensor was started and it automatically recorded. The test person was placed on a chair and was asked to lean back and forth a couple of times. The angles could then be reviewed, based on the placement of the sensor the relevant angle was the one called X. It showed the rotation around the defined x-axis (sagittal plane). The sensor gave distinct results with high accuracy. Although the usability of the results depends on the position of the sensor and it only gives information about the one area where it was placed.

Shoulder-knee is a concept that was tested during the Prestudy. For more information see the sections regarding the Prestudy.

4.2.4.2 Concept screening

A concept screening was conducted for all the concept to get a clearer view of which concepts best suited the needs of the measuring method. The Tilt Sensor was chosen as the reference concept since it was the most simple concept according to the project team. The screening matrix was prepared with the needs and the produced concepts. The concepts were then rated against the reference concept. The plus and minus signs were summed up and the most promising concepts were taken to the next step. The screening matrix can be found as Table D.1 in Appendix D.

4.2.4.3 Concept scoring

A concept scoring was conducted to further refine the concept selection. The scoring matrix was prepared. The weight factor for each need were taken from the form used to determine the relative importance of the needs. The sum for each need were divided by the total sum of the needs and then normalized to a 0-1 scale. The sum of all the weight factors is 1.0 and thus the weight factors correspond to percentage. The concepts' performance were ranked on a scale 1-5 on how well a concept met a need, where 1 is not at all and 5 is very good. The score was then multiplied with corresponding weight factor and summed up to a final score for each concept. From this result and the testing, the concepts to continue with were chosen. The scoring matrix can be found as Table D.2 in Appendix D.

4.3. Concept testing

This section will address the Concept testing - the preparation, the implementation and the analysis. The Concept testing is a part of Concept development but has been given an own section since it is a prominent part of this project.

This step is a sequel to the concept selection and the goal was to refine the concept selection further and also to spot improvement opportunities.

4.3.1. Prepare laboratory work

The concepts which was considered to be reasonable and appropriate to proceed with were Xsens, Tilt Sensor and Shoulder-knee. Xsens got the highest score and both the Tilt Sensor and Shoulder-knee were easy to include in the laboratory work while testing Xsens so that is why this was done.

The thought with the laboratory work was to have two iterations, each with different focus, and to have a few weeks between the iterations. This to be able to design the second round of tests based on the results from the first test. When trying to book time slots in the Ergonomic Lab it was found out that it wasn't possible, therefore all the laboratory work was scheduled in four consecutive weeks.

The first test, Experiment 1, had focus on testing the Xsens equipment, both hardware and software and compare it to a static verification method of choice and the Tilt Sensor. The second test, Experiment 2, had focus on further test Xsens and also use it to see if the Shoulder-knee method was realistic. After these experiments were performed a final experiment, Experiment 3, was scheduled based on the findings from the two first ones. Experiment 3 had focus on dynamic testing.

When designing the tests, the aim was to originate from the list of needs to confirm or dementize if the concept worked as desired. Most of the needs were affected during the laboratory work or at the analysis. But to capture the subjective needs e.g. *Is not unpleasant to use for the test person* a questionnaire was designed. It treated both how the test person experienced the experiment and how the equipment was perceived. The questionnaire for Experiment 1 can be found in Appendix E.3 as Figure E.5 and for Experiment 2 and Experiment 3 as Figure E.6.

To find test persons for the two experiments the project team got a list from the Ergonomic department at Volvo Cars with persons who had stated that they would like to participate in the evaluation and testing of products under development. In this project, variation in body size and body shape was desired among the test persons rather than age. This to meet the need *Can be used on different human body types.* An email was formulated and sent to potential test persons. Those who answered got to sign up for time slots that suited them and got additional information. The addition information were two documents regarding the test and the handling of data according to Volvo Cars standard. They were modified from a template provided from Volvo Cars.

4.3.2. Laboratory work

The laboratory work was mainly conducted in the Ergonomic Lab at Volvo Cars facilities in Torslanda. Before the experiments the different tasks were defined and the project members received their respective main responsibilities, these are presented below in the Table 4.2. These regards Experiment 1 and Experiment 2.

Table 4.2: Main responsabilities during Experiment 1 and Experiment 2

Mathilda	**Jessica**
Introduce the experiment and setting	Provide suitable test garments
Explain the written consent	Put on the Xsens equipment
Calibrate Xsens	Take the Xsens measurements
Place Tilt Sensor (not relevant in Experiment 2)	Place the patrick markers on body landmarks
Record with Xsens and Tilt in predefined intervals	Lead the FARO measurements
Introduce the questionnaire	Take off Xsens equipment

4.3.2.1 Experiment 1

The aim with Experiment 1 was to verify how well the equipment could measure the pelvic orientation and get a sense of how well the equipment worked overall.
As verification method, a method described by Park et al. (2015) was used. It is used to locate a person's pelvis from accessible surface landmarks by considering the ASIS and PSIS flesh margins and the kinematic relationship between pelvis bony landmarks, digitized body surface landmarks, and skeletal joint locations.
More details about the method can be found in 4.4. The activities done during Experiment 1 connected to the verification method were the digitization of landmarks. To be able to find the anatomical landmarks as accurately as possible, a meeting was held with a physiotherapist. She

showed appropriate methods to find the different landmarks.

Nine test persons (five women and four men) were recruited to Experiment 1 and the testing was conducted in a static environment, see Table E.1 for more information about the test persons.

The equipment used during the experiment were Xsens MVN Awinda and Xsens MVN Analyze, a IES 1402 Dual Axis Tilt Sensor and a FARO Arm. Xsens MVN Awinda, see Figure 4.3, consists of 17 sensors placed on predefined locations on the body, those are presented in Table 4.3.

Figure 4.3: The Xsens MVN Awinda (Xsens n.d. *c*)

Table 4.3: The placement of the Xsens sensors

Sensor	Placement
Head	One, on the back of the head
Shoulder	Two, on right and left shoulder
Upper arm	Two, on right and left upper arm between bicep and tricep
Forearm	Two, above right and left wrist
Hand	Two, on right and left backhand
Pelvis	One, on sacrum
Upper leg	Two, on outer right and left thigh
Lower leg	Two, below right and left knee
Foot	Two, on top of right and left foot

A hardseat was constructed at Volvo Cars to enable measurement of the posterior spine and pelvis landmarks that are inaccessible in a normal chair or car seat, see Figure 4.4. Some of the measurements were conducted in the front passenger seat of an XC90. In addition, a measuring tape, a digital spirit level, a ruler, patrick markers (or crash test markers) and double-sided tape were used.

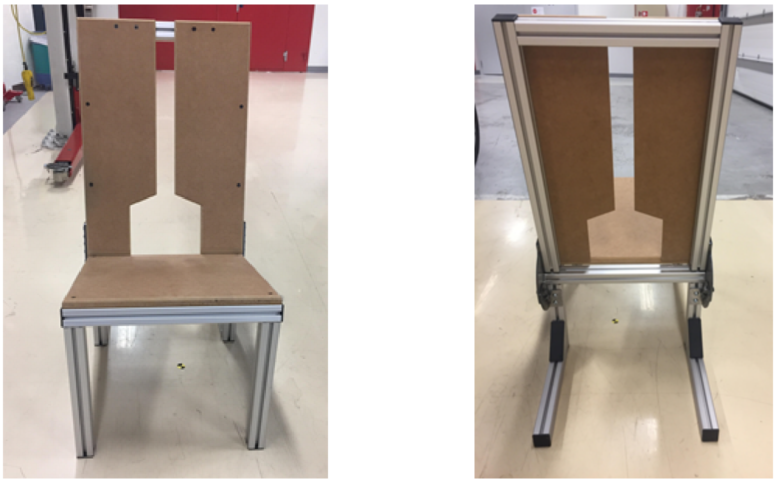

Figure 4.4: The hardseat

The procedure for Experiment 1 is presented below:

1. The test person was introduced to the test leaders also known as the project team and the agenda of the experiment was explained.

2. The test person signed a written consent and was provided closely fitting test garments.

3. The test person was equipped with Xsens MVN Awinda. Body measurements according to Table 4.4 were measured and entered in the Xsens MVN Analyze. The Xsens equipment was calibrated by performing a predefined procedure including standing in a neutral position, N-pose, walking a few meters, turning and returning to the original position. The test person was then encouraged to move around to "warm up" the equipment. The test persons also stated their weight.

Table 4.4: The measurements needed for the Xsens equipment

Measurements for Xsens equipment
Length
Foot length
Arm span
Ankle height
Hip height
Hip width
Knee height
Shoulder width
Shoulder height

4. Patrick markers were placed on predefined body landmarks according to Figure 4.5. For those landmarks not centered, markers were placed on both right and left hand side.

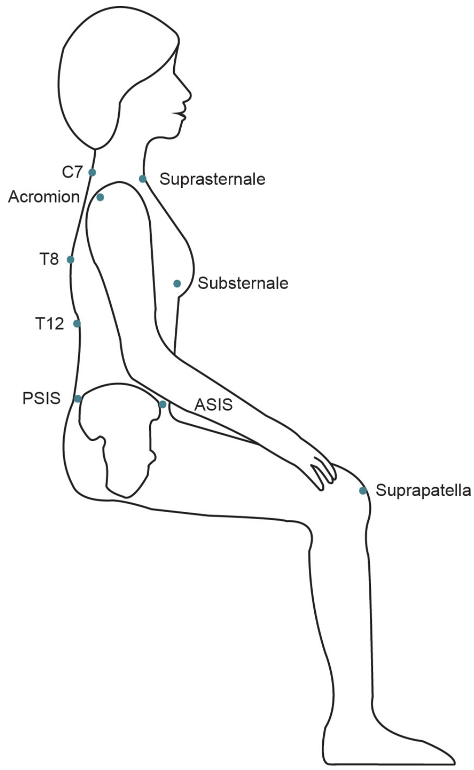

Figure 4.5: The body landmarks measured in Experiment 1

5. The Tilt Sensor was attached with double sided-tape right below the ASIS on the right hand side.

6. The test person was asked to sit in the front passenger seat. Two sets of measurements in different positions were made in the car, see Table 4.5. The measurement technician digitized the landmarks called *ASIS* and *suprapatella*. Data was collected with Xsens and the Tilt Sensor simultaneously as the FARO Arm measurements were made in each position.

7. The test person was asked to sit in the hardseat. Three sets of measurements in different positions were made in the hardseat, see Table 4.5. The measurement technician digitized all the marked landmarks. Data was collected with Xsens and the Tilt Sensor simultaneously as the FARO Arm measurements were made in each position.

Table 4.5: The positions in Experiment 1

	Position	Description
Car	Car 15N - Seat back angle: 15°, Cushion angle: 15°	Normal posture, thighs and whole back against the seat, soles of feet flat against the floor and hip width apart
	Car 38N - Seat back angle: 38°, Cushion angle: 15°	Normal posture, thighs and whole back against the seat, soles of feet flat against the floor and hip width apart
Hardseat	HS 15N - Seat back angle: 15°, Cushion angle: 15°	Normal posture, thighs and whole back against the seat, soles of feet flat against the floor and hip width apart
	HS 15S - Seat back angle: 15°, Cushion angle: 15°	Slouched posture, distance between lower back and seat, soles of feet flat against the floor and hip width apart
	HS 38N - Seat back angle: 38°, Cushion angle: 15°	Normal posture, thighs and whole back against the seat, soles of feet flat against the floor and hip width apart

8. After the data was collected the equipment was removed and the test person was asked to fill out a questionnaire.

The output from the experiment were the following:

- FARO measurements for each test person in the shape of an Excel file with 3D coordinates of each point digitized.
- Xsens files of the positions recorded. Included in these files were information about position, orientation, velocity etc. of different segments that can be exported. If the file was opened in Xsens MVN Analyze, the sequence of events could be reviewed as a movie.
- Excel files from the Tilt Sensor for each position recorded. The information included in the file was the time stamp, the angle in X and the angle in Y.
- The questionnaire filled in by the test person.

This experiment was remade about a month after the first scheduled sessions in order to evaluate new knowledge and discoveries made from the first session and after analyzing the data. The experiment was made on one of the project members to make it easier to keep track of the sensors and markers. The whole experiment was performed from the beginning twice in a row to test the repeatability of the experiment. This part of Experiment 1 will be referred to as the second session.

4.3.2.2 Experiment 2

Firstly, Experiment 2 aimed to investigate if there is a relationship between the angle formed by the shoulder and the knee and the angle of the pelvis (the Shoulder-knee method). If such a connection was found, future studies could focus on measuring the position of the shoulder and the knee and thus obtain the pelvic angle. The possibility of such a relationship was discovered in the Prestudy and the team then decided to explore this concept further as it would facilitate the determination of the pelvic angle. Secondly, Experiment 2 aimed to try the Xsens equipment on a larger group of test persons to get a better understanding of how the equipment works on a heterogeneous population. Lastly, Experiment 2 was conducted to study the postures of the test persons, both when instructed how to sit and choosing freely.

Seventeen test persons (ten women and seven men) were recruited to Experiment 2 and the testing was conducted in a static environment, see Table E.2 for more information about the test persons.

The equipment used during the experiment were Xsens MVN Awinda and Xsens MVN Analyze and a FARO Arm. All measurements were conducted in the front passenger seat of an XC90. In addition, a measuring tape, a digital spirit level, a ruler, patrick markers and double-sided tape were used.

The procedure of Experiment 2 is presented below:

1. The test person was introduced to the test leaders and the agenda of the experiment was explained.
2. The test person signed a written consent.
3. The test person was equipped with Xsens MVN Awinda. Body measurements according to Table 4.4 were measured and entered in the Xsens MVN Analyze. The Xsens equipment was calibrated by performing a predefined procedure including standing in the N-pose, walking a few meters, turning and returning to the original position. The test person was then encouraged to move around to "warm up" the equipment.
4. Patrick markers were placed on predefined body landmarks according to Figure 4.6.

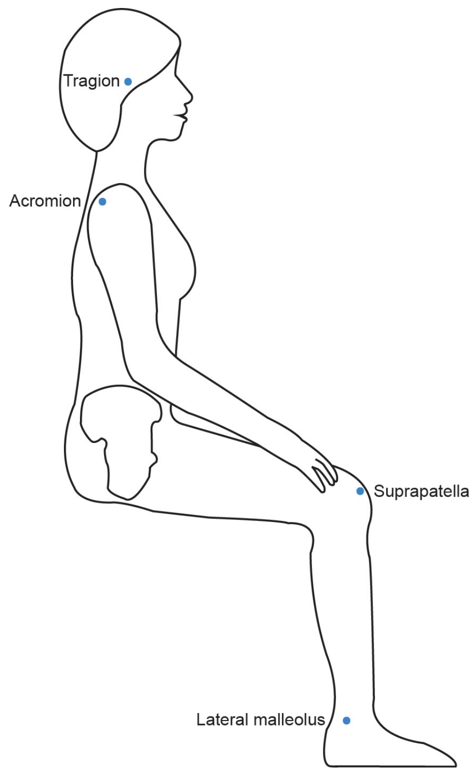

Figure 4.6: The body landmarks measured in Experiment 2

Three belt points were measured as well, see Figure 4.7. The *Belt Outer* was defined as the middle of the belt at the seam at the outer anchorage point for the lap-belt. The *Belt ASIS* was defined as the middle of the belt in height with ASIS. The *Belt Inner* was defined as the middle of the belt coming out of the buckle tongue lap-belt to shoulder-belt.

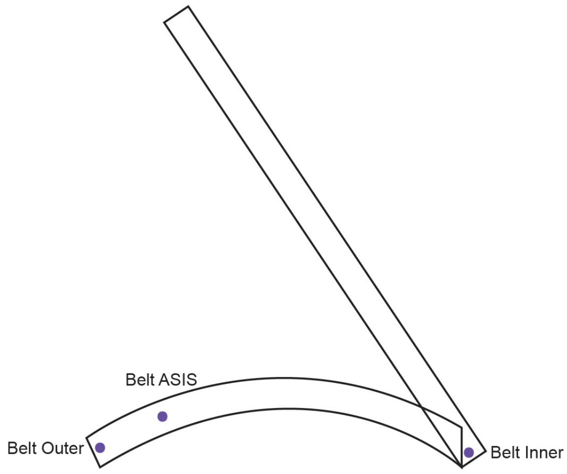

Figure 4.7: The belt points measured in Experiment 2

5. The test person was then asked to sit in the front passenger seat of the vehicle. Six sets of measurements with the backrest angle set to 23° and the cushion angle set to 15° were then made. The test person adopted a different posture for each measurement set, see Table 4.6, FC stands for feet close, FF for feet far. The measurement technician digitized all the marked landmarks for each position, see Figure 4.6. For the normal and the slouched positions the three belt points were digitized. Data was collected with Xsens continuously for the six positions.

Table 4.6: The positions in Experiment 2

Name	Description
N23 FC	Normal posture, thighs and whole back against the seat, soles of feet flat against the floor and hip width apart
N23 FF	Normal posture, thighs and whole back against the seat, legs stretched out so only heels of feet in contact with floor and hip width apart
F23 FC	Collapsed posture, back not in contact with the seat, rounded shoulders and back, soles of feet in contact with floor and hip width apart
F23 FF	Collapsed posture, back not in contact with the seat, rounded shoulders and back, legs stretched out so only heels of feet in contact with floor and hip width apart
S23 FC	Slouched posture, upper back in contact with the seat, distance between lower back and seat, rounded lower back, soles of feet flat against the floor and hip width apart
S23 FF	Slouched posture, upper back in contact with the seat, distance between lower back and seat, rounded lower back, legs stretched out so only heels of feet in contact with floor and hip width apart

6. The test person got to put the front seat in a position that he/she felt would be the most comfortable for a long drive and he/she adopted the posture thought to be most comfortable. The landmarks and belt points were digitized again by the measurement technician and Xsens was run simultaneously.

7. After the data was collected the equipment was removed and the test person was asked to fill out a questionnaire.

8. The seat settings for the last position were then measured and saved according to Table 4.7.

Table 4.7: Seat settings measured

Seat measurements
The backrest angle
The cushion angle
The horizontal position of the seat
The position of the extendable thigh support

In the original settings the backrest angle was set to 23° from vertical, the cushion angle to 15° from horizontal, the horizontal position of the seat was furthest back and the extendable thigh support was completely retracted. The definition of the measurement of the horizontal position of the seat was from the front of the rail to the counterpart on the seat, this was measured to 168 mm. When moving the seat forward this distance decreased. For the position of the extendable thigh support it was the horizontal length from the very front of the seat cushion to the most prominent part of the thigh support, this was measured to 31 mm and increased when moved forward.

The output from the experiment were the following:

- FARO measurements for each test person in the shape of an Excel file with 3D coordinates of each point digitized.
- Xsens files of the positions recorded. Included in these file was information about position, orientation, velocity etc. of different segments that can be exported. If the file was opened in Xsens MVN Analyze, the sequence of events could be reviewed as a movie.
- The questionnaire filled in by the test person.

4.3.2.3 Experiment 3

The aim of Experiment 3 was to test the Xsens equipment during a drive to evaluate how well it performed.

Four test persons (three women and one man) were recruited to Experiment 3 and the testing was conducted in a dynamic environment.

The equipment used during the experiment were Xsens MVN Awinda and Xsens MVN Analyze. All testing was conducted in the front passenger seat of an XC90. In addition, a measuring tape, a digital spirit level and a ruler were used.

The procedure of Experiment 3 is presented below:

1. The test person was introduced to the test leaders and the agenda of the experiment was explained.
2. The test person signed a written consent.
3. The test person was equipped with Xsens MVN Awinda. Body measurements according to Table 4.4 were measured and entered in the Xsens MVN Analyze. The Xsens equipment was calibrated by performing a predefined procedure including standing in the N-pose, walking a few meters, turning and returning to the original position. The test person was then encouraged to move around to "warm up" the equipment.
4. The test person was asked to sit in the front passenger seat of the vehicle with the backrest angle set to 23° and the cushion angle set to 15°. The test person adopted a comfortable posture and was encouraged to have a natural behavior. Data was collected with Xsens continuously during a drive of 24 km estimated to take approximately 40 minutes. The project member not driving took notes regarding deviations during the car drive like terrain, hills or speed bumps etc., or large movements of the test person.
5. After the data was collected the equipment was removed and the test person was asked to fill out a questionnaire.

The output from the experiment were the following:

- Notes from the car drive about terrain and the behavior of the test person.
- Xsens files of the positions recorded. Included in these file was information about position, orientation, velocity etc. of different segments that can be exported. If the file was opened in Xsens MVN Analyze, the sequence of events could be reviewed as a movie.
- The questionnaire filled in by the test person.

4.4. Verification of concept

This section informs about the work done to verify the concepts accuracy. The focus in the verification was to evaluate how well the Xsens equipment captured the pelvic orientation in particular since this area traditionally is difficult to measure. Initially, the landmarks in Table 4.8 had to be digitized in a seated position of choice.

Table 4.8: Body landmarks

Body landmark	Location
C7, T8, T12	Most posterior points of vertebral column (shaped like sinus curve)
Acromion	Most posterior point of the lateral margin of the acromial process of the scapula
Suprasternale	Superior margin of the jugular notch of the manubrium on the midline of the sternum
Substernale	Inferior margin on the midline of the sternum
ASIS	Located through palpation of the midline of anterior thigh surface until the anterior prominence of the iliac spine is reached
PSIS	Located through palpation along the margin of the iliac spine until the most posterior prominence is located, adjacent to the sacrum
Suprapatella	Most prominent part of the knee in sagittal plane

The landmarks called ASIS and PSIS were both digitized on the surface and also with one of the test leaders firmly pressing the flesh over the bony landmark. When all landmarks were collected, they were exported to Excel and transformed to MATLAB functions as an input function. As script was written in MATLAB and it followed the subsequently steps.

1. The location of the joints C7/T1 and T12/L1 were calculated using lankmarks, see Figure 4.8. The vector C was calculated and rotated 8 degrees counterclockwise. The joint was estimated 0,55C from the C7 landmark. The vector between T12 and T8 was calculated and rotated 94 degrees clockwise. The joint was estimated 0,52C from the T12 landmark Park et al. (2015).

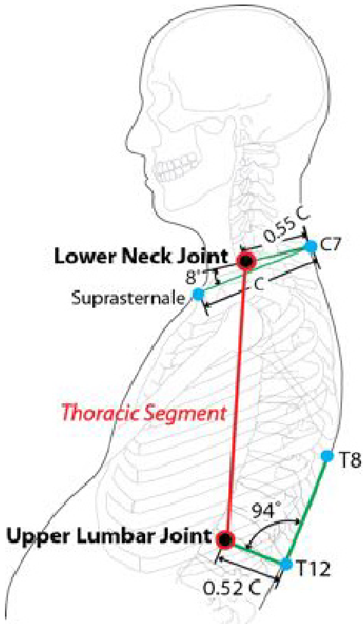

Figure 4.8: Calculation method for C7/T1 and T12/L1 joints (Reed & Ebert 2013)

2. A vector between the midpoint of ASIS landmarks to the midpoint of the PSIS landmarks was constructed. The pressed points were used in this step, called ASIS$_{pressed}$ and PSIS$_{pressed}$. The length of the vector was considered to be the measured Pelvic Depth (PD), PD$_{meas}$ and the direction the pelvic x-axis (Reed et al. 2013).

3. The pelvic depth was adjusted for BMI by using Equation 4.1.

$$PD_{adj} = PD_{min} + PD_{meas} - PD_{pred} \tag{4.1}$$

   Where PD$_{min}$ = 141 mm which is the expected pelvic depth for the subject with lowest BMI, 17,3 kg/m^2. PD$_{pred}$ is calculated using Equation 4.2 (Reed et al. 2013).

$$PD_{pred} = 65,6 + 4,38 \cdot \text{BMI} \tag{4.2}$$

4. The PSIS flesh margin was set along the pelvic x-axis and the length was set to 0,0006·BMI^3 (Reed et al. 2013).

5. The ASIS flesh margin was defined by calculating the pelvic depth from the ASIS$_{surface}$ and PSIS$_{surface}$ landmarks and then use Equation 4.3 (Reed et al. 2013).

$$ASIS_{flesh} = PD_{surface} - PSIS_{flesh} - PD_{adj} \tag{4.3}$$

6. The measured Bispinous Breadth (BB), BB$_{meas}$, was adjusted for BMI according to Equation 4.4.

$$BB_{adj} = BB_{min} + BB_{meas} - BB_{pred} \tag{4.4}$$

   Where BB$_{min}$ = 212 mm which is the expected pelvic depth for the subject with lowest BMI, 17,3 kg/m^2. BB$_{pred}$ is calculated using Equation 4.5 (Reed et al. 2013).

$$BB_{pred} = 165,3 + 2,64 \cdot \text{BMI} \tag{4.5}$$

7. The bone ASIS and PSIS locations were estimated using the flesh margins along the pelvic x-axis (Park et al. 2015).

8. The midpoints for ASIS_{bone} and PSIS_{bone} were calculated.

9. The hip joint centre (HJC) and the L5/S1 joint location were calculated by using the pelvic depth and bispinous breadth to move from the ASIS landmark according to Figure 4.9 and 4.10 (Reed & Ebert 2013).

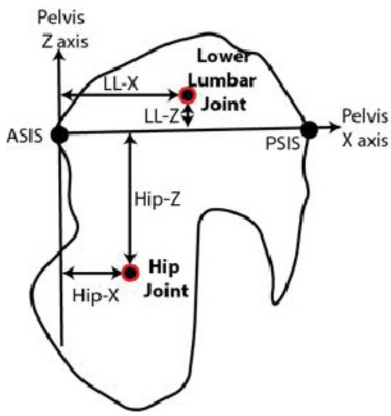

Figure 4.9: Illustration of the hip and lower lumbar joints in the xz-plane of the pelvis coordinate system (Reed & Ebert 2013)

		Function	Female		Male	
Joint	Axis	of Pelvis	Intercept	Slope	Intercept	Slope
Hip Joint Center	Hip-X	Depth	-13.6	0.3822	-11.1	0.3686
	Hip-Y	Width	-54.5	- 0.1439	-56.8	-0.1372
	Hip-Z	Depth	-70.7	- 0.0512	-74.3	- 0.0606
Lower Lumbar Joint Center	LL-X	Depth	-42.8	0.8640	-51.6	0.8693
	LL-Y	Midline				
	LL-Z	Depth	4.6	0.0686	-2.6	0.1280

Figure 4.10: Joint locations as a function of PD and BB (Reed & Ebert 2013)

10. When all the joint locations were calculated, angles and segments of interest could be calculated, for example the angle between HJC and L5/S1, which is the definition of the pelvic angle.

A subsequent step was that with the help of the digitized landmarks from the hardseat, the pelvic orientation in a car seat can be determined with fewer landmarks based on a few different assumptions. The pelvic orientation is found by performing an optimization in MATLAB. Due to the limited time range this step was excluded.

4.5. Analysis

This section will explain what analysis work has be done from the different experiments.

Common analysis for all experiments were to summarize the questionnaires. The average grade for each statement was calculated and reviewed.

4.5.1. Experiment 1

Verification: calculation of pelvic angle and posture
From the verification method the primary objective was to calculate the pelvic angle, which was defined as the angle between the horizontal plane and the vector between the HJC and L5/S1 joint in the sagittal plane. To ensure the relative accuracy of the measurements, other angles and segment lengths were calculated in addition according to Table 4.9. All angles are defined in the sagittal plane and as the angle between the horizontal plane, or x-axis, and the vectors described below, for a visual representation see Figure 4.11.

