Numerical tools for comfort analyses of automotive seating

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Numerical tools for comfort analyses of automotive seating

PROEFSCHRIFT

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voor Michiel

voor mijn ouders en broer

Summary

Anno 2004, the majority of the people in the western society can afford to buy a car. Many factors play a role in the purchase of a new car, e.g. styling, safety, environment and driving preferences. Seating comfort is also an important issue. Manufacturers use comfort to distinguish their products from their competitors. The introduction of a new car seat or interior is both time consuming and costly: the process requires many prototypes, because the assessment of seating comfort is still mainly based on subjective measurements. In addition, more cars than ever are used professionally. The prolonged sitting in automotive conditions of professional drivers introduced new physical complaints, resulting in high social costs. However, the cause of these complaints is not well understood. The use of virtual testing tools can provide a partial solution for the above described problems. Computer models of human and seat will enable comfort analyses of prototypes in early stages of the design process. Thereby, the development time and costs can be reduced. Moreover, the models can provide insight in the mechanics in the human body due to the human–seat interaction in both static and dynamic conditions and allow investigations of parameters that are hard to measure or even not measurable in relation with (dis)comfort and physical complaints.

This research aims at the development of numerical tools that can be used for comfort analyses of automotive seats. In literature, relationships have been defined between comfort and objective parameters. Vertical vibrations and seat pressure distributions appear to be mechanical objective parameters that have been related to comfort. Currently, no numerical tools exist that enable analyses of these parameters. Therefore, this study has concentrated on the development of numerical tools suitable for analyses of human behaviour in vertical vibrations and analyses of the seat pressure distributions at the contact interface between human and seat.

Analyses of human behaviour in vertical vibrations require models of a human and a seat. The multi-body 50th percentile occupant model developed in MADYMO has been used because of its realistic geometric description of the outer surface and detailed spinal representation. A protocol has been defined for the

development of seat models using numerically efficient simulation techniques, which are preferred for the prolonged simulation times of vibration analyses. Experiments for determination of seat properties, required for the development and validation of the seat model, have been performed. For validation of the human model in vertical vibrations, volunteer experiments have been performed with a rigid seat and a standard car seat. Transmissibility of accelerations from floor to seat and human have been investigated in the frequency domain from 0-15 Hz. Comparison of data on the rigid seat and the standard car seat showed the large influence seat properties have on the human response to vertical vibrations. The human model showed realistic responses in both the rigid seat and standard car seat condition. Investigation of spinal loading at each vertebra level showed a large influence of the interaction between human back and seat back on the spinal shear and compressive forces.

For analyses of the seat pressure distribution at the contact interface between human and seat, a finite element (FE) model of the human buttocks has been developed. The model comprises a detailed geometric description of the skin, soft tissues and bony structures. The soft tissues have been lumped together; only the skin has been modelled separately. The bones have been assumed rigid. The hip-joints have been implemented to allow investigations on the influence of the hip angle on the contact interaction. The FE buttocks model allows analyses of parameters that are important in the human-seat contact interaction but are hard to measure, like the shear stresses at the contact interface and the stress distribution inside the human soft tissues under the bony structures. The FE buttocks model has been validated for static conditions based on volunteer experiments with a rigid and soft cushion. The FE buttocks model showed realistic responses in both the rigid and the soft cushion condition.

Both the human model and the FE buttocks model have been used in a sensitivity study. It has been evaluated whether the output of the models is sensitive to variations in seat parameters relevant for seat developers in the design process of new seats. The sensitivity study on vertical vibrations showed that the human model responses in vertical vibrations are sensitive to variations in cushion and suspension stiffness. The sensitivity study on seat pressure distributions showed that the cushion stiffness and thickness have a large influence on the human-seat contact interaction. Summarising, it can be concluded that both the human model and the FE buttocks model are rather promising tools for comfort analyses of automotive seating.