Table 4.9: The angles and segments calculated from the verification method

Angle/length	Definition
Upper back	Vector between T12/L1 and C7/T1
Lower back	Vector between L5/S1 and T12/L1
ASIS/HJC	Vector between HJC and ASIS$_{bone}$
L5S1/HJC (pelvic angle)	Vector between HJC and L5/S1
PSIS/HJC	Vector between HJC and PSIS$_{bone}$
Knee	Vector between HJC and suprapatella
PD	Length of pelvic depth

Figure 4.11: The angles from the verification method

The angles *Upper back*, *Lower back* and *Knee* were examined and compared between the test

persons to evaluate if the test persons were positioned similarly. The mean value and standard deviation (SD) were calculated for these for the three positions in the hardseat, as well as for the other parameters in Table 4.9.
The difference between *ASIS/HJC* and *L5S1/HJC (pelvic angle)* was taken as well as between *L5S1/HJC (pelvic angle)* and *PSIS/HJC*, see Figure 4.12.

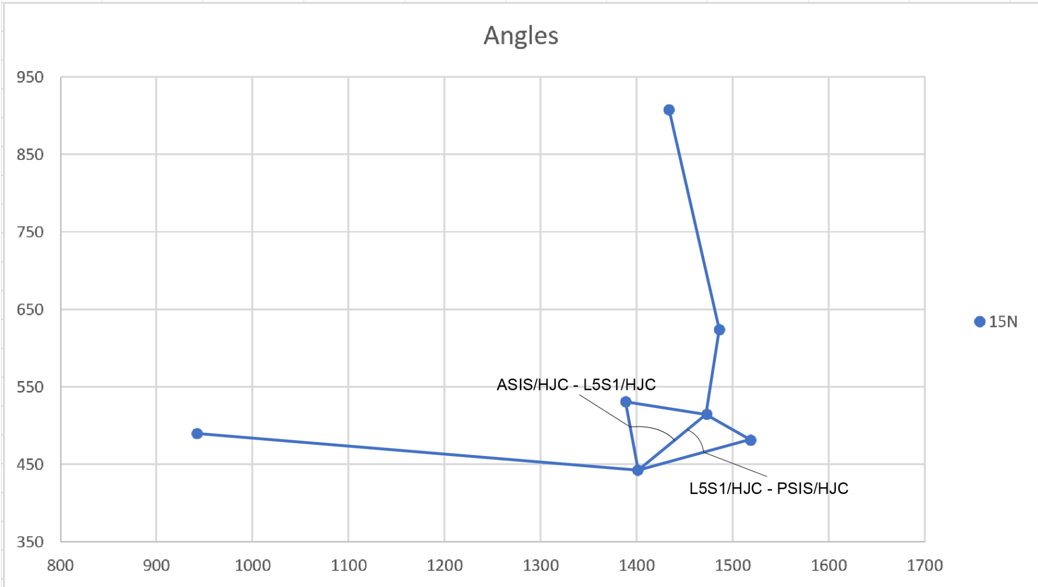

Figure 4.12: The the relative angles of pelvis

These relative angles and *PD* were used to evaluate if the pelvis was measured in the same way for the three positions in the hardseat for each test person, the mean and SD were calculated here as well. If they would be similar or equivalent within each test person, this would mean that a rigid transformation occurred.
To get a visual representation of how the test persons sat in the hardseat, the joint locations and selected landmarks were plotted in the xz-plane, or saggital plane. An evaluation was done if the results seemed reasonable.

The same steps in the analysis were made for the second session made a month later. In addition, the visual representation of the test person from both measurements were plotted in the same graph to easily compare the repeatability.

Xsens: adjustments in Xsens Analyze
The data obtained from Experiment 1 was reprocessed two times for each TP in the Xsens Analyze software. The three versions obtained were:

1. the original version in scenario *Single Level*.
2. the original version reprocessed in HD using scenario *No Level*
3. the original version reprocessed in HD using scenario *Single Level*

The first reprocessing from 1 to 2 was done after talking to an expert in biomechanics at Xsens. He recommended the use of version 2 to get the more accurate results. A reprocessing from 1 to 3 was later done to evaluate the impact of reprocessing the data in HD. A complete description of the scenarios can be found in Appendix G.

The HD quality is only available for the scenarios *Single Level* and *No Level*. Reprocessing collected data in HD means that the quality of data will be improved (Xsens 2018*b*). For instance, disturbances or unreasonable values are sorted out.

The data from each subject in the three different versions could be exported to Excel for further analysis and plotting.

Xsens: calculation of the pelvic angle

From the Xsens MVN Analyze, the orientation of the pelvis was obtained in quaternions, a number system often used for systems involving three-dimensional rotations. This is done to prevent Gimbal locks in the calculations. A Gimbal lock is the loss of one degree of freedom in a three-dimensional mechanism which occurs when two of the three axis are driven to a parallel configuration (Strickland 2008).

For the Xsens equipment the origin of the pelvic orientation is defined as (Xsens 2017), see Figure 4.13 and Table 4.10:

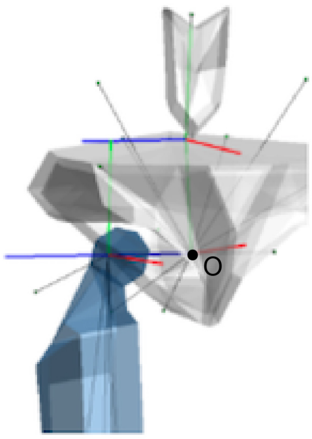

Figure 4.13: Definition of centre of rotation of the pelvis (Xsens 2017), modified

Table 4.10: Definition of the centre of rotation of the pelvis

	Definition
O	Midpoint between right and left hip centre of rotation
X	Perpendicular to Y and Z
	Pointing forward
Y	Left hip joint to right hip joint
	Pointing right
Z	Hip origin to L5/S1 joint
	Pointing up

Rotations around the three different axis are therefore obtained by the following movements:

- Rotation around the x-axis: movement of the body in the frontal plane
- Rotation around the y-axis: movement of the body in the sagittal plane.

- Rotation around the z-axis: movement of the body in the transverse plane.

Calibration gives unique start values (zeros) for each person for the x-, y- and z-axis. The x and y starting points are fixed according to the posture the test person has when standing in a neutral position and the z-axis is fixed in the ground at the point where the person stood during calibration.

In this study, the angular rotation of the pelvis around the y-axis is in focus, as it is the angle that will get most affected when a passenger reclines the car seat or chooses to sit in a slouched position for instance. The conversion from quaternions to Euler angles for the y-axis was calculated according to Equation 4.6 (Xsens 2018*a*):

$$Y = -\arcsin(2q_1q_3 - 2q_0q_2) \tag{4.6}$$

For each test person, the average pelvic angle value during each set of measurement (five sets) was then calculated.

Tilt Sensor
The data from the Tilt Sensor was reviewed for each test person, it was found that for TP5 in "Car 15N" something went wrong when saving the file and the data could not be reached.

A change in the x-axis for the Tilt Sensor corresponds to a movement of the body in the sagittal plane and a change in the y-axis corresponds to a movement of the body in the frontal plane. The resulting angles in the x-axis and in the y-axis were compared to BMI. The Tilt Sensor can bee seen in Figure 4.14.

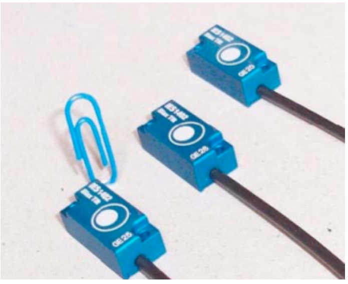

Figure 4.14: The Tilt Sensor (IES 2006)

Comparison between the systems
The mean pelvic angle value and the standard deviation were calculated for each position using the data from Xsens for each test person and the data from the verification method for each test person separately. The obtained values were compared.
For further analysis, the difference between the mean pelvic angle value obtained with the verification method and the Xsens equipment was calculated for each test person in each position. See the following example:

- Mean pelvic angle value with verification method = 62,5°
- Mean pelvic angle value with Xsens equipment = 47,6°
- Pelvic angle difference between verification method and Xsens equipment = 14,9 °

From the difference of the pelvic angle between the verification method and the Xsens equipment, the mean difference for each test person and for each position were calculated. The mean difference for each test person was then plotted against the test person's BMI.

4.5.2. Experiment 2

FARO: calculation of the shoulder-knee and belt angle

The measurements from the FARO Arm were exported to Excel and transformed to MATLAB functions as an input function. A script was written in MATLAB, it calculated the shoulder-knee angle as well as the belt angle. The belt angle was defined as the angle between the horizontal plane and the vector between Belt Outer and Belt ASIS, see Figure 4.7. The angle was defined in the sagittal plane, or the xz-plane.

Xsens: calculation of the pelvic angle

The pelvic angles were calculated in same way as in Experiment 1. For each test person the average pelvic angle during each set of measurements was calculated.

Xsens: pelvis position data

From the Xsens MVN Analyze, the position of the pelvis was obtained in meters in the global frame. The global frame for the Xsens equipment is defined in Table 4.11, an illustration is available in Figure 4.15 (Xsens 2017).

Table 4.11: Definition of the origin of the pelvis position

	Definition
O	Midpoint between right and left hip centre of rotation
X	Positive when point to the local magnetic North
	Perpendicular to Y and Z
Y	According to right handed co-ordinates (West)
	Perpendicular to X and Z
Z	Positive when pointing up
	Perpendicular to X and Y

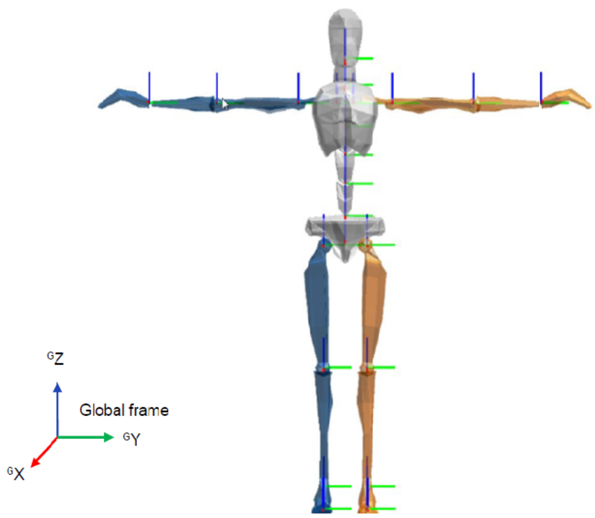

Figure 4.15: Segment coordinate system at each segment origin (Xsens 2017)

Comparision between the systems

The pelvic angle from Xsens were compared with the shoulder-knee angle, see Figure 4.16, to see if there was some form of relationship. This was done by taking the difference between Xsens and Shoulder-knee for all positions, then calculate mean value and SD for each test person. The same thing was done but with only the difference for the normal and slouched positions as well.

The movement of pelvis position along the x-axis was compared with the movement of knee position along the x-axis and the movement of shoulder position along the z-axis. The N23 FC position was used as starting point and the difference was calculated for the following scenarios:

- Pelvis (x): N23 FC - N23 FF
  Knee (x): N23 FC - N23 FF
  Shoulder (z): N23 FC - N23 FF
- Pelvis (x): N23 FC - F23 FC
  Knee (x): N23 FC - F23 FC
  Shoulder (z): N23 FC - F23 FC
- Pelvis (x): N23 FC - F23 FF
  Knee (x): N23 FC - F23 FF
  Shoulder (z): N23 FC - F23 FF
- Pelvis (x): N23 FC - S23 FC
  Knee (x): N23 FC - S23 FC
  Shoulder (z): N23 FC - S23 FC
- Pelvis (x): N23 FC - S23 FF
  Knee (x): N23 FC - S23 FF
  Shoulder (z): N23 FC - S23 FF

These scenarios were plotted with the pelvis movement on the x-axis and the knee and shoulder movement on the y-axis.

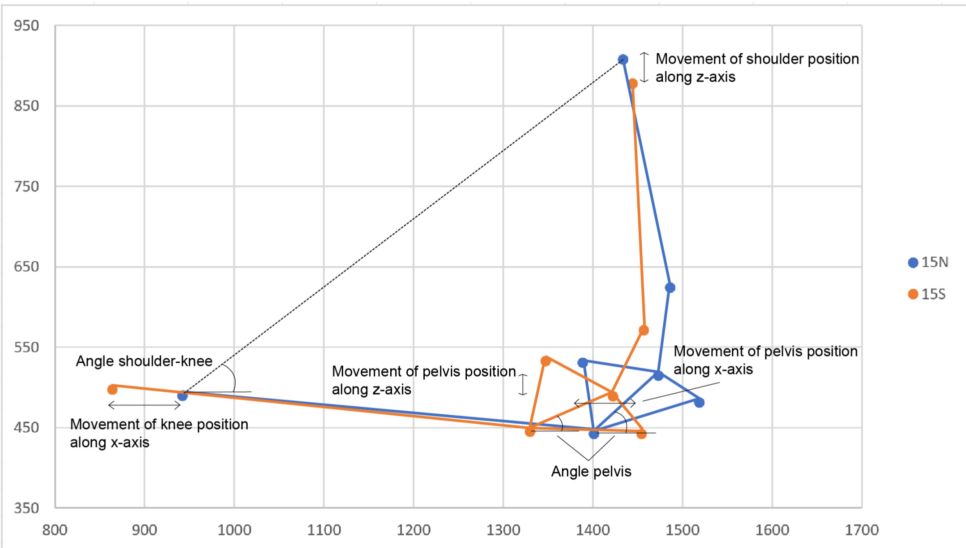

Figure 4.16: Measurements compared in Experiment 2

Position of choice
The seating settings for the car seat were compared between the test persons and to relevant body measurements. The pelvic angle was compared to the pelvic angle in N23 FC.

4.5.3. Experiment 3

Xsens: calculation of the pelvic angle
The pelvic angles were calculated in same way as in Experiment 1 and Experiment 2. For each test person the average pelvic angle value during the drive was calculated. The lowest and highest recorded pelvic angle values and the difference between these values were also noted in order to evaluate the variation.

During each drive, one of the test leaders was studying the test person and the data recorded simultaneously and making notes of important changes of position and road obstacles encountered. When analysing the data, these notes were used to explain major pelvic angle changes.

5 Results

This chapter will present the results of the project.

5.1. Prestudy

The results regarding the ATDs showed that in the first +15°, it was easy to position both dummies. From +20° from the starting point 18°, it started to be harder to maintain contact between the shoulder and backrest, even though the dummy was pushed into the seat. The leg position had to be adjusted and pressed into the seat cushion to maintain contact with the floor. The volunteers followed more smoothly than the ADTs but the volunteers felt the need to adjust their backs to get a more comfortable posture from +20°.

The data given from the measurements was in the form of 3D coordinates. The three dimensional coordinate system in cars in this project was defined following: the x-axis is positive rearward, the y-axis is positive to the driver's right, and the z-axis is positive upward according to SAE (2009). This was the coordinate system used throughout the whole project. The points in the sagittal plane were the most interesting for this project, the side view of the body, which correspond to the xz-plane.

The data showed an evident correlation between the reclination of the backrest and the ear and shoulder as expected. The upper and lower ASIS moved as well but visually much less. The knee was almost static. See Figure B.2 - B.4 for more details. Some correlations could be seen, observe that the angles calculated originates from the horizontal plane, see Table B.1 and Figure B.5 - B.7 for details:

- It appears that the reclination in the back is about double the size than the reclination in the pelvis for Female 1. See Figure B.8.
- The angle between the shoulder and knee and the pelvis is comparable, see Figure B.8. The relationship can be seen as uniform triangles.

5.2. Concept development

The results produced during the Concept development phase are presented below.

The user needs related to the measuring method were established, the needs and the properties of the measuring method should coincide as far as possible. The ranking of the needs resulted in three categories, 20 needs were sorted in the *very important* category, 9 needs were sorted in the *important* category and 3 needs were sorted in the *slightly important* category. A complete list of the user needs can be found as Table C.1 and the results from the ranking can be seen in Table C.2, see Appendix C.

The needs were converted into metrics and a complete list of the metrics compared to the needs can be found as Table C.3. The metrics helped to further understand the demands on the measuring method. Although, many of the needs were not as intuitive to transform to a measurable description.

After the concept generation, six different concepts were considered, these are presented in 4.2.3.2 in order to provide a clearer understanding of the following activities under the method chapter. The results of the concept screening and concept scoring are presented in Table 5.1 and Table 5.2. From the screening the concepts Scanning and Medical imaging were removed.

Table 5.1: The result from the screening matrix

Concept:	Xsens	Qualysis	Tilt Sensor	Shoulder-knee	Scanning	Medical imaging
Positive:	13	14		10	8	12
Negative:	1	10		4	13	17
Sum:	**12**	**4**	**0**	**6**	**-5**	**-5**

Table 5.2: The result from the scoring matrix

Concept:	Xsens	Qualysis	Tilt Sensor	Shoulder-knee
Sum:	**4,17482**	**3,83072**	**3,37638**	**3,61913**

To see the total rankings see Table D.1 and Table D.2.

5.3. Concept testing

5.3.1. Experiment 1 and Experiment 2

The results from Experiment 1 and Experiment 2 were quite similar since both included static measurements.

Time
Experiment 1 took from 45 minutes up to 1 hour and 40 minutes, the designated time was 2 hours. It took the longest the first three sessions. Each measuring session in the hardseat took around five minutes. Experiment 2 took from 25 minutes up to 55 minutes, the designated time was 1 hour. The measuring session with the predefined positions took around ten minutes and the position of choice took circa two minutes. The time from the start when the Xsens equipment was put on till it was ready to use took between 15 minutes to 30 minutes.

Hardware and equipment
Some photographs were taken during Experiment 1, see Figure E.1 - E.4 in Appendix E. These show the setting for the experiment as well as the equipment in context with each other.
The Xsens equipment was more difficult to calibrate on certain persons. The software said the calibration was poor repeated times while for some other persons, the calibration was successful on the first try.

After some calibrations, a leg could be seen spinning around in the software even though the person stood still. The feet had a tendency to slowly drift during the test session, see an example of a leg and a foot drifting in Figure 5.1. The arms and hands could also be bent in unnatural positions but this problem was often solved with a recalibration.

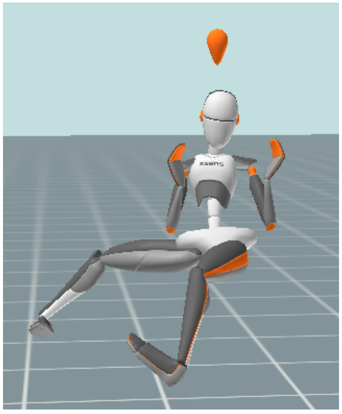

Figure 5.1: Example of a leg and a foot drifting during a recording

Sometimes some sensors could appear to lose connection, these were then restarted to solve the problem. When a test person was very still, sensors could go to sleep mode, this was solved by asking the person to move the affected body part. The strap with the sensor on the sacrum had a tendency to move upwards on many test persons when they moved around. It was therefore adjusted during the experiments.

The Tilt Sensor was placed right below ASIS on the right hand side. This landmark was chosen as it is easy to find. It is also a central point when looking at passenger restraint as the upper edge of the seat belt should be right below the ASIS. The placement of the Tilt Sensor in Experiment 1 varied in difficulty and on some test persons it had problems staying in place during the experiment. The Tilt Sensor was positioned when standing up and when sitting down the Tilt Sensor ended up in a starting position that mostly depended on the test person's abdominal fat, see Figure 5.2. For test persons with little abdominal fat, the Tilt Sensor would stay in place (as shown on the left in Figure 5.2) and for test persons with more abdominal fat, the Tilt sensor would get stuck between the thighs and the stomach of the test person (as shown on the right in Figure 5.2).

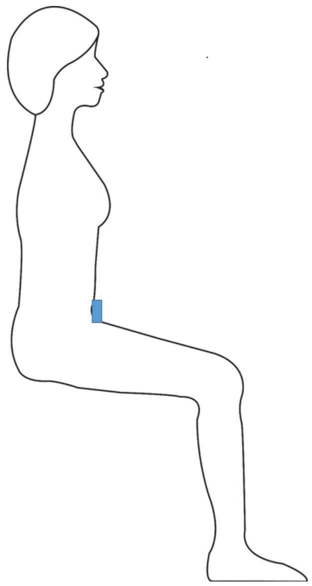

Figure 5.2: Positioning of the Tilt Sensor depended on the test person's abdominal fat

It was fairly easy for the measurement technician to measure the point when the test person was placed in the XC90.

Software
For some recordings problems appeared when trying to save the files. For some files it helped to choose the assigned folder again and for some the folder had to be changed. A few times the software froze for a few seconds or for nearly a minute.

5.3.2. Experiment 3

The results from Experiment 3 showed that the Xsens equipment handled dynamic testing in a car environment well. The body segments represented the test persons appropriately and did not drift visually with time. The associated equipment, computer etc. could smoothly be handled in the rear seat although the software consumed a lot of the computer's battery. At the moment, the manikin has the reference point of the centre of the earth but to eliminate the impact of hilly terrain while driving, the reference point would have to be the car. However, a working method to compensate for this is not currently available. Thus, while looking at the manikin while e.g. turing the car, the manikin would rotate around the z-axis, see Figure 5.3 (x is red, y is green, z is blue).

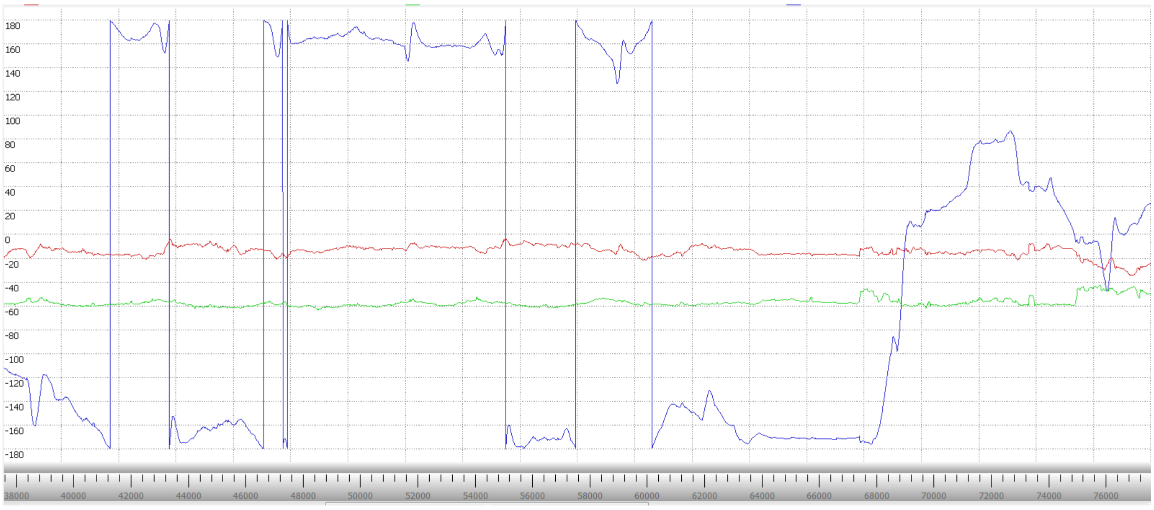

Figure 5.3: The orientation of the pelvis around the x-, y- and z-axis, especially z is affected by the car's movement [°]

5.4. Verification of concept

The result from the verification method were primarily angles of different segments. These and the length of PD are presented in Table F.1, Table F.2 and F.3. The tables are organized after position in the hardseat to be able to compare between the test persons. The mean and SD for each segment for the three positions are presented in Table 5.3. The interpretation of data is, for example, that the *Upper back* and *Lower back* show that the entire back was tilted backwards when changing from 15N to 38N, but only the *Lower back* was tilted backwards when the person adopted the 15S position.
These results were used to evaluate if the test persons were positioned in the same way. The SD for *Upper back*, *Lower back* and *Knee* are around 4-5° and for the angles related to pelvis SD is around 10-11°.

Table 5.3: The mean and SD for the angles and segment length in the three positions in hardseat for the nine test persons

		Angles and segment						
		Upper back	Lower back	ASIS/HJC	L5S1/HJC	PSIS/HJC	Knee	PD
15N	Mean	112,1°	81,4°	105,5°	55,2°	29,0°	170,9°	148,8 mm
	SD	4,0°	4,9°	10,9°	11,6°	10,8°	4,1°	8,1 mm
15S	Mean	110,7°	70,6°	87,9°	37,3°	12,1°	170,2°	149,7 mm
	SD	4,3°	7,3°	10,2°	11,2°	9,3°	5,0°	9,4 mm
38N	Mean	92,7°	55,9°	89,3°	39,4°	13,4°	169,6°	148,0 mm
	SD	4,7°	4,2°	11,7°	11,0°	9,6°	2,7°	8,5 mm

The corresponding results from the second session are presented in Table 5.4. Here the SD is lower for all angles which shows a repeatability of the experiment.

Table 5.4: The mean and SD for the angles and segment length in the three positions in hardseat, for one test person twice for the second session

		Angles and segment						
		Upper back	Lower back	ASIS/HJC	L5S1/HJC	PSIS/HJC	Knee	PD
15N	Mean	100,4°	82,2°	99,6°	47,1°	20,9°	173,8°	146,6 mm
	SD	0,0°	1,5°	2,4°	2,8°	3,5°	0,4°	1,0 mm
15S	Mean	95,5°	68,1°	80,5°	27,8°	3,0°	173,3°	147,0 mm
	SD	4,5°	1,2°	2,9°	3,5°	2,5°	0,4°	1,5 mm
38N	Mean	76,8°	60,4°	78,0°	24,3°	1,4°	171,0°	149,3°
	SD	2,5°	1,4°	1,0°	0,2°	0,5°	0,2°	3,0 mm

5.5. Analysis

5.5.1. Experiment 1

The results from the questionnaire which aimed to evaluate the more subjective needs of the measuring method can be seen in Table E.3. The overall results were high meaning the test persons had a pleasant experience using the equipment and during the experiment in general. The text answers which were for comments about the experiment regarded the tight fitting test garments, which by some were experienced as a bit uncomfortable.

Verification: calculation of pelvic angle and posture

An example of a visual representation of how a test person sat in the different positions in the hardseat can be seen in Figure 5.4. This can be compared to the visual representation in Figure 5.5.

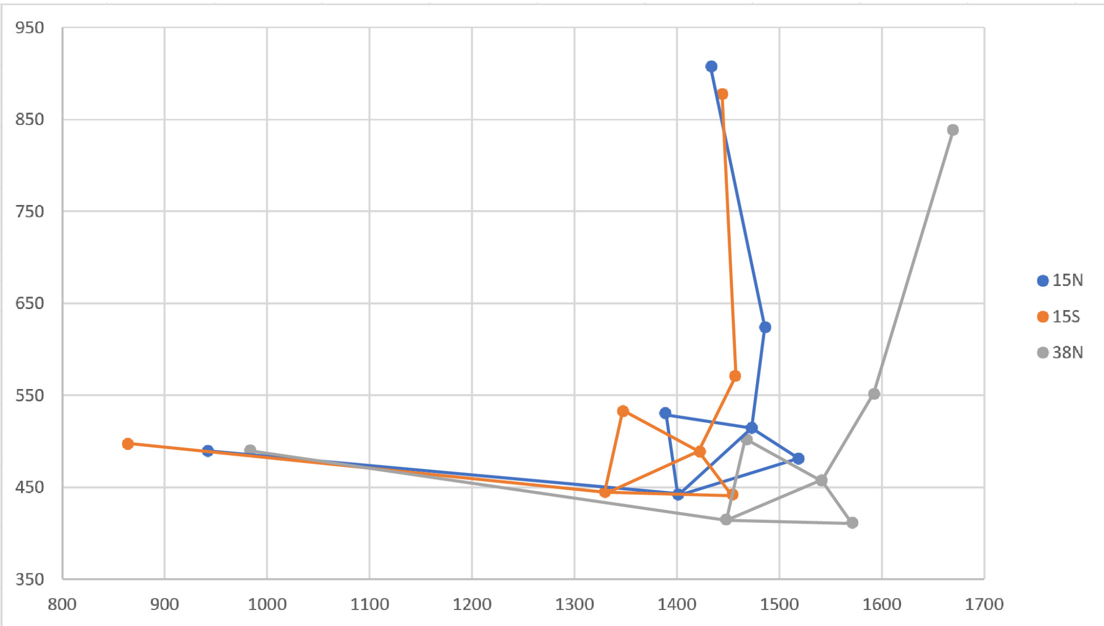

Figure 5.4: An example of the visual representation of how the test persons position in the hardseat

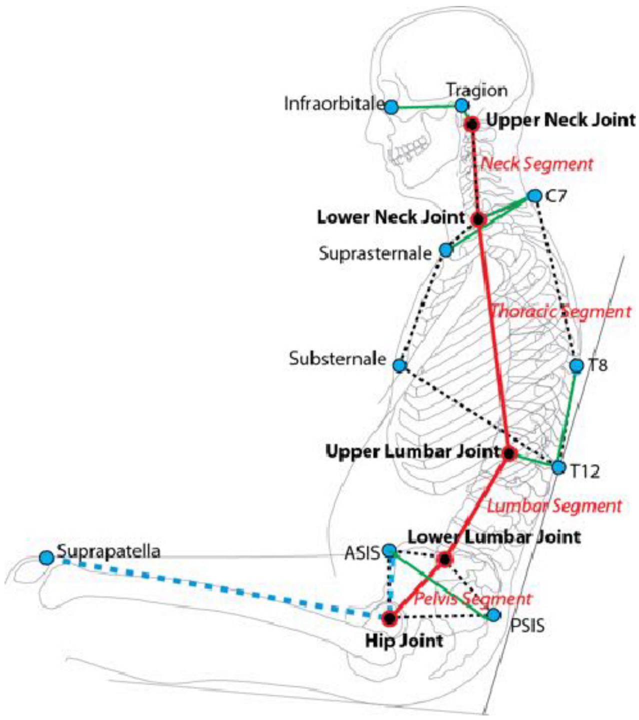

Figure 5.5: The joint locations illustrated from Reed & Ebert (2013)

The visual representations for all test persons can be seen in Figure G.1 - G.9 and from the second session in Figure G.10. These can be compared with Figure 5.5 according to Park et al. (2015) for increased understanding.

The calculation of the relative angles for the pelvis and PD resulted in quite similar values between the test persons, with a low SD within each test person, see illustrated in Figure 5.6 - 5.8. The exact values for all test persons can be seen in Table G.1 and the results from the second session of Experiment 1 can be seen in Table 5.5.
1th round and 2nd round refers to Experiment 1 being performed on the same test person twice, the test person was one of the project members. The results show good repeatability as the angle varies max 2° and PD up to a maximum of 3,2 mm. These results were used to evaluate if the pelvis were measured in the same way in the three positions in the hardseat.

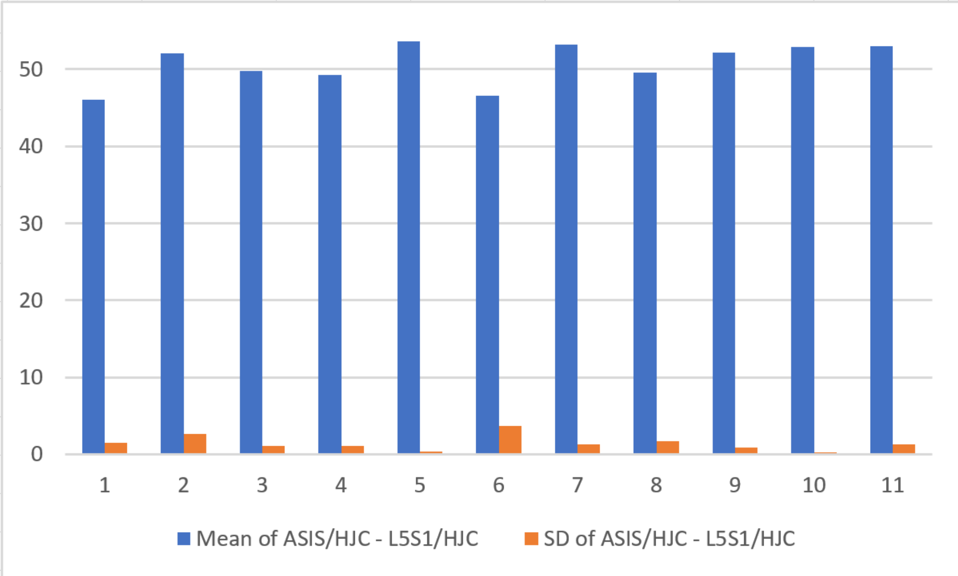

Figure 5.6: The mean and SD of ASIS/HJC - L5S1/HJC for all test persons (second session as 10 and 11), in all positions in the hardseat [mm]

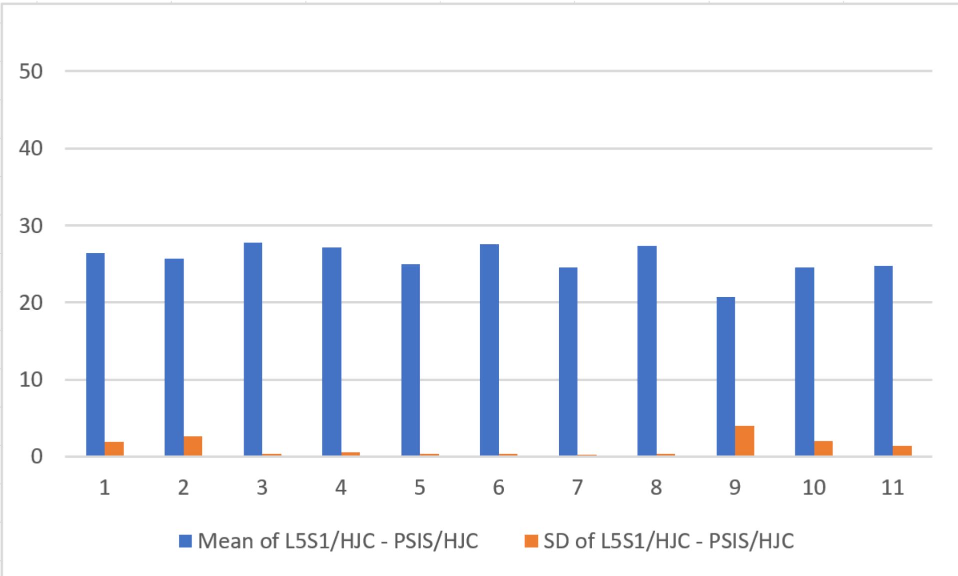

Figure 5.7: The mean and SD of L5S1/HJC - PSIS/HJC for all test persons (second session as 10 and 11), in all positions in the hardseat [mm]

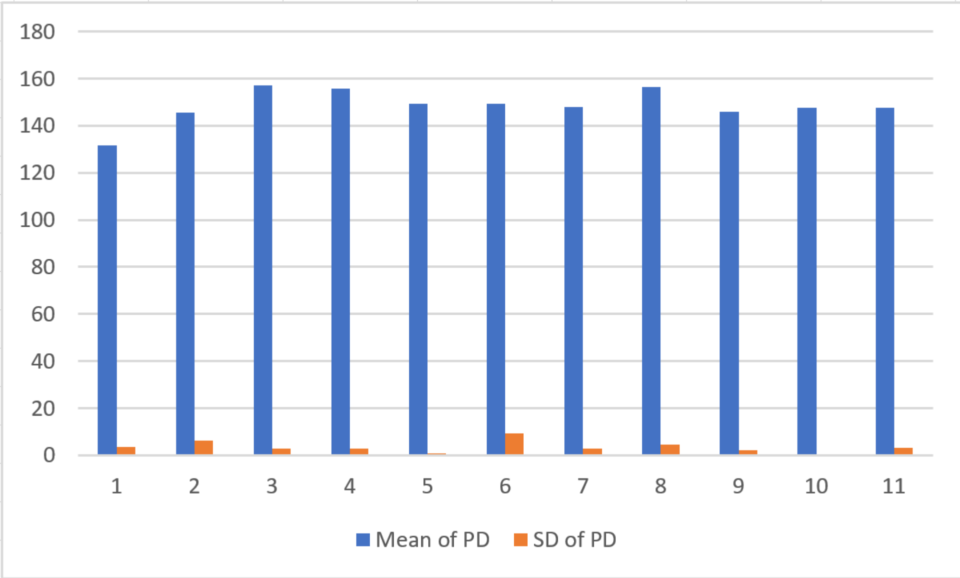

Figure 5.8: The mean and SD for PD for all test persons (second session as 10 and 11), in all positions in the hardseat [mm]

Table 5.5: The mean and SD of the relative angles for pelvis and PD for the test person in second session

		ASIS/HJC - L5S1/HJC	L5S1/HJC - PSIS/HJC	PD
TP 1th round	Mean	52,9°	24,5°	147,5 mm
	SD	0,2°	2,0°	0,5 mm
TP 2nd round	Mean	53,0°	24,8°	147,7 mm
	SD	1,3°	1,4°	3,2 mm

Xsens: adjustement in Xsens Analyze
The three versions obtained after reprocessing the data from Experiment 1 were compared. The original version (scenario: *Single Level* without reprocessing in HD) was chosen, the details can be found in Appendix G.

Xsens: calculation of the pelvic angle
The data from the two first test persons was saved on an inappropriate space on the computer and therefore most of this data became inaccessible afterwards. Consequently, only the results from the TP3 - TP9 can be presented.

Tilt Sensor
The plots in Figure 5.9 show the mean angle values obtained with the Tilt Sensor in the x-axis, the sagittal plane (left plot) and y-axis, the frontal plane (right plot) for each test person in the five different positions used in Experiment 1. The exact mean values collect for each position can be seen in Appendix G in Table G.2.

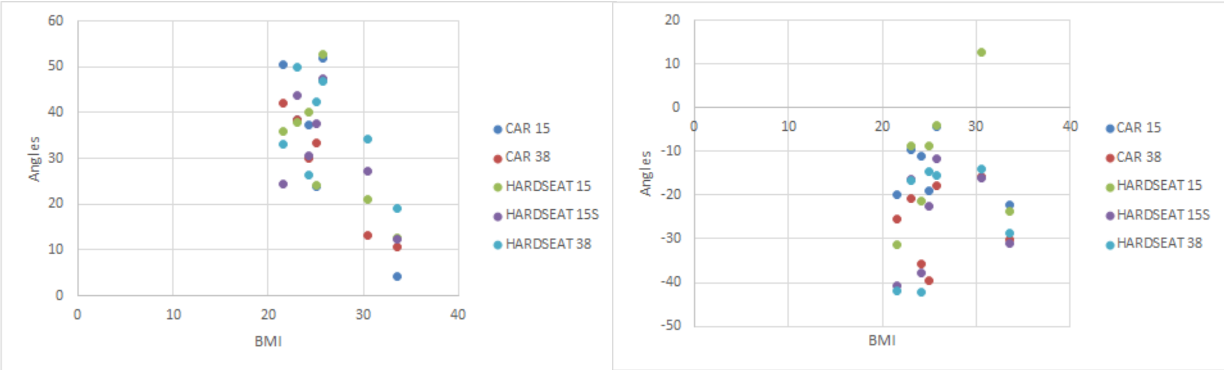

Figure 5.9: Tilt data in x-axis and y-axis for TP1 to TP9

Comparison between the systems

Plots of the pelvic angle values obtained with the verification method (in red, marked "R") and with the Xsens equipment (in blue, marked "X") for each TP in the hardseat are illustrated in Figure 5.10 - 5.13 (Experiment 1 - first session).

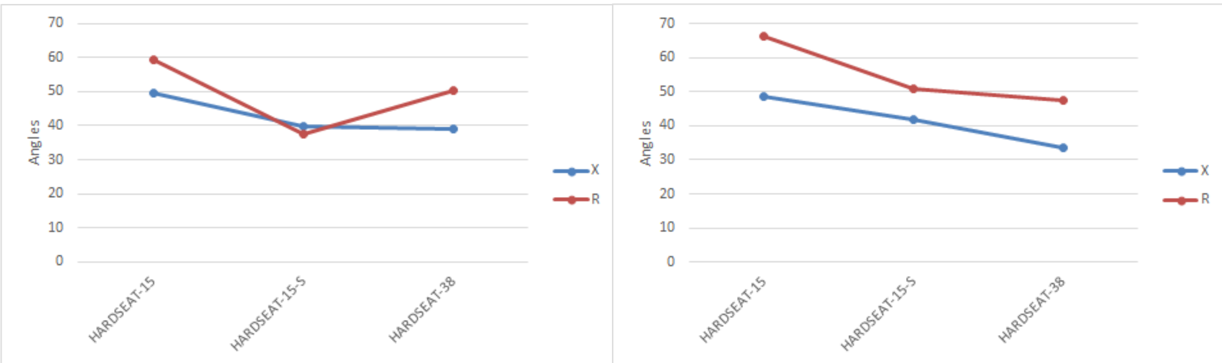

Figure 5.10: Pelvic angle values obtained for TP3 and TP4 with the verification method and the Xsens equipment

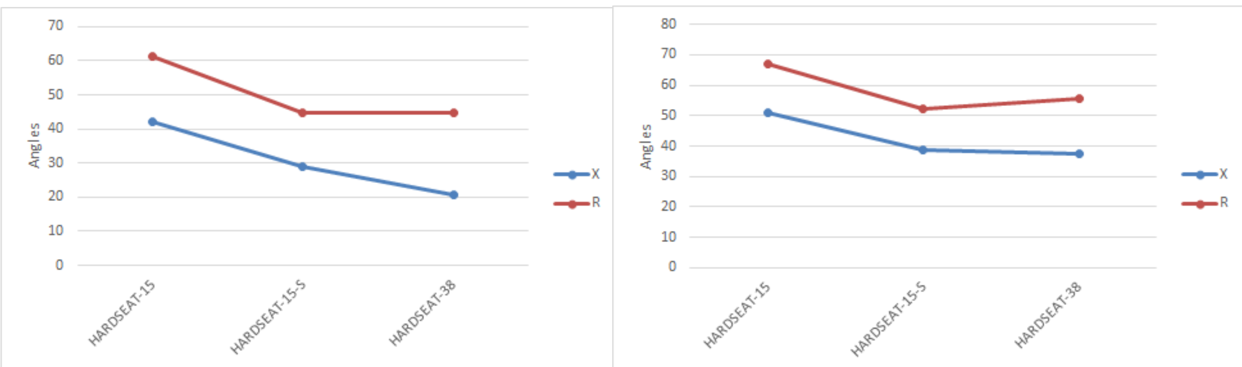

Figure 5.11: Pelvic angle values obtained for TP5 and TP6 with the verification method and the Xsens equipment

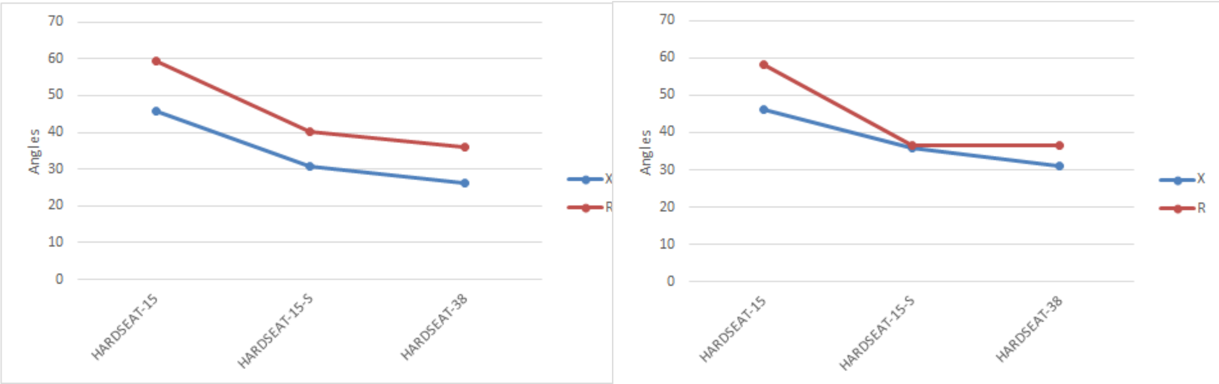

Figure 5.12: Pelvic angle values obtained for TP7 and TP8 with the verification method and the Xsens equipment

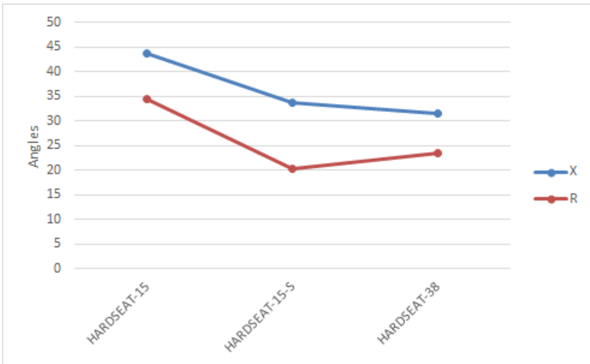

Figure 5.13: Pelvic angle values obtained for TP9 with the verification method and the Xsens equipment

Plots of the pelvic angle values obtained with the verification method (in red, marked "R") and with the Xsens equipment (in blue, marked "X") for the two rounds performed on the same TP can be seen in Figure 5.14 (Experiment 1 - second session).

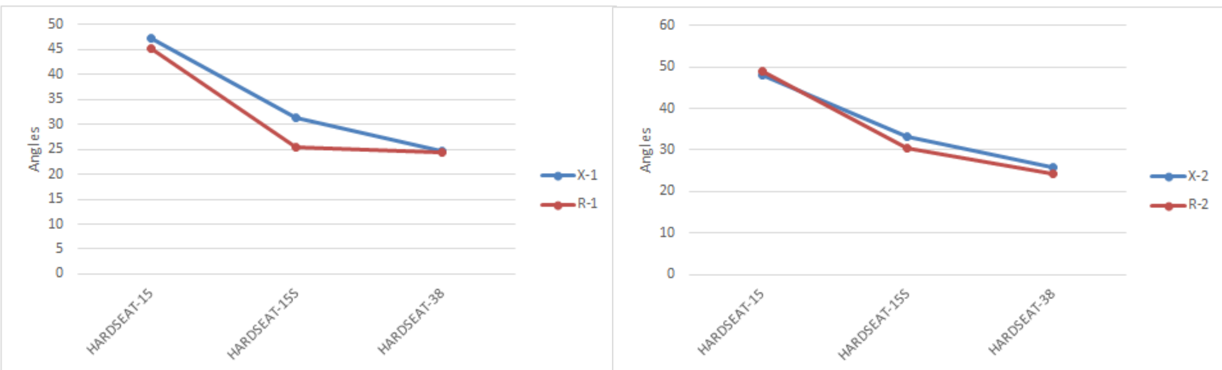

Figure 5.14: Pelvic angle values for the two rounds performed on the same TP with the verification method and the Xsens equipment

The exact mean pelvic values used to plot the figures above are available in Table G.3 and Table G.4 in Appendix G. The mean and SD values for the pelvic angle values for the group of test persons can be seen in Table G.5 and in Table G.6 in Appendix G.

The difference between the pelvic angle values obtained with the verification method and with the Xsens equipment for each position performed in the hardseat can be found in Table 5.6 and in Table 5.7.

Table 5.6: Difference between the pelvic angle values obtained with the verification method and with the Xsens equipment (Experiment 1 - first session)

Pelvic angle difference between the verification and Xsens					
TP	BMI	Hardseat 15N	Hardseat 15S	Hardseat 38N	Mean diff.
TP3	25	9,8°	-2,2°	11,2°	7,8°
TP4	25,8	17,9°	9,4°	14,2°	13,8°
TP5	30,5	19,2°	15,6°	24,2°	19,7°
TP6	33,6	15,8°	13,5°	18,2°	15,8°
TP7	24,2	13,6°	9,4°	9,5°	10,8°
TP8	23,1	12,0°	0,9°	5,4°	6,1°
TP9	21,6	-9,2°	-13,5°	-8,2°	-10,3°
Average diff.		13,9°	9,2°	13,0°	

Table 5.7: Difference between the pelvic angle values obtained with the verification method and with the Xsens equipment (Experiment 1 - second session)

Pelvic angle difference between the verification and Xsens					
TP	BMI	Hardseat 15N	Hardseat 15S	Hardseat 38N	Mean diff.
TP 1th round	20,3	-2,2°	-6,1°	-0,1°	-2,8°
TP 2nd round	20,3	1,1°	-2,9°	-1,6°	-1,9°
Average diff.		-1,7°	-4,5°	-0,9°	

Figure 5.15 shows the mean difference between the pelvic angle value for each test person plotted against the test person's BMI. For a higher BMI, the difference between the pelvic angle values obtained with the verification method and the Xsens equipment increases.

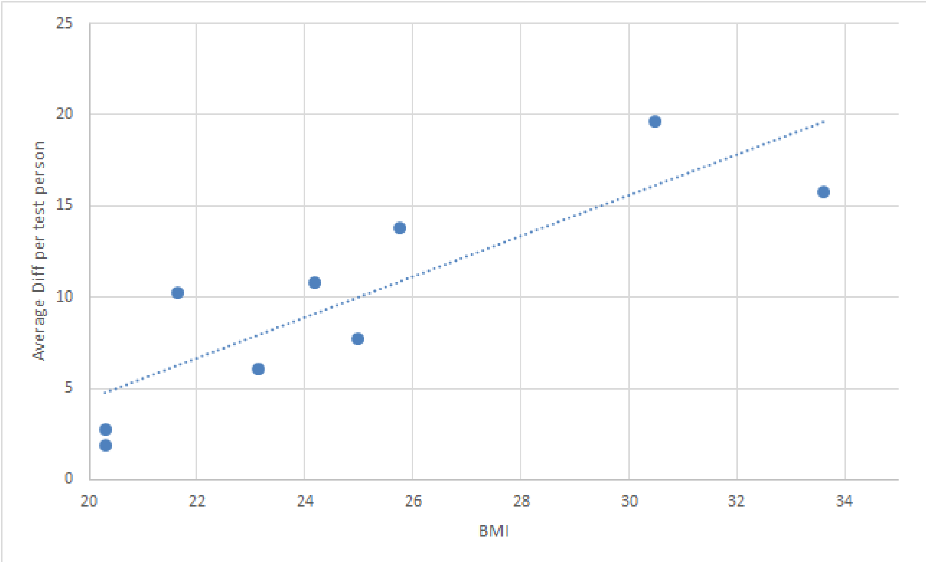

Figure 5.15: Mean difference in pelvic angle for each test person plotted against the test persons BMI (Experiment 1 - all sessions)

5.5.2. Experiment 2

The results from the questionnaire which aimed to evaluate the more subjective needs of the measuring method can be seen in Table E.4. The overall results were high meaning the test persons had a pleasant experience using the equipment and during the experiment in general. The text answers which was for comments about the experiments regarded the tight fitting test garments as well as the head sensor, which by some was experienced as a bit uncomfortable.

FARO: calculation of shoulder-knee and belt angle

The belt angle had a fairly small variation. The mean value was 60,3° with SD 4,6° and the maximum value was 72,6° and minimum value 49,9°. In the own choice of position the mean value and SD were 62,5° and 4,2° respectively.

When comparing the belt angles between a normal and a slouched position the difference had the mean value 4,9° and SD 2,6°. The angle thus decreased slightly when the person slouched, a schematic illustration can be seen in Figure 5.16.