Samenvatting

Anno 2004 kan het overgrote deel van de westerse bevolking zich een auto veroorloven. Bij de aanschaf van een auto spelen verschillende factoren een rol, variërend van styling tot veiligheid, milieu en rijgedrag. Zitcomfort is ook een belangrijke factor. Autofabrikanten gebruiken comfort om hun eigen producten te onderscheiden van die van de concurrent. De introductie van een nieuwe autostoel is echter een tijdrovend en duur proces: comfort onderzoek bij nieuwe autostoelen is nog voornamelijk gebaseerd op subjectieve maatstaven, waardoor tijdens het proces veel prototypes gemaakt moeten worden. Daarnaast zijn ook meer mensen dan ooit voor hun beroep afhankelijk van een auto. Deze mensen zitten langdurig in dezelfde houding in een voertuig. Dit heeft geleid tot nieuwe lichamelijke problemen, die uitmondden in hoge sociale kosten, maar waarvan de oorzaak nog niet goed begrepen wordt. Het gebruik van virtual testing kan een deel van de oplossing zijn voor de hierboven beschreven problemen. Met behulp van computer modellen van mens en stoel kan in een vroeg stadium van het ontwerpproces een nieuw ontwerp getest worden op comfort. Hiermee kunnen de kosten en tijd van het ontwerpproces worden gereduceerd. Bovendien kunnen computermodellen, zowel in statische als dynamische condities, inzicht verschaffen in de reactie van het menselijk lichaam op de contact interactie tussen mens en stoel en analyses mogelijk maken van parameters, die niet of moeilijk experimenteel te meten zijn.

De doelstelling van dit onderzoek is de ontwikkeling van numerieke modellen die geschikt zijn voor comfort analyses van autostoelen. In de literatuur worden verticale trillingen en drukverdelingen beschreven als twee objectieve parameters die relateren aan comfort. Op dit moment bestaan er nog geen numerieke modellen die deze parameters kunnen voorspellen. Daarom richt dit onderzoek zich op de ontwikkeling van numerieke modellen die geschikt zijn voor analyses van de menselijke respons op verticale trillingen en analyses van de zitdrukverdelingen op het contactvlak tussen mens en stoel.

Voor analyses van de menselijke respons op verticale trillingen zijn een computer model van de mens en de stoel twee vereisten. Het multi-body mensmodel ontwikkeld in MADYMO is gebruikt vanwege de realistische oppervlakte beschrijving en gedetailleerde beschrijving van de wervelkolom. Een protocol is opgezet voor het ontwikkelen van stoel modellen gebruik makend van numeriek efficiënte technieken. Deze zijn zeer gewenst bij trillingsimulaties, die een lange simulatietijd vergen. Experimenten ter bepaling van de stoeleigenschappen, die nodig zijn bij de definitie van het stoelmodel, zijn uitgevoerd. Bij de validatie van het multi-body mensmodel voor verticale trillingen is gebruik gemaakt van vrijwilligersexperimenten met een starre stoel en een standaard autostoel. In deze experimenten is de overdracht van trillingen naar stoel en mens geanalyseerd in het frequentiedomein tussen 0-15 Hz. Vergelijking van de data uit beide experimenten laat de grote invloed zien die de stoeleigenschappen hebben op de reactie van de mens in verticale trillingen. Het mensmodel vertoont een realistische respons in zowel de conditie met de starre stoel als de conditie met de standaard autostoel. De interactie tussen rug en rugleuning heeft een grote invloed op de compressie- en afschuifkrachten in de wervelkolom.

Een eindige elementen model van het menselijk zitvlak is ontwikkeld om analyses van zitdrukverdelingen op het contactvlak tussen mens en stoel mogelijk te maken. De geometrie van de botten en zachte weefsels is gedetailleerd weergegeven. De zachte weefsels zijn samengevoegd, alleen de huid is apart gemodelleerd. De botten zijn star verondersteld. Definitie van heupgewrichten maakt het mogelijk het model te gebruiken voor analyses van de contactinteractie onder variërende heuphoeken. Het model maakt tevens studies mogelijk naar parameters die van belang zijn in het contact tussen mens en stoel, maar moeilijk te meten zijn; schuifspanningen op het contactoppervlak en spanningen in de zachte weefsels zijn hiervan twee voorbeelden. Het model is gevalideerd op basis van zitdrukverdelingen gemeten in vrijwilligersexperimenten op een harde en zachte ondergrond. Het model vertoont een realistische respons in zowel de conditie met de harde als de zachte ondergrond.