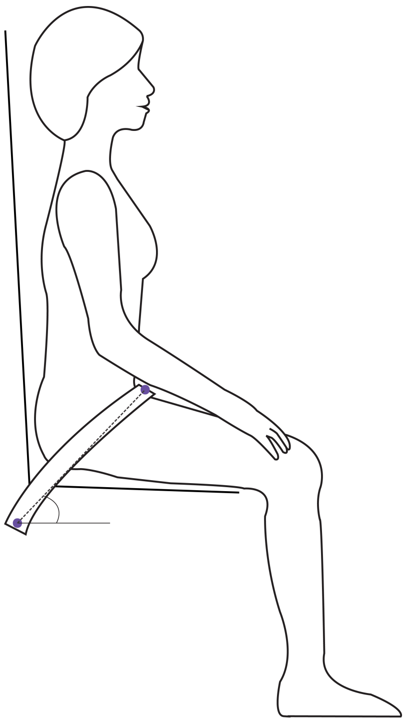

Figure 5.16: The belt angle in a upright and slouched position respectively

Xsens: calculation of the pelvic angle

The Xsens Analyze software gave the following interface while recording data from a subject, see Figure 5.17 and Figure 5.18:

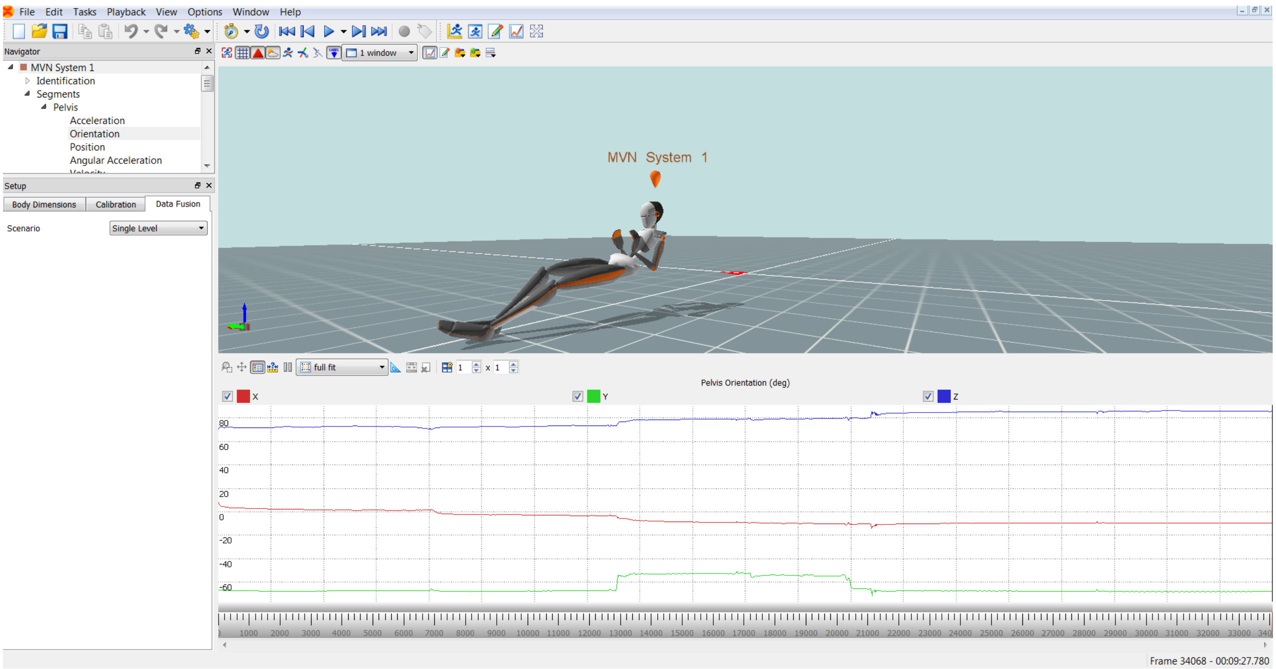

Figure 5.17: Xsens MVN Analyze software for TP11

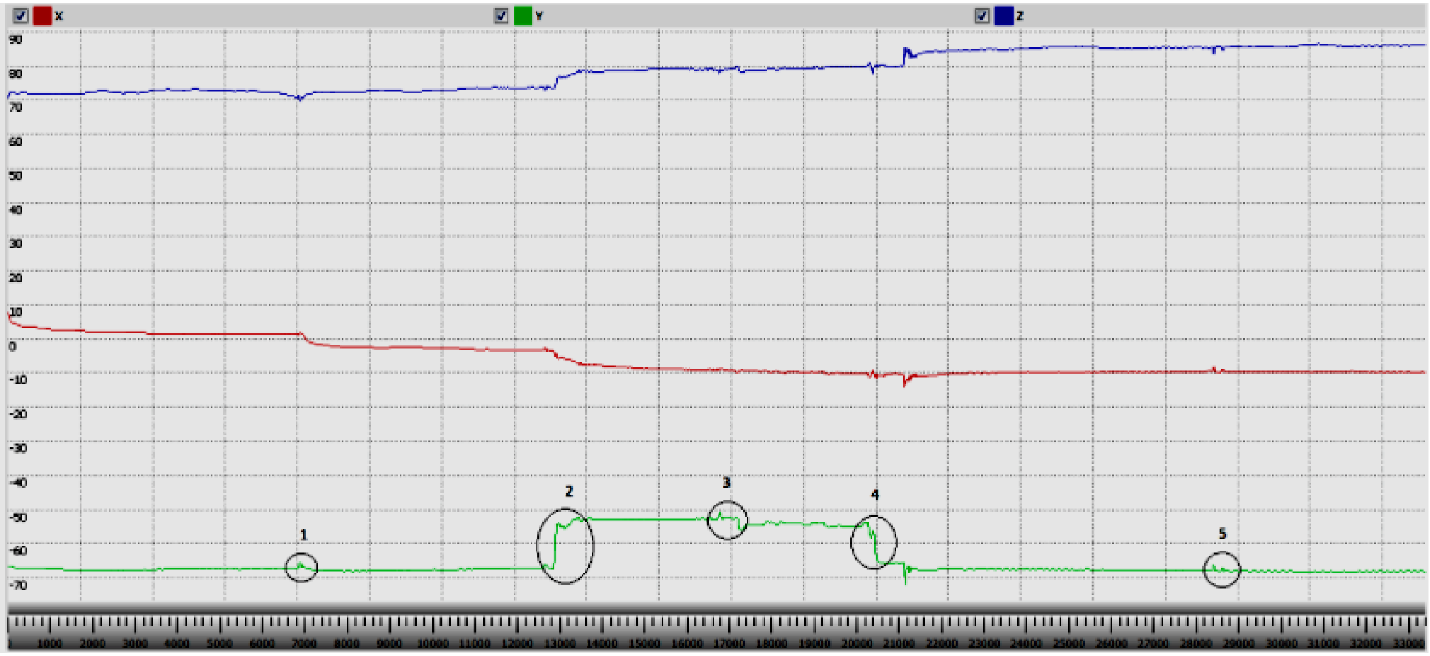

Figure 5.18: Representation of the orientation, as angles [°], of the pelvis in the x-, y- and z-plane on the Xsens Analyze software for TP11

The orientation of the pelvis in the x-, y- and z-plane when changing position according to Table 4.6:

1. Sitting in a Normal posture, repositioning feet from being flat against the floor to only having the heels in contact with the floor.
2. Change of position from Normal posture to Collapsed posture, feet repositioned to flat on the floor.
3. Sitting in a Collapsed posture, repositioning feet from being flat against the floor to only having the heels in contact with the floor.
4. Change of position from Collapsed posture to Slouched posture, feet repositioned to flat on the floor.
5. Sitting in a Slouched posture, reprositioning feet from being flat against the floor to only having the heels in contact with the floor.

Comparison between the systems

The results from the analysis regarding the comparison of the pelvic angle and shoulder-knee angle are presented in Table 5.8 and Table 5.9.
The mean difference between the angles varied widely between the test persons. The SD within most test persons was fairly large.

Table 5.8: The mean and SD for the difference between Xsens pelvic angle and shoulder-knee angle for all positions

Test person	Mean	SD
TP1	11,4°	2,7°
TP2	30,9°	6,7°
TP3	15,0°	11,2°
TP4	15,5°	7,5°
TP5	18,2°	8,1°
TP6	17,1°	5,3°
TP7	12,8°	4,8°
TP8	11,5°	6,1°
TP9	11,7°	8,9°
TP10	15,4°	5,1°
TP11	-8,8°	3,7°
TP12	14,8°	7,8°
TP13	5,3°	11,1°
TP14	13,8°	6,8°
TP15	20,7°	9,8°
TP16	14,6°	10,8°
TP17	10,0°	6,3°

Even when only the normal and slouched positions were studied, the mean difference between the angle varied widely. The SD within each test person was fairly large.

Table 5.9: The mean and SD for the difference between Xsens pelvic angle and shoulder-knee angle for normal and slouched position

Test person	Mean	SD
TP1	12,0°	2,2°
TP2	29,6°	8,7°
TP3	13,6°	14,3°
TP4	14,2°	8,8°
TP5	19,6°	10,7°
TP6	18,8°	4,7°
TP7	12,4°	5,8°
TP8	8,7°	5,0°
TP9	8,2°	10,5°
TP10	14,5°	6,5°
TP11	-6,8°	2,5°
TP12	11,8°	8,6°
TP13	1,6°	14,2°
TP14	13,5°	8,5°
TP15	19,2°	13,0°
TP16	11,6°	13,3°
TP17	8,3°	7,5°

In Figure 5.19 - 5.23 the plots for the pelvis, knee and shoulder movement is shown. An explaination for what happened between the "normal" position, N23 FC, and the adopted position can be seen above each figure.

When moving the feet forward the knee moved forward as well and the shoulder stayed in about the same place or was lowered slightly. The pelvis moved forward (note that this results in negative values due to the definition of the x-direction for Xsens) for most of the test persons, some values are far from the others, see Figure 5.19.

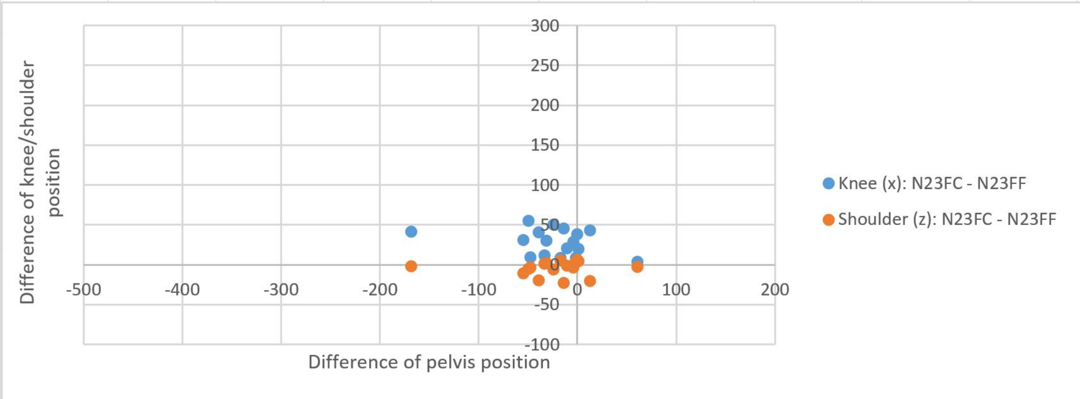

Figure 5.19: The movement of the knee and shoulder in comparison with the movement of the pelvis along the x-axis between N23 FC and N23 FF [mm]

When adapting a collapsed position with the feet to the ground the knee moved backwards and the shoulder was raised. The pelvis moved (note that this results in negative values due to the definition of the x-direction for Xsens) for some of the test persons and backwards for some, some values are far from the others, see Figure 5.20.

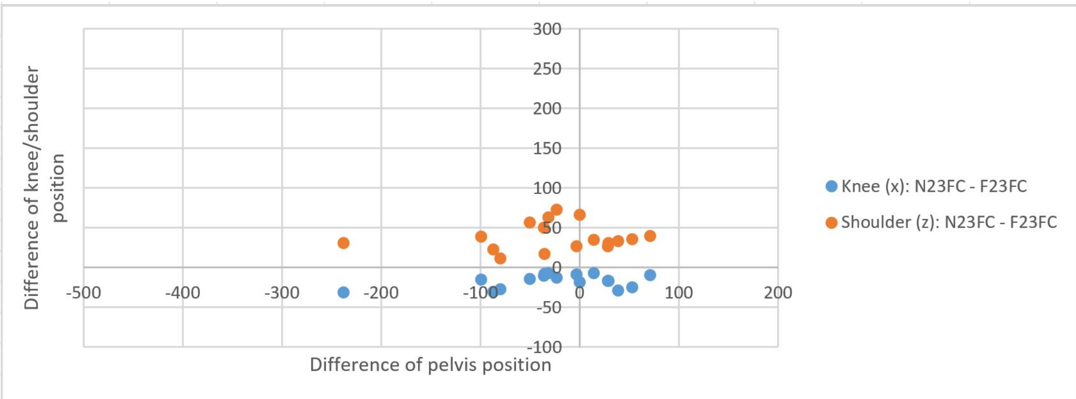

Figure 5.20: The movement of the knee and shoulder in comparison with the movement of the pelvis along the x-axis between N23 FC and F23 FC [mm]

When adapting a collapsed position with the feet moved forward the knee moved forward or stayed in about the same place and the shoulder was raised. The shoulder was not raised as much compare to the collapsed position with feet to the ground, see Figure 5.20. The pelvis moved forward (note that this results in negative values due to the definition of the x-direction for Xsens) for some of the test persons and backwards for some, some values are far from the others, see Figure 5.21.

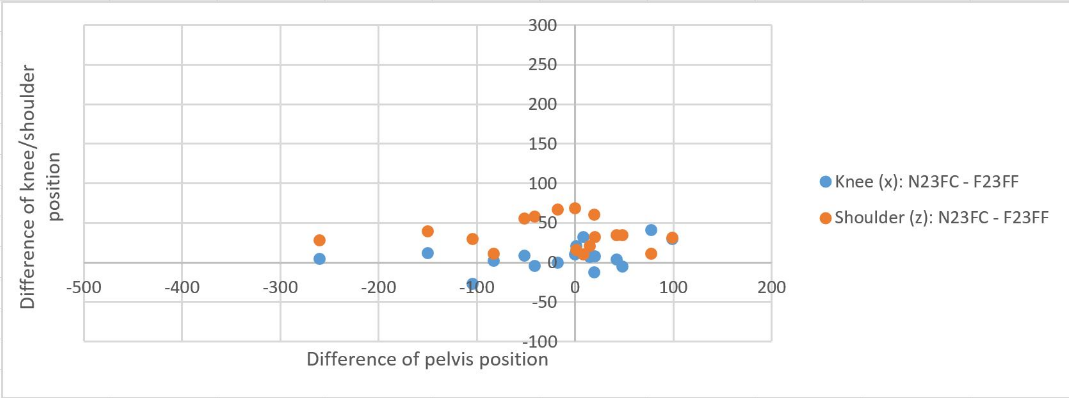

Figure 5.21: The movement of the knee and shoulder in comparison with the movement of the pelvis along the x-axis between N23 FC and F23 FF [mm]

When adapting a slouched position with the feet to the ground the knee moved forward and the shoulder was raised for some people and lowered for some. The pelvis moved forward (note that this results in negative values due to the definition of the x-direction for Xsens) for the majority of the test persons and backwards for some, some values are far from the others, see Figure 5.20.

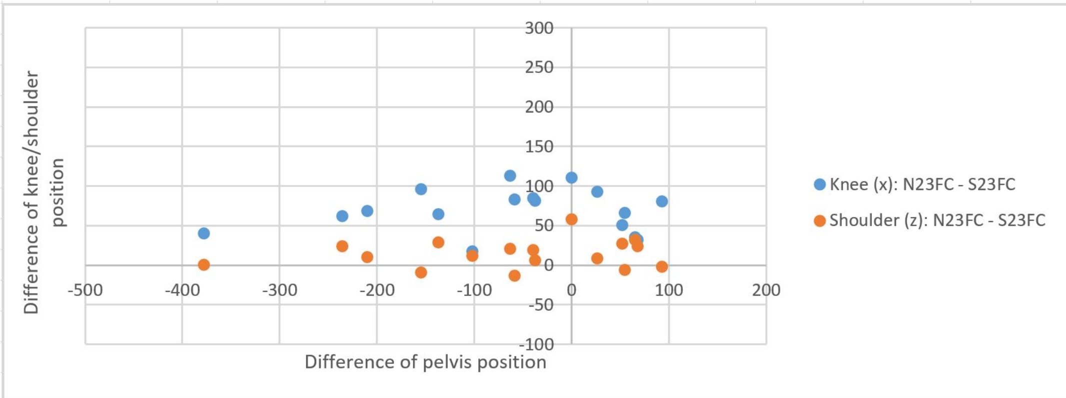

Figure 5.22: The movement of the knee and shoulder in comparison with the movement of the pelvis along the x-axis between N23 FC and S23 FC [mm]

When adapting a slouched position with the feet moved forward the knee moved forward and the shoulder was lowered for the majority of people. The pelvis moved forward (note that this results in negative values due to the definition of the x-direction for Xsens) for some of the test persons and backwards for some, some values are far from the others, see Figure 5.21.

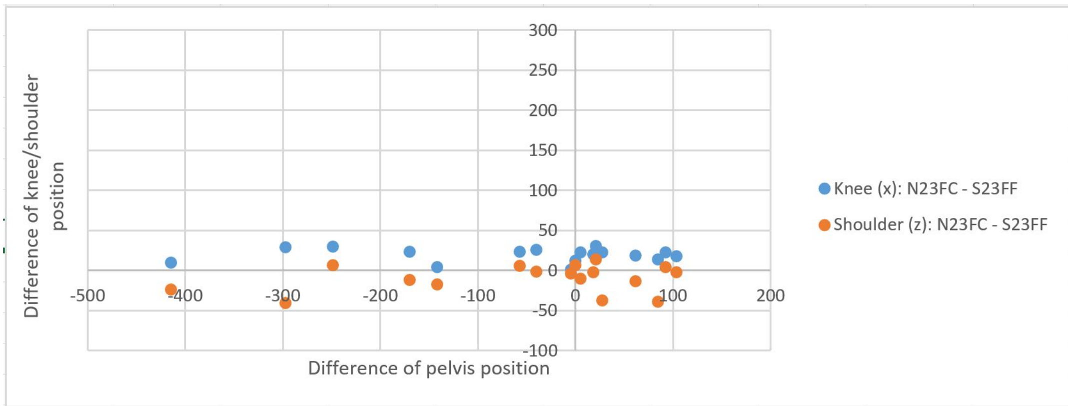

Figure 5.23: The movement of the knee and shoulder in comparison with the movement of the pelvis along the x-axis between N23 FC and S23 FF [mm]

The knee and shoulder moved as expected in most cases. The movement of the pelvis had a large variation and did not follow as expected in some cases. The movement of the knee and the shoulder appeared to be connected together when the shoulder was lowered, the knee moved forward and vice versa. The movement of the pelvis was in many cases considerably larger than the movement of the knee or shoulder. Uncertainty prevails if the pelvis position from Xsens was true to reality.

Position of choice

The seat settings for the position of choice can be seen in Table 5.10. The majority chose to further recline the backrest from 23°. The cushion angle was adjusted around 15°. The horizontal adjustment was compared to stature, see Figure 5.24. The thigh support was used by roughly half of the test persons.

Table 5.10: The seat settings in the position of choice

Seat settings	Backrest angle	Cushion angle	Horizontal position of the seat	Position of extendable thigh support
Original	23,0°	15,0°	168 mm	31 mm
TP1	23,5°	17,0°	2 mm	60 mm
TP2	26,6°	14,1°	165 mm	61 mm
TP3	29,4°	15,0°	106 mm	67 mm
TP4	26,1°	16,3°	62 mm	31 mm
TP5	30,3°	15,1°	89 mm	31 mm
TP6	22,7°	16,5°	111 mm	74 mm
TP7	25,6°	15,6°	124 mm	31 mm
TP8	34,0°	15,4°	90 mm	53 mm
TP9	23,5°	15,0°	54 mm	31 mm
TP10	20,3°	13,3°	120 mm	31 mm
TP11	23,7°	16,3°	135 mm	42 mm
TP12	25,0°	14,5°	99 mm	31 mm
TP13	26,1°	14,4°	118 mm	80 mm
TP14	26,5°	15,0°	112 mm	31 mm
TP15	20,0°	15,0°	71 mm	62 mm
TP16	28,7°	14,8°	149 mm	31 mm
TP17	21,6°	15,2°	91 mm	31 mm

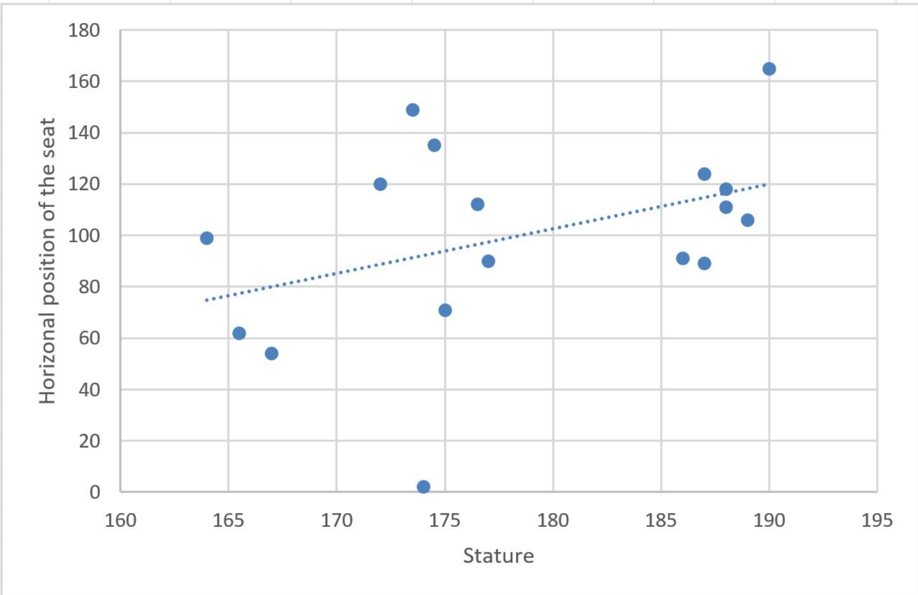

Figure 5.24: Position of the seat compare to stature [mm]

To get an perception of how people sat in comparison with a relatively controlled and "correct" position from a safety point of view, the pelvic angle for the position of choice was compared with the pelvic angle of the N23 FC, see Table 5.11. For most of test persons the pelvic angle decreased in the position of choice.

Table 5.11: A comparison of the pelvic angle for the position N23 FC and the position of choice

TP	Pelvic angle in N23 FC	Pelvic angle in position of choice	Difference
TP1	38,4°	29,5°	-8,9°
TP2	60,8°	54,7°	-6,1°
TP3	50,6°	45,2°	-5,4°
TP4	50,3°	36,9°	-13,4°
TP5	56,0°	38,1°	-17,9°
TP6	45,4°	43,2°	-2,1°
TP7	42,5°	37,3°	-5,2°
TP8	36,7°	30,9°	-5,8°
TP9	41,2°	42,0°	0,8°
TP10	44,5°	44,7°	0,1°
TP11	23,5°	24,0°	0,6°
TP12	49,9°	52,0°	2,0°
TP13	43,9°	41,9°	-1,9°
TP14	42,6°	43,5°	0,9°
TP15	56,5°	57,4°	0,9°
TP16	43,5°	35,9°	-7,6°
TP17	37,9°	35,0°	-2,9°

5.5.3. Experiment 3

The results from the questionnaire, which aimed to evaluate the more subjective needs of the measuring method, can be seen in Table E.5. The overall results regarding Xsens were a bit lower in the dynamic testing and the test persons expressed that the equipment affected them. The text answers regarded the sensor on sacrum which was experienced as a bit uncomfortable.

The mean, the maximum, the minimum and the difference between the maximum and the minimum pelvic angle around the y-axis, measured during the car drives, are presented in Table 5.12 for each test person.

Table 5.12: Mean, min and max pelvic angle values recorded during drives with TP1 - TP4

The values of the pelvic angle				
TP	Mean	Min	Max	Max - Min
TP1	32,3°	24,3°	47,2°	22,9°
TP2	46,0°	38,3°	54,7°	16,4°
TP3	47,3°	36,9°	61,2°	24,3°
TP4	50,2°	36,5°	62,3°	25,8°

One of the test person's data collected with the Xsens equipment during a drive was selected to be commented in detail. The following graphs only represent the pelvic rotation around the y-axis (which is the most interesting for this study), see Figure 5.25 - 5.28.

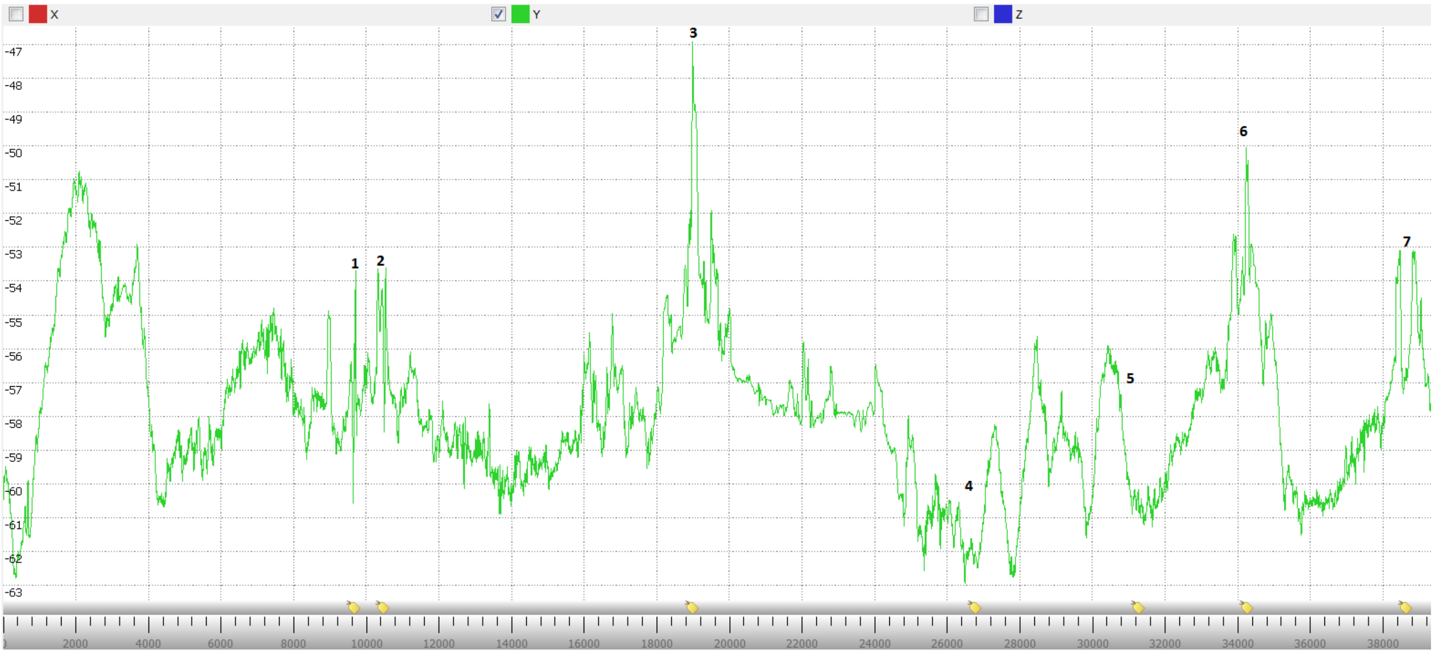

Figure 5.25: Rotation around the Y-axis for a test person during a drive (0 min to 11 min) [°]

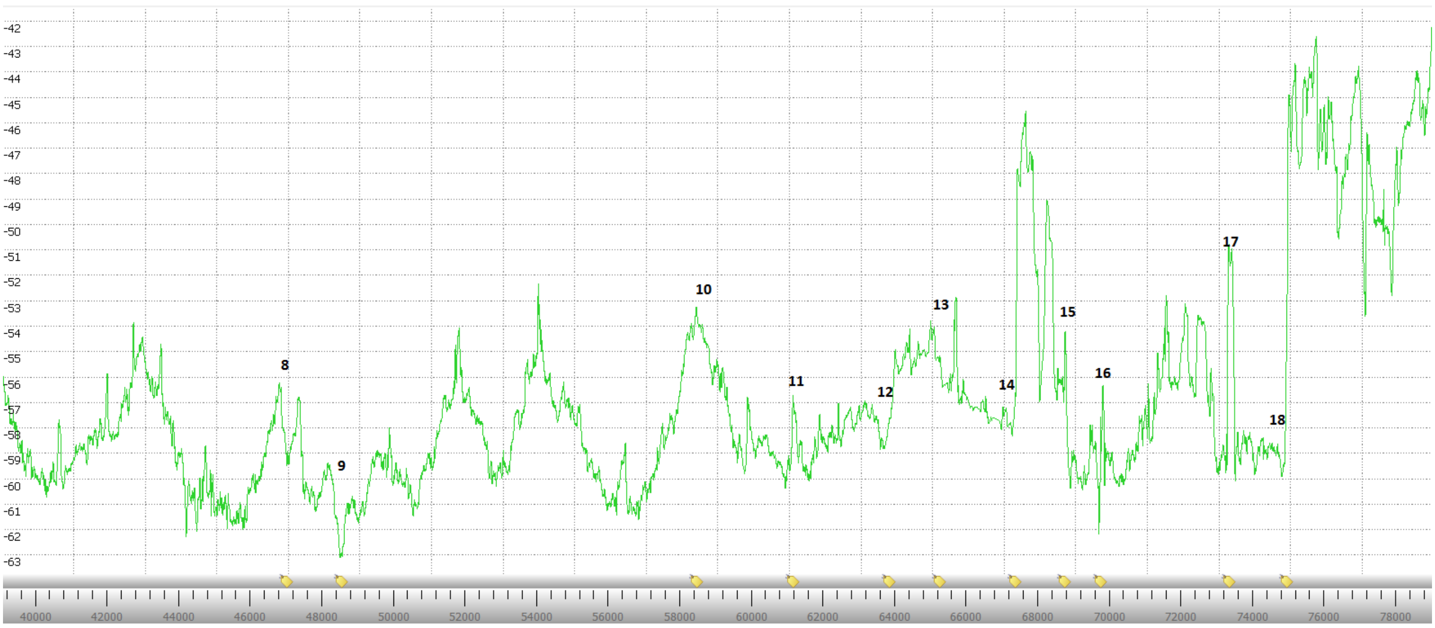

Figure 5.26: Rotation around the Y-axis for a test person during a drive (11 min to 22 min) [°]

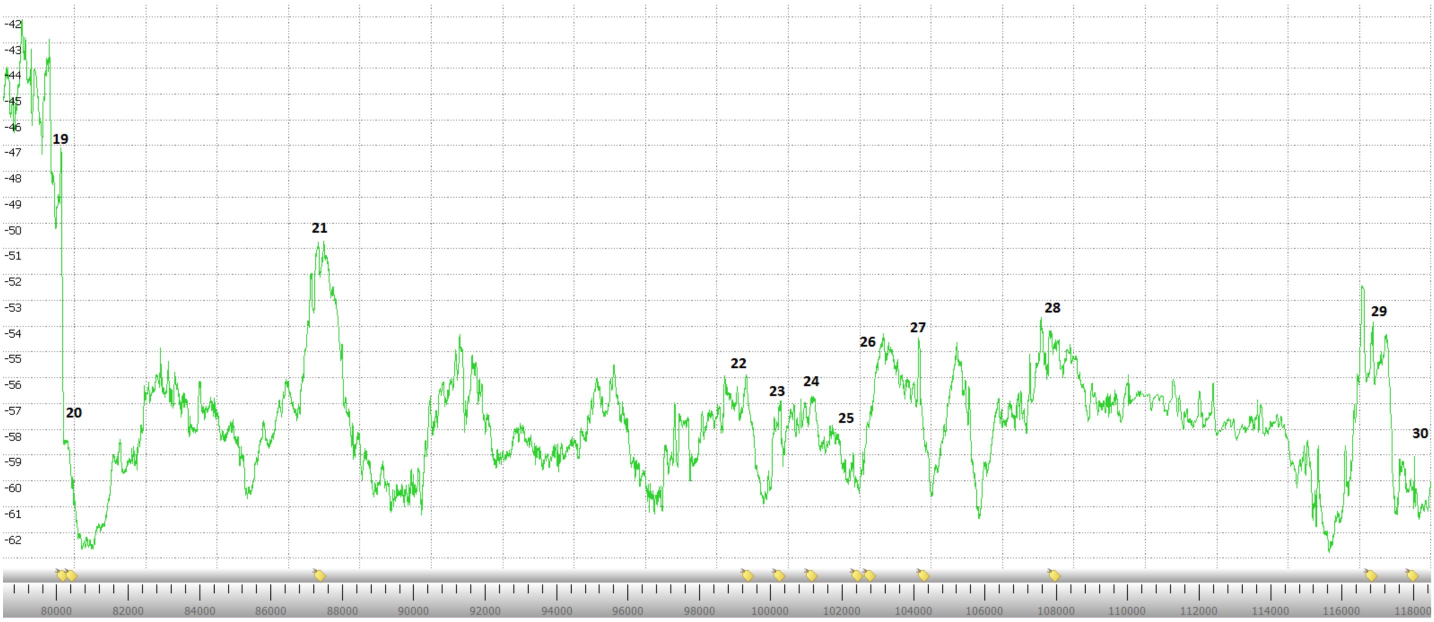

Figure 5.27: Rotation around the Y-axis for a test person during a drive (22 min to 33 min) [°]

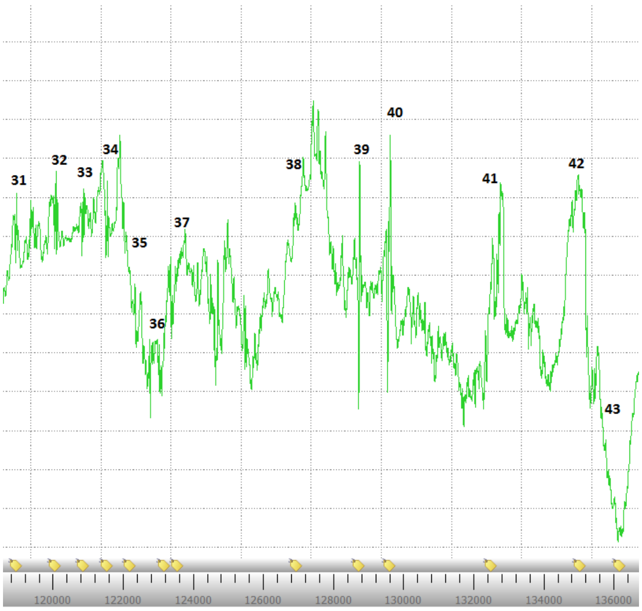

Figure 5.28: Rotation around the Y-axis for a test person during a drive (33 min to 38 min) [°]

Events marked in Figure 5.25 - 5.28 are explained below:

1. Speed bump
2. Speed bump
3. Lowers hand to lap and turns head both sides to look
4. Start: hilly area
5. Stop: hilly area
6. Looks around
7. Rotates head to left side and then right side
8. Start: uphill
9. End: uphill
10. Holds up right hand
11. Rotates head to the left
12. Start: rests right elbow against window to support head
13. End: rests right elbow against window to support head
14. Start: bend forward
15. End: bend forward
16. Speed bump
17. Looks down at feet
18. Start: changes GPS settings
19. End: changes GPS settings
20. Uphill
21. Downhill
22. Uphill
23. Looks back on left side
24. Start: uphill
25. End: uphill
26. Downhill
27. Uphill
28. Moving feet
29. Bending forward
30. Speed bump
31. Speed bump
32. Speed bump
33. Speed bump
34. Speed bump
35. Changes position of feet
36. Start: gives road directions
37. End: gives road directions
38. Changes position of feet
39. Start: uneven road
40. End: uneven road
41. Turns upper body left, moves whole body
42. Start: uphill
43. End: uphill

When traveling uphill and downhill a decrease and an increase of the pelvic angle value was expected, respectively. Note that the values in the plot are negative and originate from the vertical axis.

6 Discussion

This chapter contains the discussion about the results, the project and further recommendations.

6.1. Prestudy

The results showed promising correlations. Since the pelvic orientation is difficult to measure an ideal solution would be to measure more easily found body landmarks and get a relationship between them and pelvis. Although there are some possible sources of error:

- The tests were done without clear predetermined structure.
- The outfit of the test person affected the results especially when measuring the ASIS landmarks, see the results of angle α for Female 2 in Table B.1. A tightly fitted outfit is to prefer. See the difference in clothing in Figure B.1.
- The position of the feet might affect the position of the pelvis.
- The data on the left side (inner side) was poor since it was difficult to measure.
- If the test persons adjusted their sitting posture during the test it might affect the results.
- Also would the correlations disappear if the different reclined positions were measured with a randomized order? E.g. start with the + 20° position then change to the most reclined and then to + 5°.
- Would the correlations disappear if the test person had to step in and out from the car between each position or if the test person would sit for a longer period in every position?

The Prestudy gave knowledge about the limitations with ATDs and an understanding of the difficulties when measuring on test persons. If the test person would have been a bit overweight, it would have been even harder to find the anatomical landmarks than it was in this case. The data from the measurements on the volunteers indicated that there might be a relationship between pelvic orientation and the movements of other body parts. Hence, it might be useful to conduct a more structured and larger study to evaluate this possible correlation.

6.2. Concept development

The resulting user needs for the measuring method seem to have covered the most important areas. The approach for collecting raw data was by taking notes during e.g. workshops. Notes were considered more flexible and not as time consuming as audio recordings. However, notes are not as precise and opinions and thoughts can have been missed or misinterpreted. Although, one thing that speaks against this was that nothing was brought up during the process when the relative importance of the need was determined. The ranking of the needs included many of the persons who came with opinions, consequently possible gaps would have been filled. In the ranking the project team chose to include few persons with expertise and inside knowledge rather than many persons with a lack of deep knowledge. It was considered that having many persons unfamiliar with the project could give misguiding results. Converting the user needs to metrics helped the project team to define the aim and objective for the measuring method further.

All generated concepts except Medical imaging were demonstrated or tested which was valuable for understanding how the concepts worked while using them. Based on these experiences, the generated concepts underwent the concept selection in two steps. The screening clearly sorted out two of the concepts, which were Scanning and Medical imaging. Both these had many advantages but also many disadvantages, especially Medical imaging which would be very effective for determine pelvic orientation but it is too advanced equipment and it would not be appropriate to expose test persons to radiation.
During the scoring Xsens got the highest score and Qualysis got the second best. The reason why Qualysis not proceeded to the Concept testing was because even though the concept had many advantages it also had many disadvantages which can be seen primarily in the screening process. In the project's range of time it was considered that it would not be possible to perform tests with Qualysis in an appropriate way. The Tilt Sensor and Shoulder-knee concept were included since the Tilt Sensor could easily be borrowed at Volvo Cars and the necessary measurements for Shoulder-knee were already included in the testing. The rankings in the concept selection were considered fair but the project team's opinions were probably somewhat affected from the demos.

6.3. Concept testing

During the concept testing many valuable experiences were made.

6.3.1. Experiment 1 and Experiment 2

After the testing various sources of measurement error could be established:

- Xsens was put on in the same way during every experiment. However, due to different body dimensions, it is not likely that the sensors ended up in the exact corresponding positions. It could affect the results but it is hard to estimate how much. An attempt to minimize this source of error was made by letting the same test leader put on the equipment every time.
- Since the pelvic angle are dependent on the calibration of Xsens, errors can have occurred in this step, a more detailed discussing will be held below.
- The patrick markers were put on in different ways on the test persons. An attempt to minimize this source of error was made by letting the same person put on the markers every time. It was challenging to estimate the position of the body landmarks especially on the spine. On the other hand, these landmarks do not directly affect the calculation of the pelvic angle.

- The Tilt Sensor in Experiment 1 was difficult to place in the same way on every test person. Especially if the test person had some abdominal fat, the sensor could not be placed appropriately and ended up nearly horizontal.

- According to the project team, a major source of error is the fact that both the sensors and the markers could have been moving around during the testing. Controls were made during the tests to minimize this issue.

- Different measurement technicians performed the FARO Arm measurements and might have digitized the landmarks in different ways. It could have affected the results but probably no more than a couple of millimeters in every direction.

- During Experiment 1 some body landmarks were pressed during the digitization, this might have been done differently for some test persons.

As mentioned above, the calibration was of high importance to get representative values. A discovery made after Experiment 1 and Experiment 2 was that when the calibration was applied, the test person was supposed to stand in the neutral starting position. Instead the test persons stood leaning forward to look at their manikin. After correspondence with Xsens we were informed that this should not affect the results too much.

In order to correct all the aspects discovered which could affect the results and to study the repeatability of the measuring method, the project team chose to redo Experiment 1. Since one of the team members acted as a test person it was easier to palpate more accurately and the markers and sensors were controlled to an even greater extent. It might have been more difficult to get as exact results with a test person that is not familiar with the experiments. The calibration was considered successful since the manikin followed the test person well.

Typical errors or deviations for Xsens observed during the testing could be:

- When placing the palms against each other the manikin's hands would cross.

- When touching the head the hands would be a bit off, often above the head.

- The feet could be slightly turned from the actual position of the feet.

- When seated the feet of the manikin often would have the greater distance between them compared to the actual position.

It would not be recommended to use Xsens to study the hand and foot interactions in cars in detail for this reason.

It also seemed like the equipment worked more accurately on tall thin persons especially during the calibration process. For the shortest test person the calibration was not successful, despite several attempts on two separate occasions. This might be because the sensors ended up too close to each other on shorter test persons. During the correspondence with Xsens the team was informed that when calibrating the equipment on slightly overweight persons or persons with prominent hips, the test person should stand in so called T-pose instead (legs together and arms reached to the sides). This is because the arms and hands should be in a straight line and this might have been why the arms and hands could appear in unnatural positions.

6.3.2. Experiment 3

Experiment 3 was the first test evaluating how the Xsens equipment would work in the desired setting, which is during a car drive. To evaluate the performance the experiences were compared with the user needs established in the beginning of the project. The measuring method, Xsens, could be used during a car drive, both in the front and rear passenger seat. It did affect the natural behavior and limit the test person but not to a great extent. E.g. the sensor on the head was perceived as a bit disturbing and the hands could get stuck due to the velcro. The equipment was easy to learn and registers small deviations, the data collection was flexible. It could be used on different human body types although it appear to agree better with certain body types. It gave data of the whole body and various types of data. However, it did not register data of specific points e.g. ASIS or HJC but gives information about a whole segment instead.

6.4. Verification of concept

As previously mentioned, related to the sources of error above, this method of verification was advanced and difficult to perform to perfection. Since the project team was not trained to e.g. palpate landmarks this complicated the process, although the session with the physiotherapist was valuable and facilitated the work.

One deviation made from the original method was that the hardseat was adjustable in two positions. Although, the backrest angles were supposed to be 23° and 43° from vertical to originate from the hardseat used by Park et al. (2015). 23° is supposed to produce postures similar to those in a car seat. When the hardseat arrived the backrest angles were 15° and 38° consequently Experiment 1 had to be adjusted based on these conditions. The results should not have been affected by these changes except the absolute values.

When reviewing the results from the verification it seems that the test persons sat relatively alike, the segments not related to pelvis had a standard deviation around 4-5°. The SD for the pelvis related measurements were larger, around 10-11°, and for PD the SD was around 8-9 mm. According to Park et al. (2016) the root mean square error for pelvic angles in that study wass around 13° between test persons. These values are not directly comparable but are both a measure of the distribution of the deviations and give an idea of the variation between individuals. In discussion with Reed (2018) he explained that the pelvic orientation varies more than other segments across different individuals which means that our results are reasonable. It is therefore more relevant to compare the pelvic orientation within each individual.

The slouched position was the most challenging to control which could be seen in the second session where the test person was positioned very similar in position 15N and 38N but 15S varied slightly more.

As previously mentioned in the method chapter, the last step including the positions in the car was excluded due to limited time. It was also considered sufficient with the data from the hardseat to perform the verification. The data from the hardseat was easier to control as it was easier to access the body landmarks and to obtain the pelvic orientation in the car seat a number of assumptions had to be made from the data from the hardseat. Hence, the pelvic orientation in the car might have had larger deviations and would have been less appropriate to use as verification.

6.5. Analysis

6.5.1. Experiment 1

Verification: calculation of pelvic angle and posture
When comparing the visual representation of the test persons' postures with Figure 5.5, it appeared that the lumbar spine, the segment between T12/L1 and L5/S1, was longer than expected for all the test persons. This was probably due to the difficulty to palpate the landmarks on the spine. This should not, however, have affected the calculations of the pelvic orientation. The second session gave a more reasonable lumbar length and the visual representation from the second session showed that the joint locations more or less overlap for the same positions, but as previously mentioned the slouched position was more difficult to recreate.

The relative angles for pelvis and PD generally had a low standard deviation, around 1-2° and 2-4 millimeters, which should mean that the markers have stayed in place and the measurements have been done alike. To summarize, the measurements done for the verification method appears to be accurate and correctly represent the pelvic orientation for the test persons. The second session shows that with careful implementation, the measurements can be repeated to get the same results.

Xsens: adjustements in Xsens MVN Analyze
A complete comparison of the three data versions obtained after reprocessing the data in Xsens MVN Analyze can be found in Appendix G. The most important conclusion that could drawn is that the *Single Level* is the most relevant scenario for this type of study. The *No Level* should be used when there are no primer interest in the floor interaction and change of position in space.
In this study, the floor interaction was not in focus, however the change of orientation in space was a central setting. Moreover, fixing the floor to a single level made it easier to focus on orientations of body parts in relationship to the floor.

Reprocessing the data in HD made the values smoother and more uniform. This was an advantage when it was noticeable that a value had drifted. Nevertheless, when applying the HD filter on all recordings it was hard to determine exactly how the filtering had been done. It seemed that the original more accurate values had been corrected to match a mean. Therefore, no further reprocessing in HD was done for the following experiments and the scenario was set to *Single Level.*

Tilt Sensor
The results obtained with the Tilt Sensor seemed quite random and it was difficult to draw relevant parallels between the data from each test person. The Tilt Sensor had the value zero in the x- and y-axis when the sensor was laying flat on a horizontal surface (as shown in Figure 4.14). When "standing on one of the short sides" the x-axis would increase to ±90° and when rotating the Tilt Sensor around the long side the y-axis would increase to ±90°. It was clear that for most test persons, the angle values in the x-axis were higher than in the y-axis (see Figure 5.9), this was expected. For a person with a lower BMI, one can see that the x-axis value tended to be higher and for a person with a higher BMI the x-axis value tended to be lower (see Figure 5.9). The abdominal fat of the test persons decided how the Tilt Sensor ended

up during the experiment (see Figure 5.2). The y-axis shows that most test persons were not sitting completely straight and/or that the sensor was twisted to one side.

It was not possible to determine if a special position during Experiment 1 affected the orientation of the Tilt Sensor. The Tilt Sensor was attached with double-sided tape on a body area where many test persons have a lot of abdominal fat. It moved around a lot because it got stuck between the abdominal fat and the lap when the test person sat down during experiments and the output data was therefore considered to be unreliable.

The conclusion drawn was that the placement of a sensor directly on the ASIS would be difficult. In a heterogeneous population all persons have varying body dimensions, placing a sensor in a place where fat tends to accumulate is not recommended. This increased the understanding of the way in which the Xsens sensors, calculating the pelvic orientation, were placed (flat on the sacrum and on the lateral side of the upper leg above the knee).

Comparison between the systems
The mean pelvic angle values for the three different positions adapted during the first session of Experiment 1 were higher with the verification method than with the Xsens equipment (see Figure 5.10 - 5.14). Moreover, the SDs were also higher with the verification method than they were with the Xsens equipment (see Table G.5). A low standard deviation means that most values are close to the average whereas a higher standard deviation means that the values are more spread out. The difference in standard deviation could depend on a variety of factors.

To start with, some of the sources of errors already mentioned in Chapter 6.3.1 have most likely had an impact. Firstly, the patrick markers that were put on specific body landmarks were difficult to put on the exact same spots on each test person. One could imagine, that this estimation of the body landmark location could contribute to values with higher standard deviations for the verification method (which depended on the digitization of these points). Secondly, different measurement technicians were used for the digitization of the landmarks which could affect the results as different people work with varying accuracy. Thirdly, the body landmarks that had to be pressed (in order to eliminate a flesh margin on the test person) were hard to press in the same way for each person. Some test persons with higher BMI had more abdominal fat, it then became harder to decide how firmly to push. However, after a meeting with Reed (2018) (developer of the verification method), it became clear that a standard deviation between 10-15° was to be expected between the test persons because all look different.

When comparing the pelvic angles obtained from the verification method and the Xsens equipment, the values from the Xsens equipment seemed a bit low. This was due to the fact that during the first session of Experiment 1, calibration was not done in the most optimal way. After talking with a biomechanical expert working at Xsens, it became clear that the quality of the calibration could have been increased if the test persons stood still in the N-pose until the processing of the calibration was done and applied to the equipment. Most of our test persons were bent forward looking at the computer screen in order to spot their manikin instead of standing in N-pose. Their shoulders were then moved forward which resulted in the pelvis rotating backwards when standing, as mentioned in Chapter 2.1.3. This may have affected the unique zero value around the y-axis (sagittal plane) which was of interest in this analysis. The zero would then have been set to much backwards resulting in pelvic angles that are lower than they should be. It was interesting to note that it was only for TP9 that the Xsens values are higher than the verification values (see Figure 5.14). This test person was the only one wearing heels and one plausible explanation is that in order to keep balance on heels, the pelvis was rotated more forward which results in a more forward starting point than for the other test persons.

Another source of error for the Xsens equipment, already mentioned in Chapter 6.3.1, was that it was difficult the put on the sensors in the exact same way for each test person. The equipment fitted certain body types better, Xsens seemed to work optimally on tall and thin persons. For test persons with higher BMI, the difference between the results obtained with the verification method and the Xsens equipment differ more (see Figure 5.15). This was also noted during experiments as the Xsens sensors moved around more on, for instance, shorter women with wider hips.

In the second session of Experiment 1, the results corresponded much better, the experiment was repeated twice for the same person (see Figure 5.14) which made the results credible. Some of the sources of errors from the first session had then been eliminated. The patrick markers on the body landmarks were positioned very carefully and probably more accurately as both the test leader and the test person had knowledge about the anatomy and could work together to find the body landmarks. The positions of the landmarks were also verified more frequently, each time the test person felt that a patrick marker had moved and between each change of position. Flesh margins could also be pressed in a more accurate way as the test person helped deciding if the landmark had been pressed equally firm for each position. Moreover, the same measurement technician digitized all the landmarks which also reduced errors.

The calibration of Xsens was also done in the way that had been recommended by Xsens and as a consequence one can see that the pelvic angle values had increased (see Table G.6). The difference between the values obtained with the verification method and with the Xsens equipment had diminished (see Table 5.7). The values from the Xsens equipment were now higher than the values from the verification method in five out of six cases.

To conclude, the results from the Xsens equipment and from the verification method were comparable and corresponded well. However, the Xsens equipment could have become even more accurate if one could insure that the sensors stayed in the same place, perhaps using a jumpsuit with pockets for the sensors or tight shorts for the sensor placed on sacrum. It is also important to keep in mind that the test person used for the second session had a lower BMI than the test persons from the first session which could contribute to the good repeatability.

6.5.2. Experiment 2

FARO: calculation of shoulder-knee and belt angle
It was expected that the belt angle would have a larger spread between the different test persons and positions. Although the max and min value were fairly far apart, the SD was quite low. Since all test persons were placed the furthest back in the horizontal position of the seat it could have affected the results. Therefore the mean and SD for the position of choice were calculated as well, the SD was similar and the mean was slightly higher. As expected the belt angle changed when the test person slouched and it was logical that it decreased since the hips and accordingly the lap-belt moved forward.
A choice was made when planning the experiment to exclude the belt angle in the collapsed position. This due to the difficulty in measuring the position and the project team considered that the angle would not change significantly from the normal position.

Xsens: calculation of the pelvic angle
When reviewing the results from the Xsens recordings it was clear that the equipment caught small and big movements. To illustrate a figure of the plot showing orientation of the pelvis was included and it clearly shows that something happens when the test person, for example, moves the feet which should be seen according to the theory.

Comparison between the systems
The pelvic angle was compared with the shoulder-knee angle. Unfortunately, the results showed that no clear correlation could be found, at least not when the comparison has been made in this way. Both the mean and SD in the comparison varied without a clear pattern between the test persons. If some relationship were present the SD would be quite low within the test person even though it might differ between them. The pelvic angle was compared to the shoulder-knee angle for only the normal and slouched positions as well to see if there was a relationship for a closer span of positions. These results showed no closer relationship than for the analysis for all positions together.

The reason why only the change in x-direction of the knee was analyzed originated from when examining the postures of the test persons from Experiment 1. The biggest change when moving from e.g. a normal to a slouched posture was the knee position in the x-direction. The knee position varied slightly in the z-direction as well but the value could both decrease and increase. The position of the shoulder decreased in the z-direction and with a fixed backrest angle not as much in the x-direction. The position data of the pelvis was difficult to interpret as it did not change as expected between the positions. The accuracy of the position data has not been evaluated or verified in the same way as the orientation data. Thus, it was uncertain how accurate the data was.
A more thorough study would need to be performed to eliminate sources of error or other complications.

Position of choice
One of the reasons why this project was executed is due to the hypothesis that people will choose a more relaxed and reclined position as a passenger and the results showed that most test persons chose to reclined their seat further from 23°, an angle chosen from Park et al. (2015). Most of the test persons had a lower pelvic angle in the position of choice compared to a "normal" upright position. The horizontal position of the seat had some relation to the stature as expected based on this test group.

6.5.3. Experiment 3

In the results where the mean pelvic angle values are shown (see Table 5.12), the lowest and highest pelvic angle values are presented for each test person, one can notice that TP2, TP3 and TP4 have similar values and that the values for TP1 differ a bit more. The highest and the lowest pelvic angle values differ approximately ±10°-15° from the mean pelvic angle for each test person.

As results from Experiment 1 and discussions with Matthew P. Reed have shown, one can expect quite big variations in mean pelvic angle values for different test persons. In Experiment 1, the mean pelvic angle using the verification method with the backrest angle set to 15°, were found to be between 34,4° to 66,8° when sitting in an upright position and between 20,2° to 52,4° when slouching. When the seat back angle was set at 38°, the mean pelvic angle were between 23,4° to 55,8° (see Table G.3 in Appendix G). In Experiment 3, the mean pelvic angle obtained were between 32,3° to 50,2° (see Table 5.12). These values lie within the range of values obtained using the verification method which seemed reasonable as the car seat was set at 23° in Experiment 3 and the test persons adopted less extreme postures. Note that as the values obtained with the Xsens equipment in Experiment 1 were low due to the calibration, the results from Experiment 3 were compared to the results obtained from the verification method instead.

The mean pelvic angle value was affected by how often the test person changes position and how relaxed he/she was during the drive. As stated in Chapter 2.1.3, the activity level of the passenger will affect how much they move during a drive. If test persons were communicating, for instance giving directions to the driver, they would change positions more often. The mean pelvic angle was also affected by the comfort experienced by the passenger. A test person that experiences discomfort would change positions more frequently according to Chapter 2.1.3. In Experiment 3, the seat angles were preset which could become a source of discomfort.

Some correlations were found after analyzing the graphs in Figure 5.25 - 5.28 which show the changes in pelvic angle values during a drive with TP1. The test persons own actions affect the pelvic angle value the most as can be seen in Figure 5.25, when the TP1 in 3 "lowers hand to lap and turns head both sides to look" and in 6 "looks around". Also in Figure 5.26 - 5.28 when TP1 "bends forward" in 14-15, "changes GPS settings" in 18-19 and "bends forward" in 29 have big impacts on the pelvic angle.

Less important pelvic angle changes are caused by external factors such as road obstacles. Hilly areas have noticeable effects on the the pelvic angle, see Figure 5.27 when going downhill. Speed bumps only have a very limited impact on the pelvic angle value, see 1, 2, 16 and 30-34 in Figure 5.25 - 5.28. It was expected that the actions of the test person would have a greater impact than external factors on the pelvic angle value.

Note that if a major change in the graph occurs and this change has not been commented, it means that no reason was noted by the test leader during the experiment. The change may have been caused by:

- a sudden change of driving speed
- a change of posture that was not visible on the recording, for instance a muscle contraction
- an uneven road caused by road work or that the road just leans a bit
- a sharp turn mostly cause by roundabouts
- system disturbances
- sensors being pressed on (for instance sensors positioned on the test person's back)

One of the major disadvantages with the Xsens equipment was that it took considerable time to load an Xsens file to review a recording. This became more evident after performing longer recordings. It took approximately an hour to load a recording of 40 minutes. This processing time is long when considering any future studies that might like to involve more test persons.

6.6. Results

The main results for the master thesis *Investigation of methods for quantifying sitting postures in cars* could be drawn from the theory section and the three experiments carried out.

As seen in the literature review and for all experiments performed, there is an infinite number of different body types. Moreover, all passengers strive to obtain some comfort during a car drive but comfort is a subjective concept and no sitting posture is ergonomically satisfactory over a long period of time. When passengers got to chose how they wanted to sit, most reclined the seat. This shows that being able to quantify sitting postures to increase passenger's safety is needed.

There are several technologies available today to quantify movements of the human body but most of them are applicable in a static environment. In general, these technologies require a lot of equipment which is hard to fit into a car.

Experiments showed that precision is even more important when working with real test persons. It can make a difference having a well informed test person who knows how to collaborate. As previously mentioned, the test persons' body types had more impact than the team predicted, especially focusing on the pelvis area. Sensors can not be placed in an area where some test persons will have fat accumulations such as the ASIS. Structures close to the skin, despite a higher BMI, should be used (the knee for instance).

The Xsens equipment was exact and results corresponded well to those calculated with the verification method when all steps are carried out with great care. Calibration is central to get accurate results.

Both the literature study and the results from the experiments showed to what extent the body is interconnected. Moving the feet affects the legs and also has an impact on the pelvis and the back. The team explored if any overall relationships between the position of the knee and the shoulder could predict the position of the pelvis. No clear connections were found and after working with different test persons it became more evident that such a relationship might be difficult to find. During experiments, the team noted that some test persons tended to always sit in a slouched or collapsed position. This seemed to depend on age, BMI and muscles. It was then for instance difficult to get these persons to sit in a "normal" position and then change to a slouched, as they considered the slouched position to be the "normal" one. Xsens also registered small changes in position that are not visible to the eye, such as static muscle contractions which also affects the orientation of the pelvis.

The dynamic testing of the Xsens showed that it is possible to use Xsens in such an environment. The results also stretched how different the results can be from one test person to another. It became evident that the orientation of the pelvis was more affected by the test person's movements than by external factors (such as speed bumps).
A compensation for the movement of the car would be necessary in order to eliminate changes in the pelvic orientation that were recorded due to the drive.
The recordings were longer when testing the Xsens equipment dynamically and it became more evident that it took a long time to access a recorded file to analyze it.

6.7. Future perspective

The next step in this project would have been to develop or apply a compensation for the car's movements. Xsens is currently working with such a compensation and it would be needed to retrieve the unaffected data on the pelvic orientation. If a similar project would be performed some adjustments would be recommended. Firstly, if the same verification method would be used it would be advantageous to have fewer test persons and perform Experiment 1 twice on each person and even more precisely. The reason why this was not done in this project was because it was difficult to get persons to dedicate that amount of time. Secondly, a more thorough study of Experiment 2 would have been interesting although unfortunately there probably are no quick shortcuts as there are so many aspects that affect how persons sit. After talking with Reed (2018), he said that a connection between the shoulder and the knee could probably be made. Although, he had not found any clear connections.

The next step for Volvo Cars would be to learn and test Xsens. Since there might be a problem with the sensor on the sacrum staying in place it might be worth to examine Xsens MVN Link which is a full body suit. It might remove the problem with the sensor on the sacrum although it remains to be seen how accurate it is and it probably isn't as flexible regarding different human body types.
We would recommend Xsens for this application since it is the equipment that is perceived as the most appropriate in this field of application today. Studies with Xsens could lead to an increased understanding of how people are moving during a car drive and improve the safety assessment for a heterogeneous population. It could hopefully provide data to improve the positioning of HBMs.

The future, in a broader perspective, will probably contain more and more technologies that capture body movement. During the literature study numerous projects were encountered where this type of technology was developed, used or being improved and we think that this will continue.

7 Conclusion

The conclusion of the project.

In this project a measuring method called Xsens MVN Awinda and Xsens MVN Analyze, which measures the posture of a passenger in a car seat was found and evaluated. It can measure the pelvic orientation. It is a precise method if the calibration is carefully done and the sensors stay in place. It is applicable in the front seat and can be used during a drive. Moreover, the project team see no possible obstacles to use of measuring method in the rear seat. The measuring method does affect the test persons' natural behavior but it did not seem to disturb them to a large extent. According to the project team, the measuring method is easy to learn, to use and to analyze, although it takes a long time to prepare the files.

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A Time plan

A.1. Initial time plan

The initial time plan established the first project week is shown in Figure A.1.

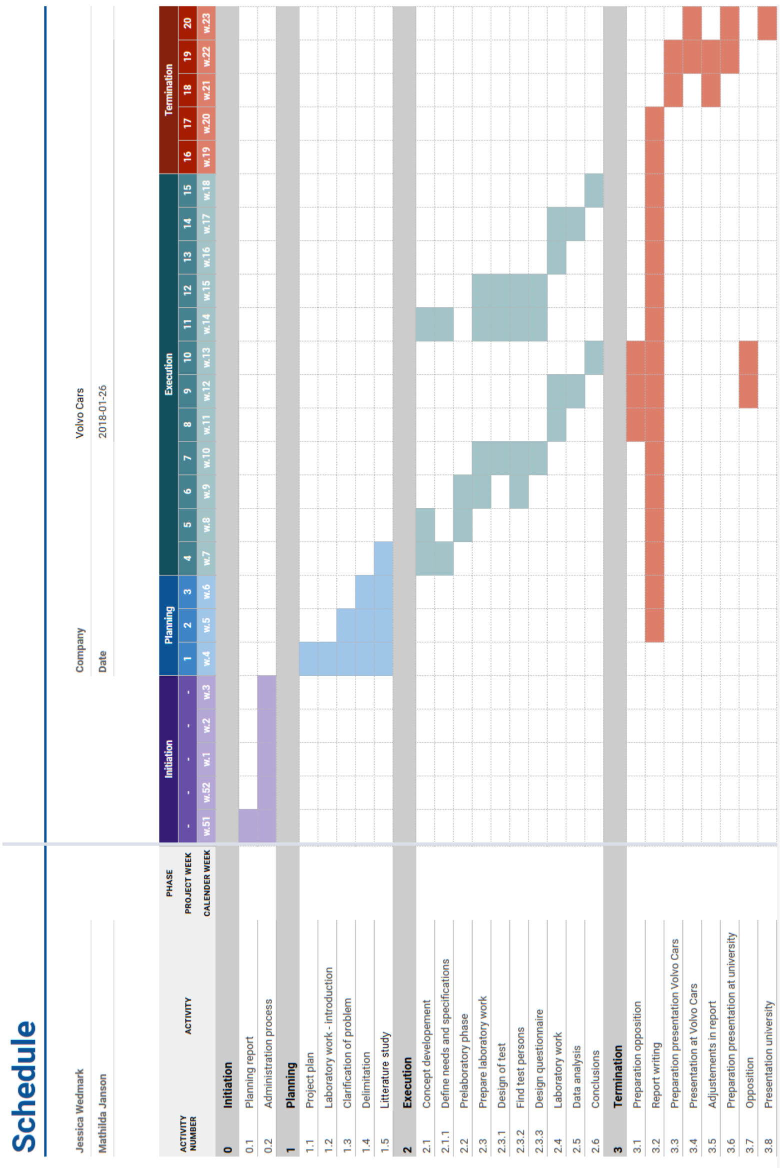

Figure A.1: The initial project schedule

A.2. Revised time plan

The revised time plan is shown in Figure A.2.

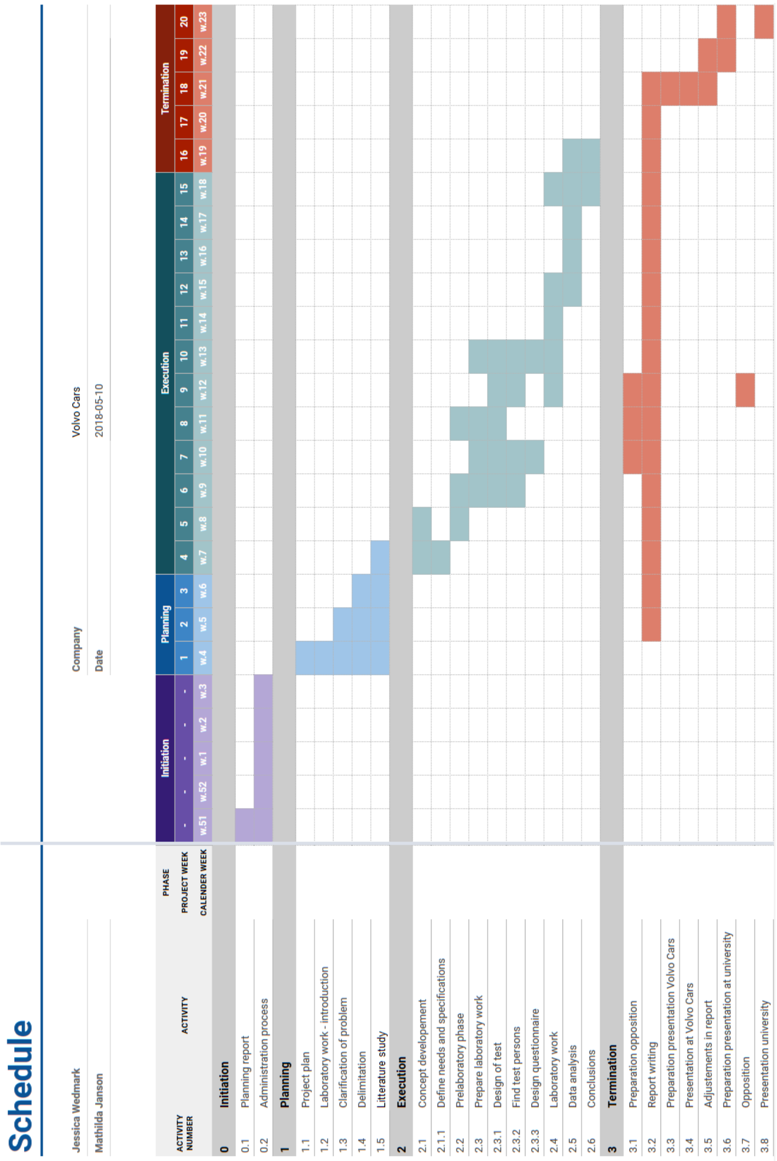

Figure A.2: The revised project schedule

B Prestudy

In this chapter the material from the Prestudy is presented. It only treats the part of the Prestudy which was conducted with volunteers. It contains photographs of postures in the car and representation of the data collected in the Prestudy.

B.1. Photographs from Prestudy

Figure B.1 shows the different conditions for the two sets of measurements. The biggest difference was the clothing, the right test person had looser clothes which complicated the measurements.

Figure B.1: The two test persons sitting in upright positions with patrick markers on body landmarks that were digitized

B.2. Graphs and tables from the data

The data measured on the volunteers from the Prestudy was processed to see if any correlations were present and if the data provide any unexpected results. Figure B.2 shows the full body results for both volunteers, Female 1 and Female 2. The different points measured were plotted in the xz-plane for every angle. A line was drawn between each measurement point for every parameter.

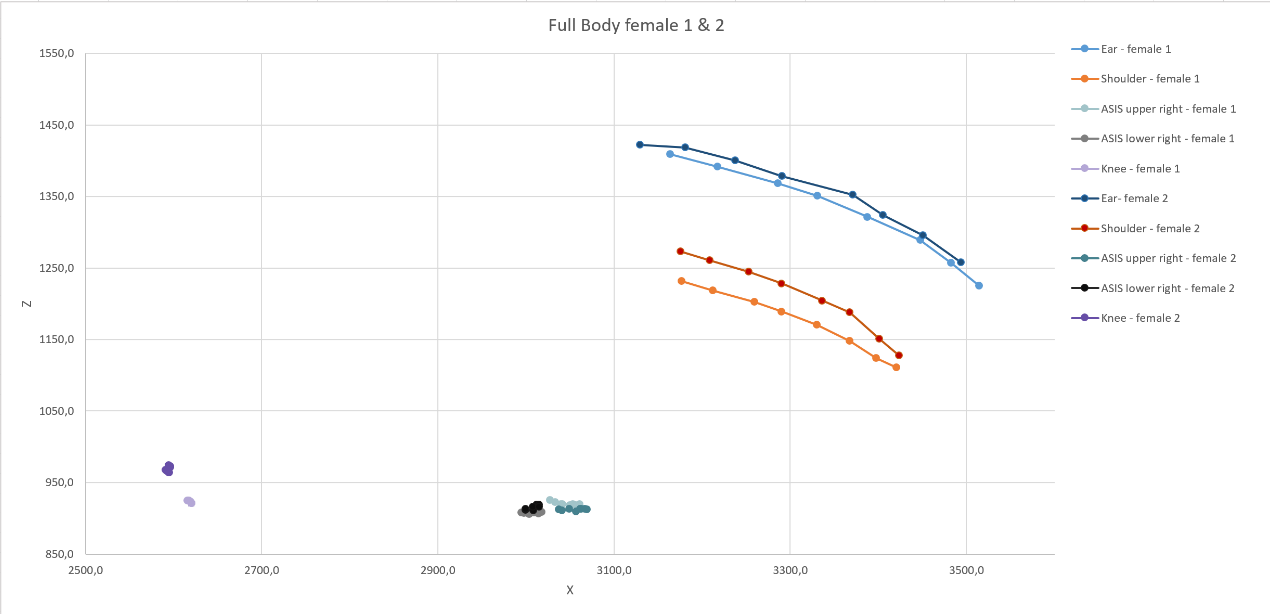

Figure B.2: Full body representation of Female 1 and Female 2 [mm]

Figure B.3 is a magnified plot of the ASIS region where ASIS upper and lower are displayed in the same way as the full body representation above. The data used is limited to the right hand side since the left (inner) side had poor data.

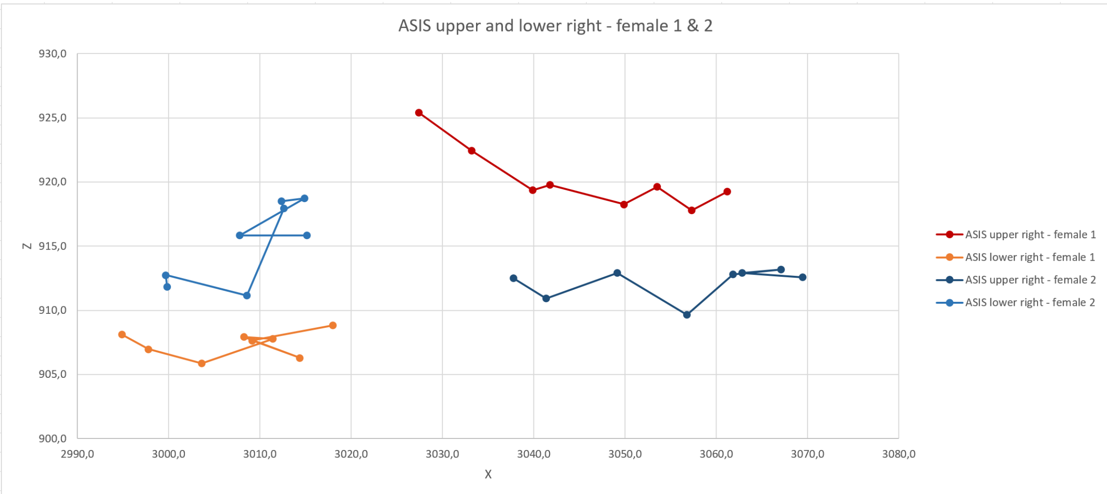

Figure B.3: Representation of upper and lower ASIS for Female 1 and Female 2 [mm]

Figure B.4 shows the course of the reclination of the back, represented by upper and lower sternum. Thus, it is the thoracic spine mainly represented in this plot and not the remaining segments of the back.

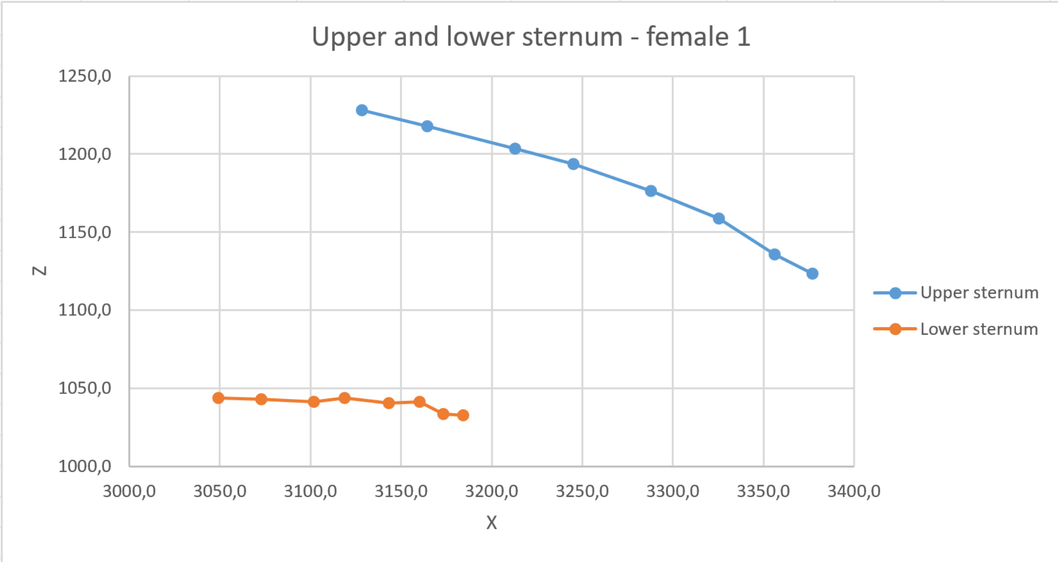

Figure B.4: Representation of upper and lower sternum for Female 1 [mm]

To be able to compare the reclinations and movements between the different body segments angles where calculated for each measured seat back angle. The angles which were considered important were the estimated angle of the pelvis respresented by ASIS upper and lower (called α), the angle between the shoulder and the knee (called β) and the angle of the thoracic spine (called γ). The three angles are illustated in Figure B.5 - B.7. The different angles for each backrest angle is collected in Table B.1.

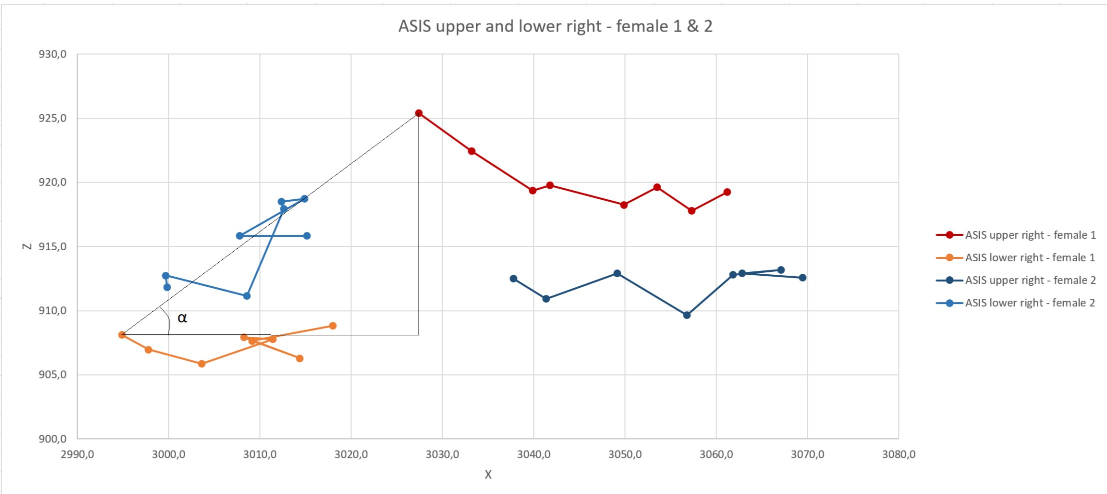

Figure B.5: The initial angle between upper and lower ASIS for Female 1, as an illustration. Here called α.

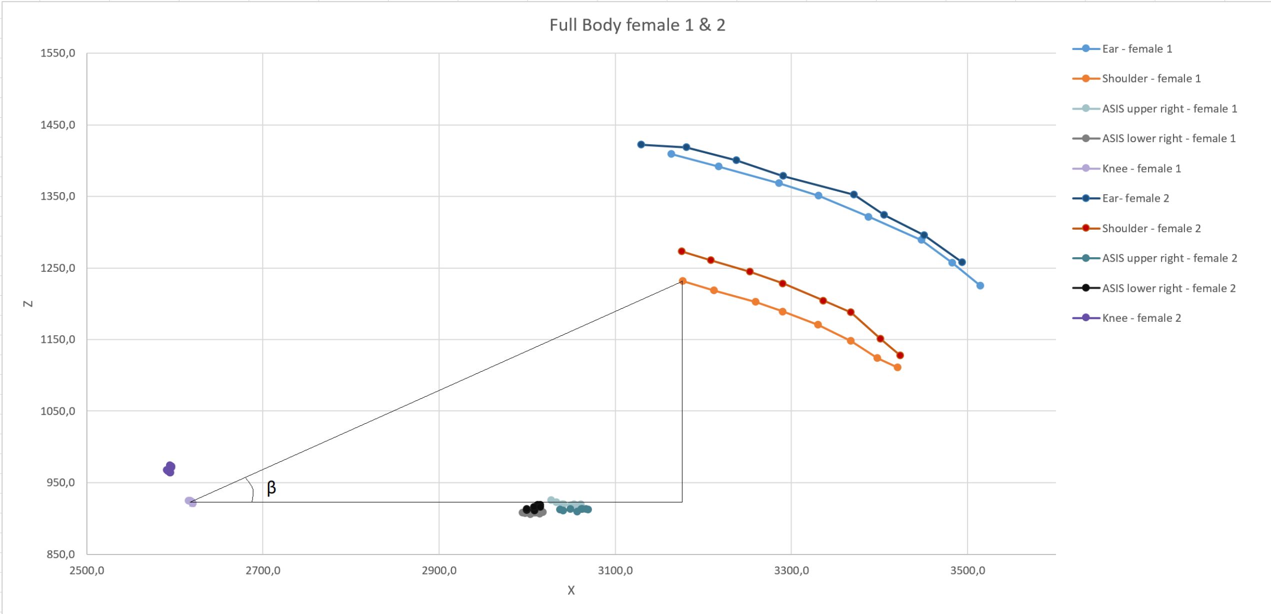

Figure B.6: The initial angle between shoulder and knee for Female 1, as an illustration. Here called β.

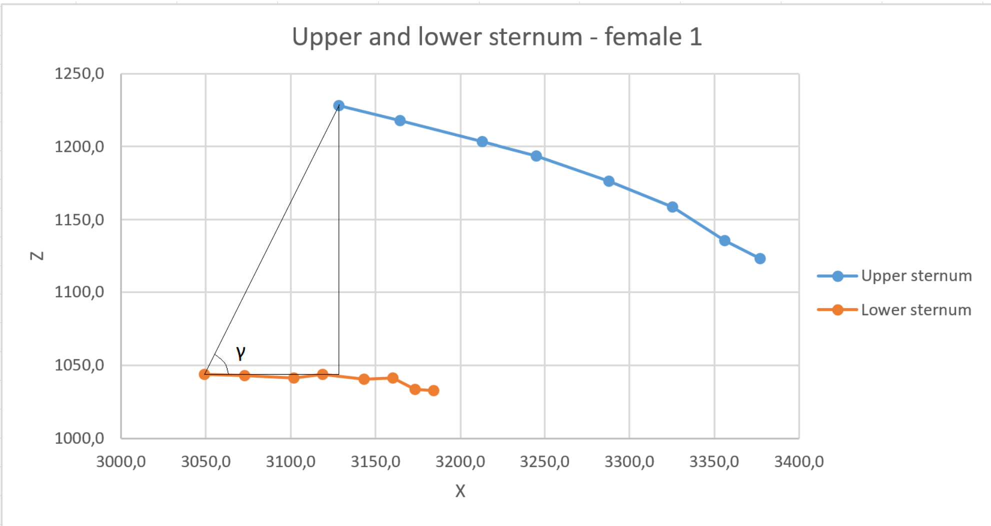

Figure B.7: The initial angle between upper and lower sternum for Female 1, as an illustration. Here called γ.

Table B.1: The angles calculated from the data

Degrees	α, Female 1	α, Female 2	β, Female 1	β, Female 2	γ, Female 1	γ, Female 2
Initial pos.	28,0°	1,0°	28,7°	27,2°	66,7°	63,9°
+ 5°	23,6°	-2,5°	26,3°	25,2°	62,4°	59,8°
+ 10°	20,4°	2,5°	23,5°	22,6°	55,6°	51,6 °
+ 15°	21,5°	-10,6°	21,6°	20,3°	49,9°	47,9°
+ 20°	13,9°	-6,6°	19,3°	18,0°	43,2°	40,6°
+ 25°	18,8°	-6,1°	16,9°	16,2°	35,4°	35,2°
+ 30°	11,9°	-3,0°	14,7°	12,8°	29,3°	27,0°
+ 35°	13,6°	-3,4°	13,4°	10,9°	25,2°	21,6°

Figure B.8 shows a compilation of the three angles for Female 1.

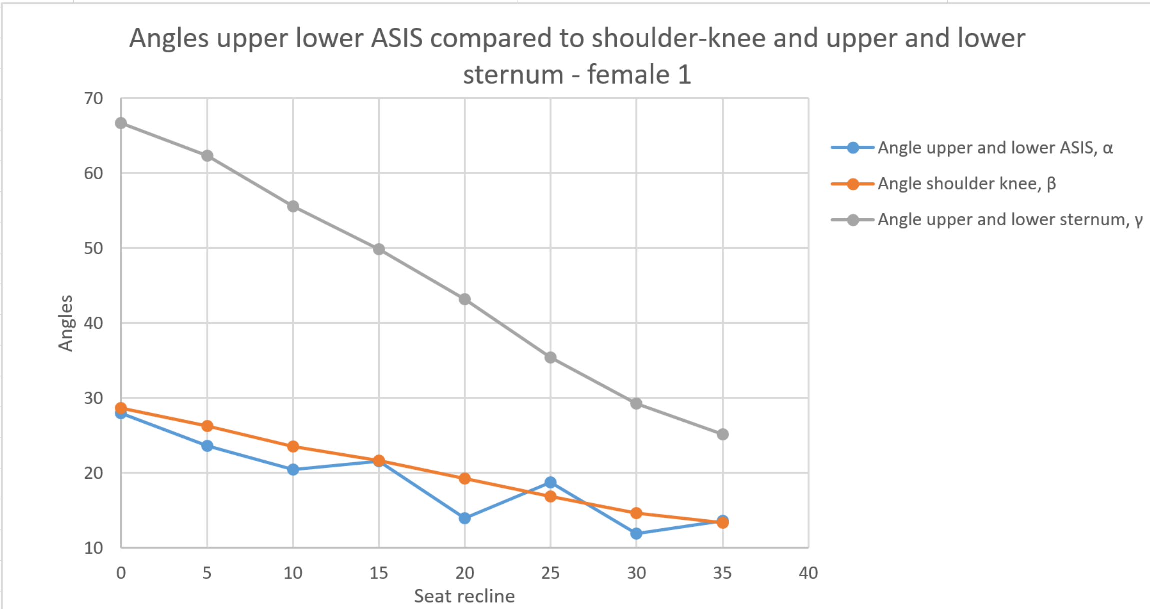

Figure B.8: Comparison of angles upper lower ASIS, shoulder-knee and upper lower sternum

C Needs and specifications

C.1. Established needs

In Table C.1 the established needs for the measuring method is presented. They are sorted in three categories which define their relative importance.

Table C.1: The needs associated with the measuring method developed

Category	Need
Very important	Can be used during a drive
	Does not affect the natural behavior
	Can be repeated
	Data can be collected quantitatively
	Can be applied when the car is stationary
	Can be used in a car
	Can be used in the front passenger seat
	Can be used in the back passenger seat
	Can be used in different car models
	Can be used on different human body types
	Does not limit the test persons range of motion
	Gives data that can be used in HBMs
	Can collect different parameters
	Data can be documented
	Can measure the position of a point on the pelvis
	Can measure the position of HJC (hip-joint centre)
	Can measure the angle of the pelvis
	Can measure the position of the shoulder
	Can measure the position of the eye
	Can measure the position of the knee
Important	Is not unpleasant to use for the test person
	Data collection can occur continuously
	Is exact with small deviations
	Can measure the entire body
	Has a high frequency of data collection to capture small and/or sudden movements
	Gives data that is compatible with VCCs system
	Data is easy to understand
	Can measure the position of the ASIS
	Can measure different segments of the back - curvature
Slightly important	Is easy to learn
	Can be used in different time ranges
	Equipment is easy to set up

C.2. Ranking of needs

In Figure C.1 the form filled in by persons with various expertise is shown. They were asked to rank ever need on a scale from 1-5. Seven people filled in the form. Based on the answers, the needs were sorted into three categories. The limits were:
Very important: 28-35
Important: 21-28
Slightly important: <21

Method	
Needs	Rank
Can be used during a drive	
Is not unpleasant to use for the test person	
Does not affect the natural behavior	
Can be repeated	
Data collection can occur continuously	
Is exact with small deviations	
Is easy to learn	
Can be used in different time ranges	
Data can be collected quantitatively	
Can be applied when the car is stationary	
Can measure the entire body	
Suggestions?	

Equipment and environment	
Needs	Rank
Can be used in a car	
Can be used in the front passenger seat	
Can be used in the back passenger seat	
Can be used in different car models	
Can be used on different human body types	
Does not limit the test persons range of motion	
Equipment is easy to set up	
Has a high frequency of data collection to capture small and/or sudden movements	
Suggestions?	

Data	
Needs	Rank
Gives data that is compatible with VCCs system	
Gives data that can be used in HBMs	
Data is easy to understand	
Can collect different parameters	
Data can be documented	
Suggestions?	

Output	
Needs	Rank
Can measure the position of the ASIS	
Can measure the position of a point on the pelvis	
Can measure the position of HJC (hip-joint center)	
Can measure the angle of the pelvis	
Can measure different segments of the back - curvature	
Can measure the position of the shoulder	
Can measure the position of the eye	
Can measure the position of the knee	
Suggestions?	

Figure C.1: The form given to persons with various expertise

Table C.2: The results from the ranking of the needs

Category	Need	Ranking	Normalized ranking
Very important	Can be used during a drive	30	0,03341
	Does not affect the natural behavior	31	0,03452
	Can be repeated	34	0,03786
	Data can be collected quantitatively	31	0,03452
	Can be applied when the car is stationary	28	0,03118
	Can be used in a car	34	0,03786
	Can be used in the front passenger seat	32	0,03563
	Can be used in the back passenger seat	31	0,03452
	Can be used in different car models	32	0,03563
	Can be used on different human body types	32	0,03563
	Does not limit the test persons range of motion	32	0,03563
	Gives data that can be used in HBMs	29	0,03229
	Can collect different parameters	30	0,03341
	Data can be documented	32	0,03563
	Can measure the position of a point on the pelvis	30	0,03341
	Can measure the position of HJC (hip-joint centre)	28	0,03118
	Can measure the angle of the pelvis	29	0,03229
	Can measure the position of the shoulder	32	0,03563
	Can measure the position of the eye	30	0,03341
	Can measure the position of the knee	30	0,03341
Important	Is not unpleasant to use for the test person	24	0,02673
	Data collection can occur continuously	25	0,02785
	Is exact with small deviations	27	0,03007
	Can measure the entire body	27	0,03007
	Has a high frequency of data collection to capture small and/or sudden movements	27	0,03007
	Gives data that is compatible with VCCs system	23	0,02561
	Data is easy to understand	23	0,02561
	Can measure the position of the ASIS	27	0,03007
	Can measure different segments of the back - curvature	22	0,02451
Slightly important	Is easy to learn	17	0,01893
	Can be used in different time ranges	20	0,02227
	Equipment is easy to set up	19	0,02116

C.3. Established metrics

To get a sense of what the measuring method actually should perform the needs was converted into metrics, see Table C.3.

Table C.3: The established metrics and corresponding needs

	Need	Metric
Method	Can be used during a drive	Car movement does not affect data collection and equipment does not affect cars performance
	Is not unpleasant to use for the test person	Does not provoke negative emotion
	Does not affect the natural behavior	Not limit range of motion or field of vision or expose test person to heavy or uncomfortable weight
	Can be repeated	Data comparable from different sessions
	Data collection can occur continuously	No irregular data collection interruptions
	Is exact with small deviations	Percentage threshold
	Is easy to learn	Possible to perform a test after reading instructions and one trial
	Can be used in different time ranges	Adjustable timing and sufficient storage
	Data can be collected quantitatively	Captures data more than once during session
	Can be applied when the car is stationary	The lack of car movement does not affect data collection
	Can measure the entire body	Single measurement session captures whole body
Equipment and environment	Can be used in a car	Scale of equipment suitable for car interior
	Can be used in the front passenger seat	Scale of equipment suitable for front seat interior use
	Can be used in the back passenger seat	Scale of equipment suitable for backrest interior use
	Can be used in different car models	Universal components used with equipment
	Can be used on different body types	5th percentile to 95th percentile body types
	Does not limit the test persons range of motion	Equipment allows expected motions
	Equipment is easy to set up	Time to set up equipment and intuitive
	Has a high frequency of data collection	Samples per time unit
Data	Gives data that is compatible with VCCs system	Output data follows VCC standards
	Gives data that can be used in HBMs	Output data gives relevant positions and angles
	Data is easy to understand	Time to understand data comparable to total test time
	Can collect different parameters	Output data more than one parameter
	Data can be documented	Sufficient storage capacity for data collection
Output	Can measure the position of the ASIS	Position
	Can measure the position of a point on the pelvis	Position
	Can measure the position of HJC (hip-joint centre)	Position
	Can measure the angle of the pelvis	Angle
	Can measure the angle of the back	Angle
	Can measure different segments of the back - curvature	Position/angle
	Can measure the position of the shoulder	Position
	Can measure the position of the eye	Position
	Can measure the position of the knee	Position

D Concept selection

D.1. Concept screening

In order to proceed with the most suitable concepts a concept screening was done. Table D.1 shows the screening matrix with the filled in rankings and results.

D.2. Concept scoring

To ensure the project team which concepts were suitable for testing a concept scoring was done. Table D.1 shows the scoring matrix with the filled in rankings and results.

Table D.1: The screening matrix

	Xsens	**Qualisys**	**Tilt Sensor**	**Shoulder-knee**	**Scanning**	**Medical imaging**
Very important						
Can be used during a drive	0	-	0	0	-	-
Does not affect the natural behavior	-	-	0	+	0	-
Can be repeated	+	+	0	+	+	+
Data can be collected quantitatively	0	0	0	0	-	-
Can be applied when the car is stationary	0	0	0	0	0	-
Can be used in a car	0	-	0	0	-	-
Can be used in the front passenger seat	0	-	0	0	-	-
Can be used in the back passenger seat	0	-	0	0	-	-
Can be used in different car models	0	-	0	0	-	-
Can be used on different human body types	+	+	0	+	+	+
Does not limit the test persons range of motion	+	0	0	-	-	-
Gives data that can be used in HBMs	+	+	0	+	+	+
Can collect different parameters	+	+	0	+	+	+
Data can be documented	+	+	0	0	0	0
Can measure the position of a point on the pelvis	0	+	0	0	0	+
Can measure the position of HJC (hip-joint centre)	0	0	0	0	0	+
Can measure the angle of the pelvis	+	-	0	0	-	+
Can measure the position of the shoulder	+	+	0	+	+	+
Can measure the position of the eye	0	+	0	0	0	+
Can measure the position of the knee	0	+	0	+	+	+
Important						
Is not unpleasant to use for the test person	0	0	0	0	0	-
Data collection can occur continuously	0	0	0	0	-	-
Is exact with small deviations	0	0	0	-	-	0
Can measure the entire body	+	+	0	+	+	0
Has a high frequency of data collection to capture small and/or sudden movements	+	+	0	-	-	-
Gives data that is compatible with VCCs system	0	0	0	0	0	-
Data is easy to understand	+	+	0	+	0	-
Can measure the position of the ASIS	0	+	0	0	0	+
Can measure different segments of the back - curvature	+	-	0	-	-	+
Slightly important						
Is easy to learn	0	-	0	0	0	-
Can be used in different time ranges	+	+	0	+	+	-
Equipment is easy to set up	0	-	0	0	-	-
Positive:	13	14		10	8	12
Negative:	1	10		4	13	17
Sum:	**12**	**4**	**0**	**6**	**-5**	**-5**

Table D.2: The scoring matrix

		Xsens		Qualisys		Tilt Sensor		Shoulder-knee	
Very important	**Weight**								
Can be used during a drive	0,03341	4	0,13364	2	0,06682	5	0,16705	3	0,10023
Does not affect the natural behavior	0,03452	3	0,10356	3	0,10356	3	0,10356	4	0,13808
Can be repeated	0,03786	4	0,15144	4	0,15144	3	0,11358	4	0,15144
Data can be collected quantitatively	0,03452	5	0,1726	5	0,1726	5	0,1726	5	0,1726
Can be applied when the car is stationary	0,03118	4	0,12472	5	0,1559	5	0,1559	5	0,1559
Can be used in a car	0,03786	5	0,1893	3	0,11358	5	0,1893	4	0,15144
Can be used in the front passenger seat	0,03563	5	0,17815	3	0,10689	5	0,17815	4	0,14252
Can be used in the back passenger seat	0,03452	5	0,1726	3	0,10356	5	0,1726	4	0,13808
Can be used in different car models	0,03563	5	0,17815	3	0,10689	5	0,17815	4	0,14252
Can be used on different human body types	0,03563	4	0,14252	3	0,10689	2	0,07126	5	0,17815
Does not limit the test persons range of motion	0,03563	4	0,14252	3	0,10689	3	0,10689	3	0,10689
Gives data that can be used in HBMs	0,03229	4	0,12916	5	0,16145	2	0,06458	2	0,06458
Can collect different parameters	0,03341	5	0,16705	4	0,13364	1	0,03341	3	0,10023
Data can be documented	0,03563	5	0,17815	5	0,17815	5	0,17815	4	0,14252
Can measure the position of a point on the pelvis	0,03341	2	0,06682	5	0,16705	1	0,03341	1	0,03341
Can measure the position of HJC (hip-joint centre)	0,03118	2	0,06236	3	0,09354	1	0,03118	1	0,03118
Can measure the angle of the pelvis	0,03229	5	0,16145	3	0,09687	3	0,09687	3	0,09687
Can measure the position of the shoulder	0,03563	4	0,14252	5	0,17815	1	0,03563	5	0,17815
Can measure the position of the eye	0,03341	2	0,06682	4	0,13364	1	0,03341	4	0,13364
Can measure the position of the knee	0,03341	3	0,10023	5	0,16705	1	0,03341	5	0,16705
Important									
Is not unpleasant to use for the test person	0,02673	3	0,08019	3	0,08019	4	0,10692	5	0,13365
Data collection can occur continuously	0,02785	5	0,13925	5	0,13925	5	0,13925	5	0,13925
Is exact with small deviations	0,03007	5	0,15035	5	0,15035	5	0,15035	3	0,09021
Can measure the entire body	0,03007	5	0,15035	5	0,15035	2	0,06014	3	0,09021
Has a high frequency of data collection to capture small and/or sudden movements	0,03007	5	0,15035	4	0,12028	5	0,15035	3	0,09021
Gives data that is compatible with VCCs system	0,02561	5	0,12805	5	0,12805	5	0,12805	3	0,07683
Data is easy to understand	0,02561	5	0,12805	4	0,10244	3	0,07683	4	0,10244
Can measure the position of the ASIS	0,03007	3	0,09021	4	0,12028	1	0,03007	3	0,09021
Can measure different segments of the back - curvature	0,02451	5	0,12255	1	0,02451	3	0,07353	2	0,04902
Slightly important									0
Is easy to learn	0,01893	4	0,07572	3	0,05679	5	0,09465	3	0,05679
Can be used in different time ranges	0,02227	5	0,11135	5	0,11135	5	0,11135	5	0,11135
Equipment is easy to set up	0,02116	4	0,08464	2	0,04232	5	0,1058	3	0,06348
Sum:	**1**		**4,17482**		**3,83072**		**3,37638**		**3,61913**

E Concept testing

E.1. Information about the test persons

Information about gender (F for female and M for male) and body measurements for the test persons in the Experiment 1 and Experiment 2 is presented in Table E.1 and E.2 respectively.

Table E.1: Information about the test persons in Experiment 1

TP	Gender	Length	Weight	BMI
TP1	F	171 cm	72 kg	24,6 kg/m^2
TP2	F	171 cm	70 kg	23,9 kg/m^2
TP3	M	184,5 cm	85 kg	25,0 kg/m^2
TP4	M	188 cm	91 kg	25,8 kg/m^2
TP5	F	169 cm	87 kg	30,5 kg/m^2
TP6	M	189 cm	120 kg	33,6 kg/m^2
TP7	F	164 cm	65 kg	24,2 kg/m^2
TP8	M	186 cm	80 kg	23,1 kg/m^2
TP9	F	172 cm	64 kg	21,6 kg/m^2
TP second session	F	169 cm	58 kg	20,3 kg/m^2

Table E.2: Information about the test persons in Experiment 2

TP	Gender	Length
TP1	F	174 cm
TP2	M	190 cm
TP3	M	189 cm
TP4	F	165,5 cm
TP5	M	187 cm
TP6	M	188 cm
TP7	M	187 cm
TP8	F	177 cm
TP9	F	167 cm
TP10	F	172 cm
TP11	F	174,5 cm
TP12	F	164 cm
TP13	M	188 cm
TP14	F	176,5 cm
TP15	F	175 cm
TP16	F	173,5 cm
TP17	M	186 cm

E.2. Photographs from Experiment 1

Photographs from Experiment 1 can be seen in Figure E.1 - E.4. These illustrate the setting of the experiment, the postures and the importance of the construction of the hardseat.

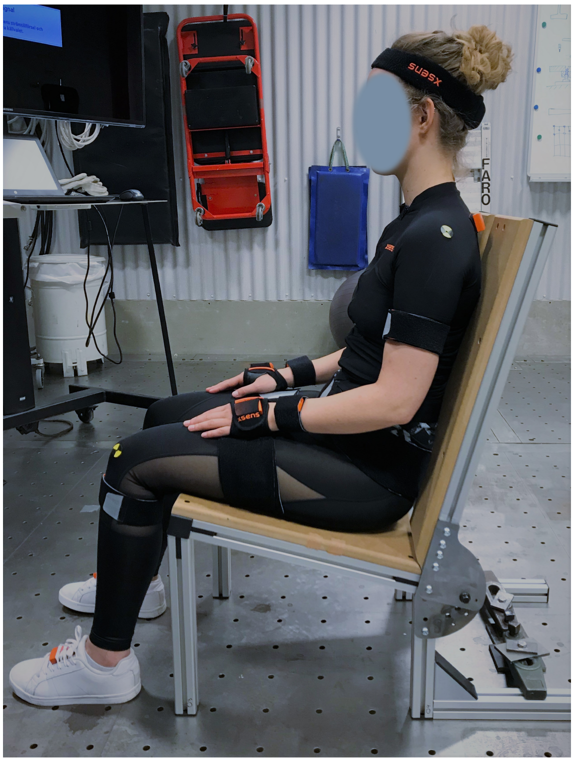

Figure E.1: The 15N posture in Experiment 1

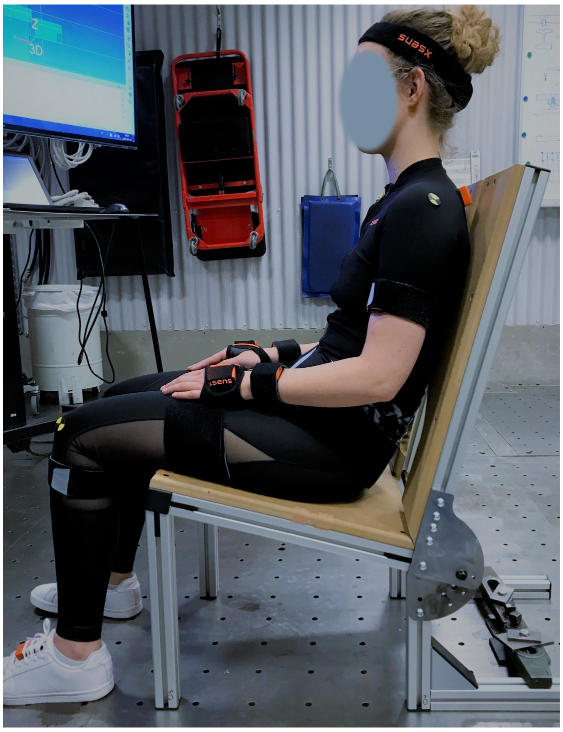

Figure E.2: The 15S posture in Experiment 1

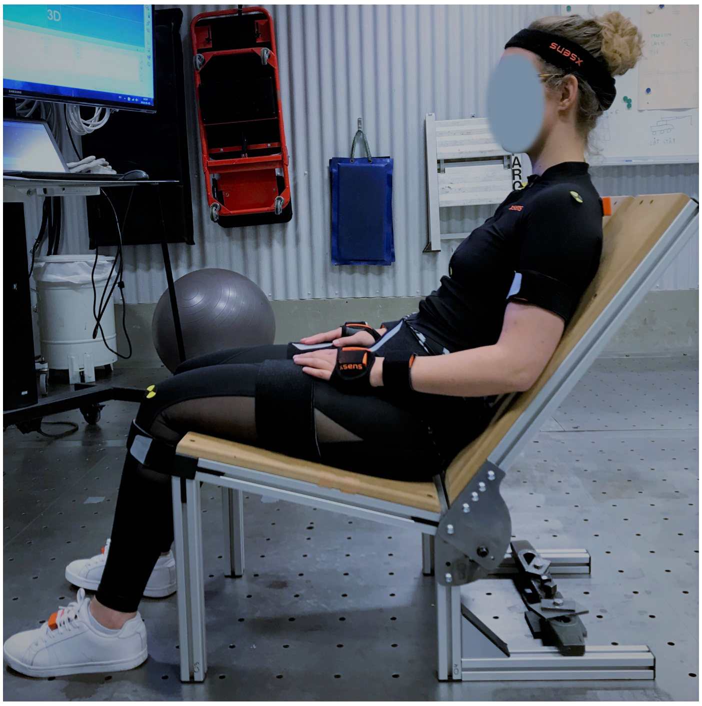

Figure E.3: The 38N posture in Experiment 1

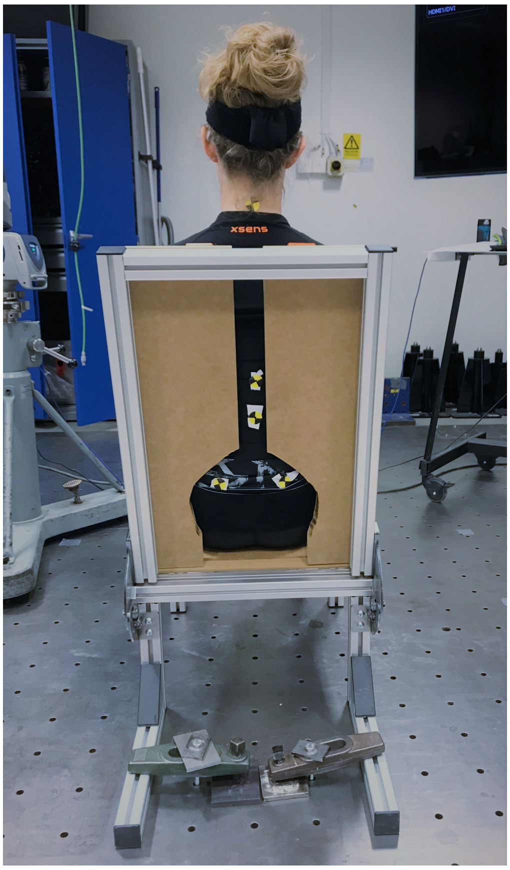

Figure E.4: The landmarks on the back, accessible due to the hardseat

E.3. Questionnaire

To capture how the concepts performed regarding subjective needs the test persons were asked to fill in a questionnaire. The layout for Experiment 1 is shown in Figure E.5 and the results in Table E.3. The results are presented by showing how many persons gave a statement a certain grade, e.g. the statement *The test was well organized* was graded 4 by one person and 5 by eight persons in Experiment 1. The layout for Experiment 2 and Experiment 3 is shown in Figure E.6 and the results in Table E.4 and Table E.5 respectively.

Questionnaire

Thank you for your participation in these tests. In order to get an understanding of your perception of the test, we would like you to fill in this questionnaire. The scale is defined as 1 to 5 where:
1: I fully disagree to this statement
3: I am neutral to this statement
5: I fully agree to the statement

TEST	
The test was well organized	
As a test person, I felt comfortable during the test	
The test leader was professional	
The test leader gave clear instructions	
The test leader was understanding of the test persons situation	
The markers placed out by the test leaders stayed in the same position during testing	
XSENS	
The Xsens equipment was easy to put on and take off	
The Xsens equipment was comfortable to wear	
The Xsens equipment did not disturb me during testing	
The Xsens sensors seemed to stay in the same position during testing	
TILT	
The Tilt sensor was comfortable to wear	
The Tilt sensor did not disturb me during testing	
The Tilt sensor seemed to stay in the same position during testing	
Comments or general thoughts (for instance, is there any additional information you would have wanted to receive before the testing):	

Figure E.5: The questionnaire given to the test persons in Experiment 1

Questionnaire

Thank you for your participation in these tests. In order to get an understanding of your perception of the test, we would like you to fill in this questionnaire. The scale is defined as 1 to 5 where:

1: I fully disagree to this statement

3: I am neutral to this statement

5: I fully agree to the statement

TEST	
The test was well organized	
As a test person, I felt comfortable during the test	
The test leader was professional	
The test leader gave clear instructions	
The test leader was understanding of the test persons situation	
The markers placed out by the test leaders stayed in the same position during testing	
XSENS	
The Xsens equipment was easy to put on and take off	
The Xsens equipment was comfortable to wear	
The Xsens equipment did not disturb me during testing	
The Xsens sensors seemed to stay in the same position during testing	
Comments or general thoughts (for instance, is there any additional information you would have wanted to receive before the testing):	

Figure E.6: The questionnaire given to the test persons in Experiment 2 and Experiment 3

Table E.3: The results from the questionnaire for Experiment 1

The questionnaire	**Grade**					**Number of test persons:** 9
TEST	1	2	3	4	5	Average grade
The test was well organized				1	8	4,89
As a test person, I felt comfortable during the test				1	8	4,89
The test leader was professional				1	8	4,89
The test leader gave clear instructions					9	5
The test leader was understanding of the test persons situation					9	5
The markers placed out by the test leaders stayed in the same position during testing			3	1	5	4,22
XSENS						
The Xsens equipment was easy to put on and take off				2	7	4,78
The Xsens equipment was comfortable to wear			1	1	7	4,67
The Xsens equipment did not disturb me during testing		1			8	4,67
The Xsens sensors seemed to stay in the same position during testing			2	1	6	4,44
TILT						
The Tilt Sensor was comfortable to wear				1	8	4,89
The Tilt Sensor did not disturb me during testing					9	5
The Tilt Sensor seemed to stay in the same position during testing	1		1		7	4,33

Table E.4: The results from the questionnaire for Experiment 2

The questionnaire	**Grade**					**Number of test persons:** 17
TEST	1	2	3	4	5	Average grade
The test was well organized					17	5
As a test person, I felt comfortable during the test					17	5
The test leader was professional					17	5
The test leader gave clear instructions					17	5
The test leader was understanding of the test persons situation					17	5
The markers placed out by the test leaders stayed in the same position during testing				2	15	4,88
XSENS						
The Xsens equipment was easy to put on and take off				3	14	4,82
The Xsens equipment was comfortable to wear			1	5	11	4,59
The Xsens equipment did not disturb me during testing			1	5	11	4,59
The Xsens sensors seemed to stay in the same position during testing				2	15	4,88

Table E.5: The results from the questionnaire for Experiment 3

The questionnaire	**Grade**					**Number of test persons:** 4
TEST	1	2	3	4	5	Average grade
The test was well organized				1	3	4,75
As a test person, I felt comfortable during the test					4	5
The test leader was professional					4	5
The test leader gave clear instructions					4	5
The test leader was understanding of the test persons situation					4	5
The markers placed out by the test leaders stayed in the same position during testing			1		3	4,5
XSENS						
The Xsens equipment was easy to put on and take off			2		2	4
The Xsens equipment was comfortable to wear			3		1	3,5
The Xsens equipment did not disturb me during testing		1	2	1		3
The Xsens sensors seemed to stay in the same position during testing			1	1	2	4,25

F Verification of concept

The result from the verification method were primary angles of different segments, the definition of these can be seen in Figure 4.11. These are presented in Table F.1, Table F.2 and F.3. The tables are organized after position in the hardseat to be able to compare between the test persons.

Table F.1: The angles and segment length from Hardseat 15, normal

Angles and segment							
TP	Upper back	Lower back	ASIS/HJC	L5S1/HJC	PSIS/HJC	Knee	PD
TP1	119,8°	79,7°	87,9°	41,1°	13,8°	175,0°	133,4 mm
TP2	110,6°	86,3°	103,1°	49,5°	23,4°	175,6°	149,2 mm
TP3	107,9°	88,4°	108,1°	59,5°	31,6°	165,4°	153,9 mm
TP4	111,5°	80,9°	116,8°	66,3°	39,8°	169,6°	158,9 mm
TP5	109,9°	74,2°	114,4°	61,3°	36,5°	174,7°	148,2 mm
TP6	114,3°	76,7°	110,0°	66,8°	38,9°	167,5°	140,8 mm
TP7	116,8°	77,6°	113,1°	59,6°	35,3°	175,0°	149,0 mm
TP8	108,6°	82,7°	108,5°	58,2°	31,2°	167,3°	158,4 mm
TP9	109,7°	86,6°	87,2°	34,4°	10,3°	167,9°	147,2 mm

Table F.2: The angles and segment length from Hardseat 15, slouched

Angles and segment							
TP	Upper back	Lower back	ASIS/HJC	L5S1/HJC	PSIS/HJC	Knee	PD
TP1	118,1°	66,7°	72,3°	28,1°	0,4°	173,4°	127,9 mm
TP2	106,2°	70,6°	78,6°	25,0°	1,0°	178,4°	149,2 mm
TP3	108,8°	77,0°	88,2°	37,6°	10,2°	163,8°	159,3 mm
TP4	112,5°	71,6°	100,2°	51,0°	23,7°	168,1°	155,4 mm
TP5	105,4°	56,2°	98,4°	44,6°	19,7°	174,6°	149,8 mm
TP6	115,6°	72,9°	98,6°	52,4°	24,5°	164,4°	147,9 mm
TP7	112,4°	65,3°	94,5°	40,3°	15,7°	173,7°	150,6 mm
TP8	110,2°	73,6°	87,4°	36,6°	9,5°	168,5°	159,6 mm
TP9	107,1°	81,7°	73,0°	20,2°	3,9°	166,7°	147,2 mm

Table F.3: The angles and segment length from Hardseat 38, normal

Angles and segment							
TP	Upper back	Lower back	ASIS/HJC	L5S1/HJC	PSIS/HJC	Knee	PD
TP1	92,1°	55,5°	72,9°	25,8°	1,6°	172,1°	134,0 mm
TP2	91,0°	59,9°	83,6°	34,5°	7,4°	173,9°	138,5 mm
TP3	88,1°	59,2°	100,3°	50,2°	22,2°	167,3°	157,8 mm
TP4	93,7°	56,8°	96,0°	47,6°	20,0°	168,2°	153,4 mm
TP5	89,5°	48,5°	98,6°	44,8°	19,3°	172,6°	149,6 mm
TP6	101,7°	53,6°	106,4°	55,8°	28,6°	168,0°	159,1 mm
TP7	99,1°	52,2°	87,6°	35,8°	11,3°	170,4°	144,8 mm
TP8	89,9°	54,9°	84,0°	36,4°	8,7°	168,0°	151,5 mm
TP9	89,2°	62,1°	74,6°	23,4°	1,5°	166,1°	143,4 mm

G Analysis

Visual representation of test persons in different positions in hardseat
The visual representation of how the test persons sat in the different positions in the hardseat are shown in Figure G.1 - G.9. These can be compared with 5.5, observe that the upper neck joint was not included in this project.

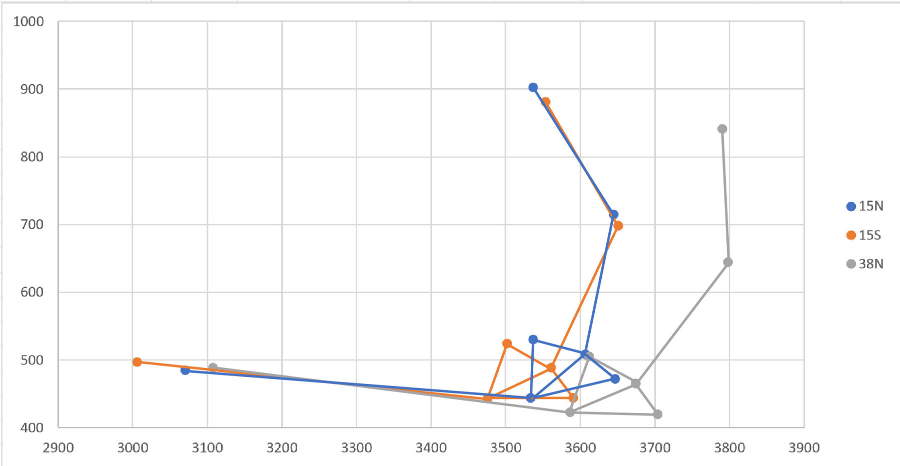

Figure G.1: The postures of TP1

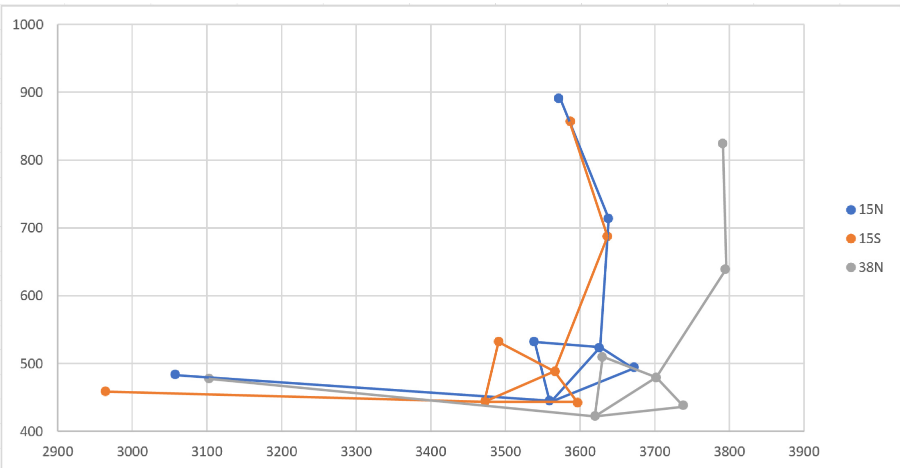

Figure G.2: The postures of TP2

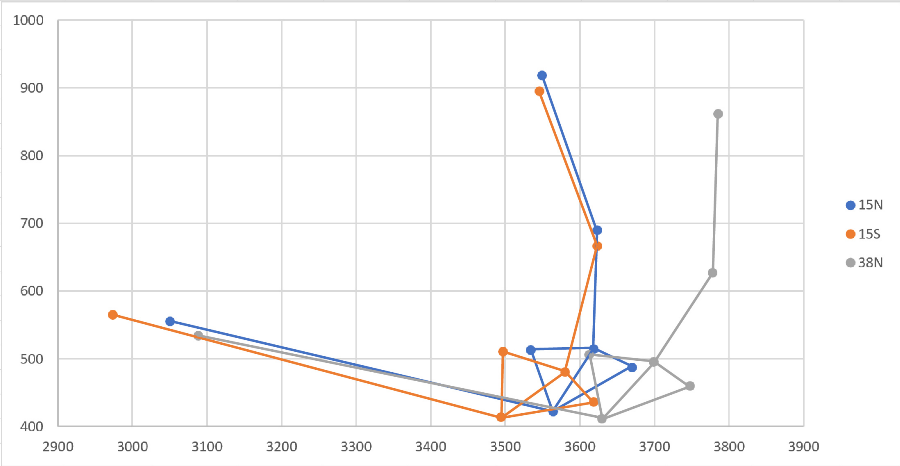

Figure G.3: The postures of TP3

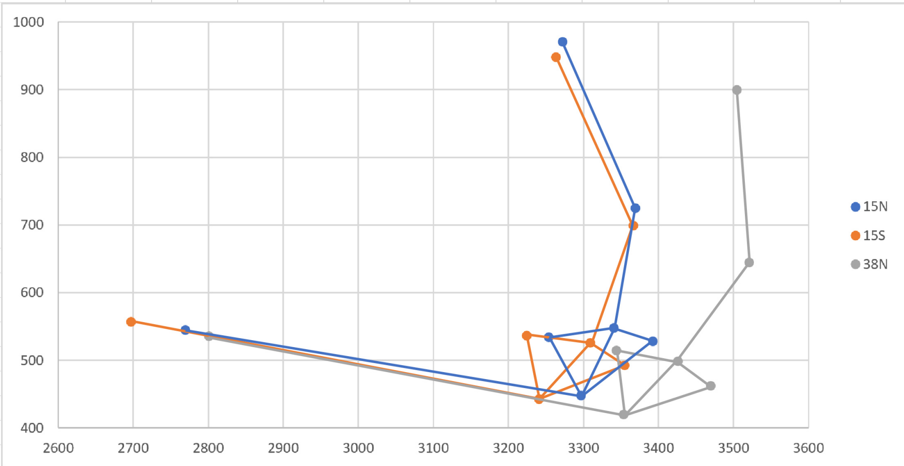

Figure G.4: The postures of TP4

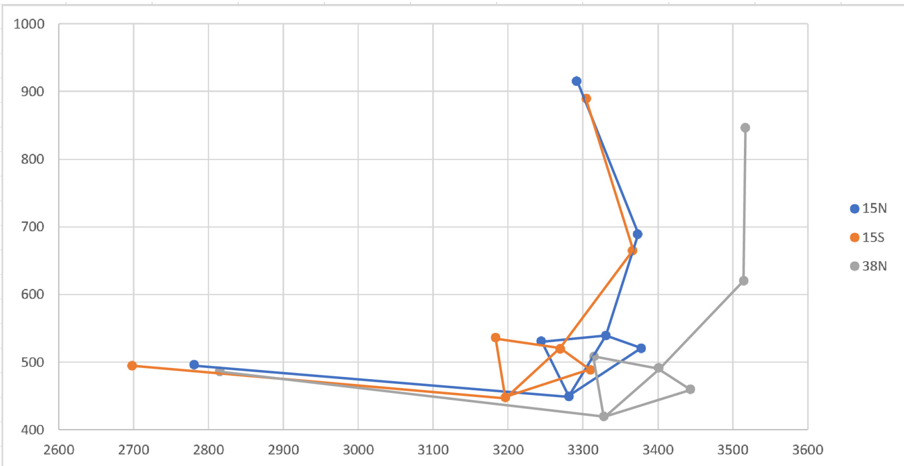

Figure G.5: The postures of TP5

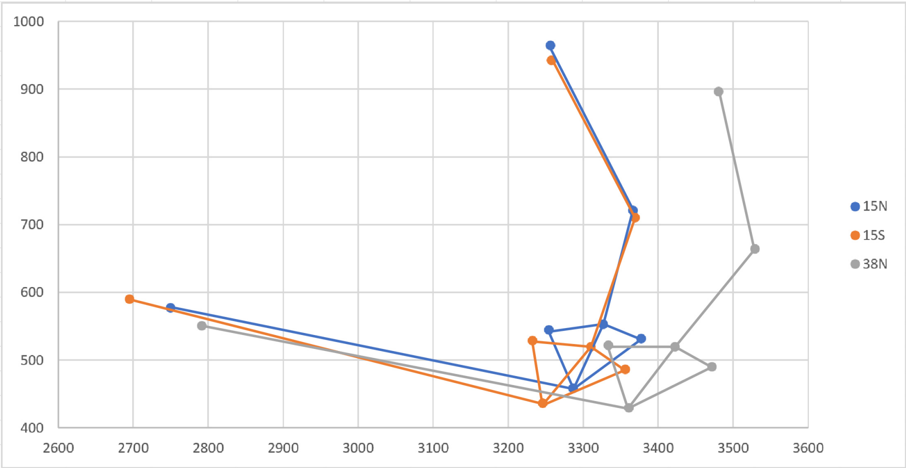

Figure G.6: The postures of TP6

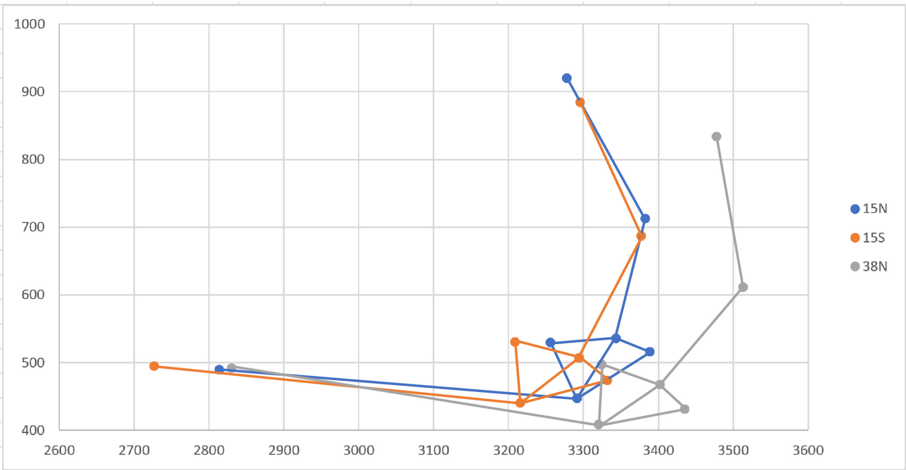

Figure G.7: The postures of TP7

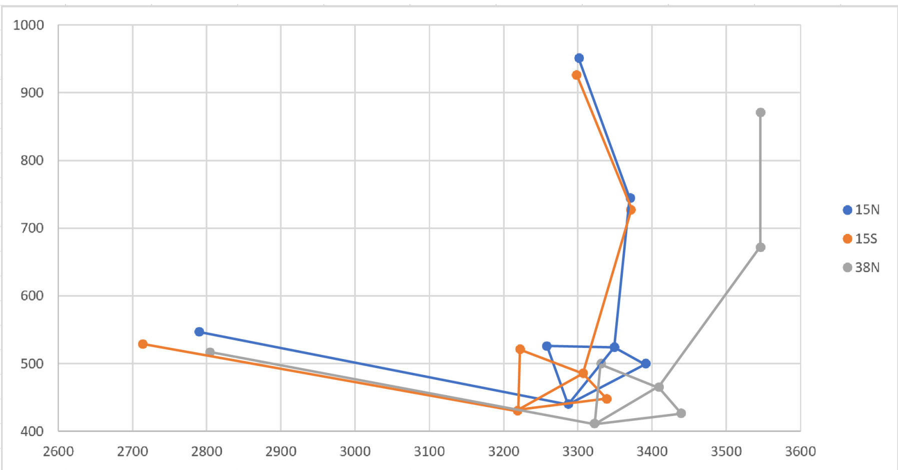

Figure G.8: The postures of TP8

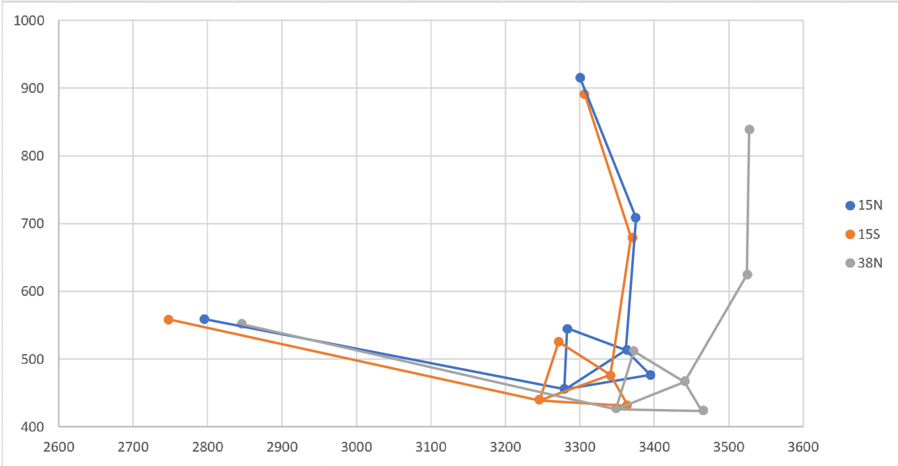

Figure G.9: The postures of TP9

The postures from the first and second round in the second session can be seen in Figure G.10.

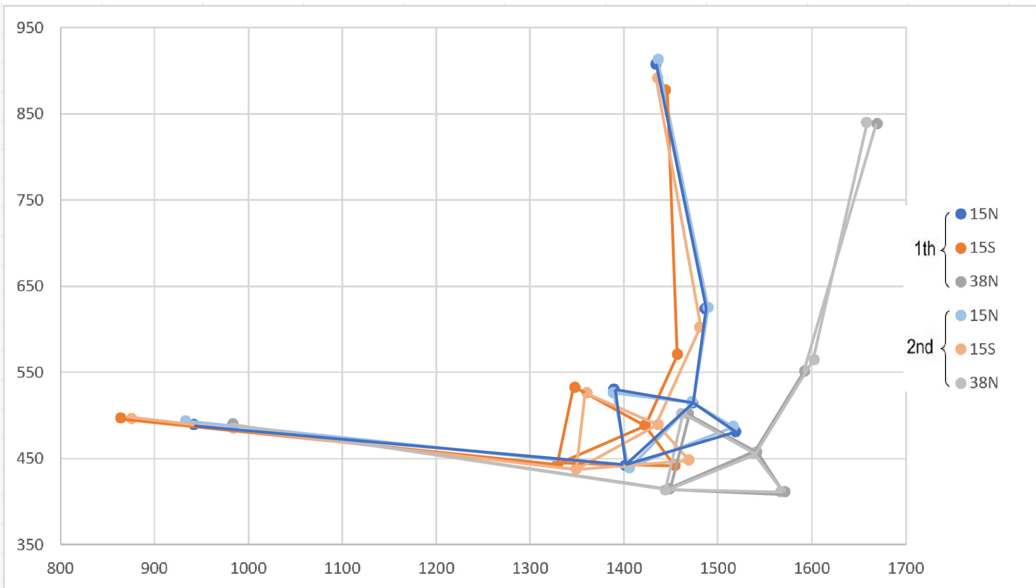

Figure G.10: The postures from the second session

The mean and SD for all relative angles calculated in the analysis of Experiment 1 for TP1 - TP9, see Table G.1.

Table G.1: The mean and SD of the relative angles for the pelvis and PD for all test persons, in all positions in the hardseat

		ASIS/HJC - L5S1/HJC	L5S1/HJC - PSIS/HJC	PD
TP1	Mean	46,0°	26,4°	131,8 mm
	SD	1,5°	1,9°	3,4 mm
TP2	Mean	52,1°	25,7°	145,6 mm
	SD	2,6°	2,6°	6,2 mm
TP3	Mean	49,8°	27,8°	157,0 mm
	SD	1,1°	0,4°	2,8 mm
TP4	Mean	49,3°	27,1°	155,9 mm
	SD	1,1°	0,6°	2,8 mm
TP5	Mean	53,6°	25,0°	149,2 mm
	SD	0,4°	0,4°	0,9 mm
TP6	Mean	46,6°	27,6°	149,3 mm
	SD	3,7°	0,4°	9,2 mm
TP7	Mean	53,2°	24,5°	148,1 mm
	SD	1,3°	0,2°	3,0 mm
TP8	Mean	49,6°	27,3°	156,5 mm
	SD	1,7°	0,4°	4,4 mm
TP9	Mean	52,2°	20,7°	145,9 mm
	SD	0,9°	4,0°	2,2 mm

Xsens: adjustements in Xsens MVN Analyze

A comparison between the three adjustements made in Xsens MVN Analyze can be seen in Figure G.11 - G.14. The legend represents the following:

1. Original (red): the original version in scenario *Single Level*
2. HD-NL (green): the original version reprocessed in HD using scenario *No Level*
3. HD-SL (red): the original version reprocessed in HD using scenario *Single Level*

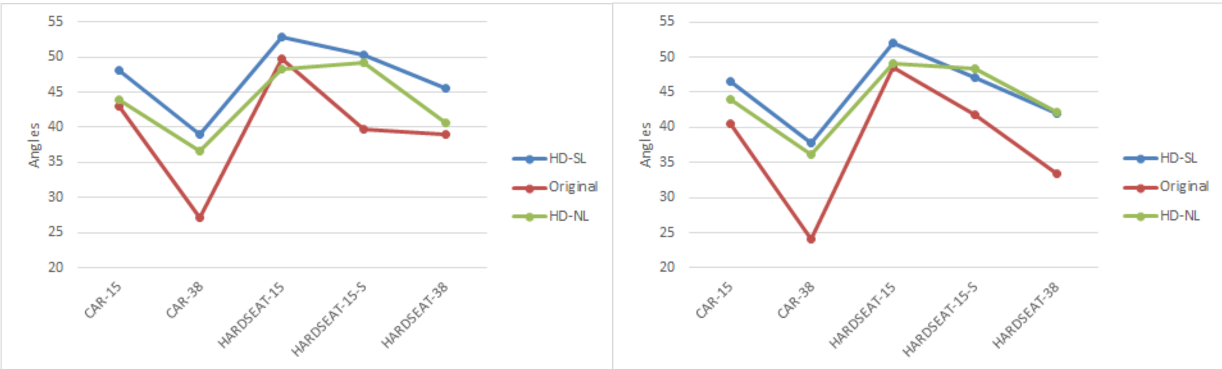

Figure G.11: A comparison between the three adjustements made in Xsens for TP3 and TP4

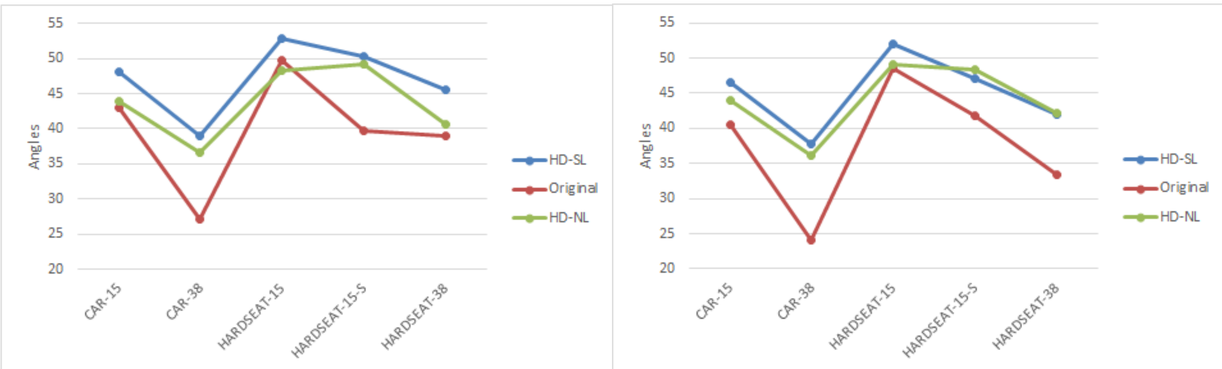

Figure G.12: A comparison between the three adjustements made in Xsens for TP5 and TP6

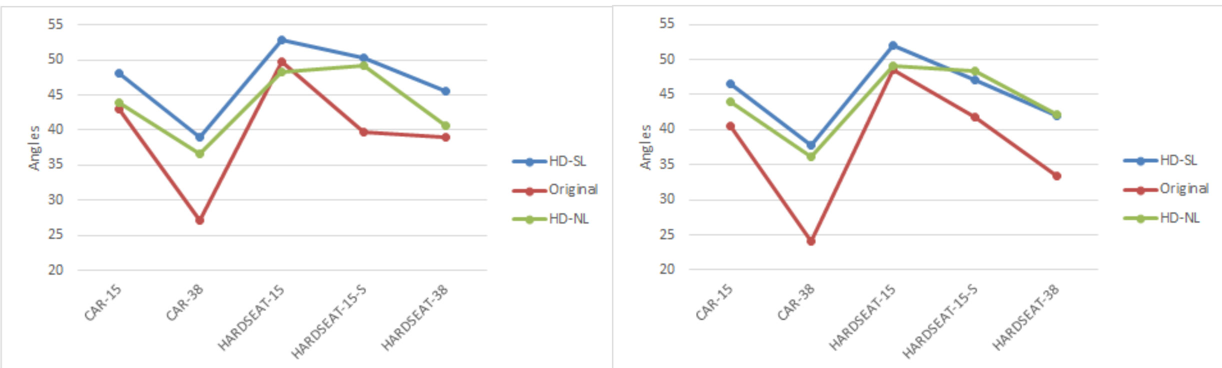

Figure G.13: A comparison between the three adjustements made in Xsens for TP7 and TP8

Figure G.14: A comparison between the three adjustements made in Xsens for TP9

The Xsens MVN Analyze has two different scenarios of interest for this project, the *Single Level* and the *No Level* scenarios. The *Single Level* is the default scenario described by Xsens as a scenario that should be used *when interactions of the subject are known to be limited to a single level. The behavior of the contact points, which can be anywhere on the body, is confined to a zero level floor. If the subject is for example climbing some stairs, each step is corrected towards the zero level floor and the height information is lost* (Xsens 2018*b*).

The *No Level* is on the other hand recommended when there is no primer interest in the floor interaction and position change in space. *In this scenario, the pelvis is fixed in space and all kinematic quantities are expressed relative to the pelvis. This could be of interest, for instance, for the analysis of human body joint angles in biomechanics, or for applications in which ground contacts are not clearly defined (like for ice skating)* (Xsens 2018*b*).

When comparing the two recordings in scenario *Single Level*, the following observations were made:

- The angle values were higher after being reprocessed in HD. However, some angles have increased more than others (the increase is not proportional when reprocessing the original values to HD).
- The angle values for the five different positions differed a little less when reprocessed in HD for each TP.
- The shape of the curves were basically the same after reprocessing in HD.

When comparing the two recordings in HD, the following observations were made:

- The angle values were generally lower after changing scenario from *Single Level* to *No Level* for each TP.
- The angle values for the five different positions differed approximately the same after changing scenario.
- The shape of the curve was more affected by the change of scenario than it was by the increase of the quality level (HD). For instance, for TP4, TP6, TP8 and TP9, one can see that in the position "Hardseat 15N", the angle value for scenario *No Level* decreases and approaches the original value whereas in the position "Hardseat 15S", the angle value for scenario *Single Level* augments further than the angle value for scenario *No Level*.

Tilt Sensor

Table G.2: Mean angles values obtained in the x-axis and the y-axis

Mean angle values											
		Car 15N		Car 38N		Hardseat 15N		Hardseat 15S		Hardseat 38N	
TP	BMI	x	y	x	y	x	y	x	y	x	y
TP1	24,6	47,0°	-24,0°	38,5°	-29,9°	44,9°	-20,4°	34,2	-31,9°	35,4°	-33,0°
TP2	23,9	35,9°	-23,5°	35,3°	-28,1°	37,9°	-32,3°	23,6	-42,0°	33,9°	-35,4°
TP3	25,0	23,8°	-19,0°	33,5°	-39,6°	24,2°	-8,7°	37,7°	-22,7°	42,4°	-14,5°
TP4	25,8	51,8°	-4,4°	47,1°	-17,7°	52,8°	-4,0°	47,3°	-11,8°	46,7°	-15,6°
TP5	30,5			13,2°	-15,7°	21,1°	12,7°	27,2°	-16,1°	34,1°	-13,9°
TP6	33,6	4,2°	-22,3°	10,8°	-30,2°	12,6°	-23,7°	12,2°	-30,9°	19,2°	-28,6°
TP7	24,2	37,4°	-11,1°	29,9°	-35,7°	40,1°	-21,3°	30,6°	-37,7°	26,2°	-42,2°
TP8	23,1	38,5°	-9,5°	38,4°	-20,7°	37,7°	-8,8°	43,7°	-16,5°	49,9°	-16,8°
TP9	21,6	50,4°	-19,9°	42,2°	-25,3°	36,0°	-31,3°	24,4°	-40,7°	33,1°	-42,1°

Comparison between the systems
Table G.3 - G.6 showed the results from the comparison with exact values as well as the mean and SD.

Table G.3: Angles obtained for each position using the verification method (R) and the Xsens equipment (X) (Experiment 1 - first session)

Pelvic Angles						
	Hardseat 15N		Hardseat 15S		Hardseat 38N	
TP	R	X	R	X	R	X
TP3	59,5°	49,7°	37,6°	39,8°	50,2°	39,9°
TP4	66,3°	48,4°	51,0°	41,7°	47,6°	33,4°
TP5	61,3°	42,1°	44,6°	29,0°	44,8°	20,6°
TP6	66,8°	51,0°	52,4°	38,9°	55,8°	37,6°
TP7	59,6°	45,9°	40,3°	30,9°	35,8°	26,3°
TP8	58,2°	46,2°	36,6°	35,7°	36,4°	30,9°
TP9	34,4°	43,6°	20,2°	33,7°	23,4°	31,6°

Table G.4: Angles obtained for each position using the verification method (R) and the Xsens equipment (X) (Experiment 1 - second session)

Pelvic Angles						
	Hardseat 15N		Hardseat 15S		Hardseat 38	
TP	R	X	R	X	R	X
TP 1th round	45,1°	47,3°	25,3°	31,4°	24,5°	24,6°
TP 2nd round	49,0°	48,0°	30,3°	33,2°	24,2°	25,7°

Table G.5: The mean and SD of the pelvic angle for each position using the verification method and the Xsens equipment (Experiment 1 - first session)

		Verification	Xsens
15N	Mean	55,2°	46,7°
	SD	11,6°	3,2°
15S	Mean	37,3°	35,7°
	SD	11,2°	4,7°
38N	Mean	39,4°	31,3°
	SD	11,0°	6,4°

Table G.6: The mean of the pelvic angle for each position using the verification method and the Xsens equipment (Experiment 1 - second session)

		Verification	Xsens
15N	Mean	47,1°	47,6°
	SD	2,8°	0,5°
15S	Mean	27,8°	32,3°
	SD	3,8°	1,3°
38N	Mean	24,3°	25,2°
	SD	0,2°	0,8°