Zowel het multi-body mensmodel als het eindige-elementen-model van het zitvlak zijn gebruikt in een ontwerpstudie naar hun toepasbaarheid als ontwerp tools voor auto- en stoelfabrikanten in een vroeg stadium van het ontwerpproces. In de studie is gekeken of de uitvoer van de modellen gevoelig is voor variaties in stoelparameters die belangrijk zijn in dit ontwerp proces. De ontwerpstudie laat zien dat de stijfheden van kussen en stoelsuspensie een grote invloed hebben op de respons van het mensmodel in verticale trillingen. De contactinteractie tussen mensmodel en stoel blijkt erg afhankelijk te zijn van de dikte en de stijfheid van het kussen. Samenvattend kan geconcludeerd worden dat zowel het multi-body mensmodel als het eindige-elementen-model van het zitvlak veelbelovende hulpmiddelen zijn voor comfort analyses van autostoelen.

Contents

Chapter 1

Introduction

Today, the majority of the people in the western society can afford to buy a car. The purchase of a car is determined by various factors ranging from styling to safety and environment to driving preferences. Comfort of cars and car seats is becoming an increasingly important issue in the design of vehicles for professional use as well as for personal use. People using cars professionally, like drivers of taxis, trucks, busses and agricultural machines, often have to drive for prolonged periods leading to a range of physical complaints, such as low back pain due to fatigue and pain in the upper extremities (Boshuizen *et al.*, 1992; Bovenzi & Zaidini, 1992; Magnussen *et al.*, 1996). Low back pain is currently one of the most debilitating and costly problems in western society and the second leading cause of sick leave (World Health Organisation, 2000). For a large number of patients with low back pain, there is only fragmented knowledge and no effective hypothesis for the cause (World Health Organisation, 2000). Although the cause of these complaints is not well understood, they can have serious consequences for the patient's professional and personal life. In 1993, back disorders accounted for 27% of all non fatal occupant injuries and illnesses involving days away from work in the United States. Estimates of the total cost of low back pain to society in the USA in 1990 were between US$50 billion and US$100 billion per year (Centres for Disease Control and Prevention). The social costs for the society are increasing. Therefore, more comfortable and healthier seats are required to reduce these inconveniences.

Car manufacturers have to innovate their model designs to stay competitive. In recent years, comfort has become a major aspect by which car manufacturers can distinguish their products from their competitors. Until now the assessment of seating comfort is largely based on subjective measures: when a prototype of a new seat has been developed, a limited number of people is asked for their opinion about this new seat. A disadvantage of such measures is that the relationship with design parameters is often unclear. Furthermore, these subjective comfort measures can only be assessed once a prototype has been made. Prototype development and testing are both time consuming and costly, while short time to market and low costs are critical for the automotive industry.

The above described social and economical problems introduce a need for efficient methods and tools which support early automotive tests and, ultimately, reduce development times and associated costs. Virtual testing can be regarded as a partial solution for the above mentioned problems. In the early stages of the design process, a new design can be tested for its degree of comfort by computer simulations, which would reduce the amount of prototypes needed to introduce a new seat design. Moreover, virtual testing tools allow investigations of parameters that are hard to measure, such as intervertebral disc pressure or pressures in the human soft tissues of the buttocks, in relation with (dis)comfort and physical complaints.

For prediction of seating comfort by virtual testing, objective parameters are required. The discrepancy between the subjective feeling of comfort and the prediction of the comfort level of new designs by virtual testing needs to be resolved by relationships between that subjective feeling and objective parameters (Figure 1.1). These relationships between objective parameters and comfort can be obtained from volunteer experiments in which the volunteers are asked for their subjective sensation of comfort and at the same time objective parameters are measured (first step). These objective parameters can be predicted by virtual testing tools (second step). This study outlines the development and application of numerical tools that can be used for comfort analyses in the design phase of a new automotive seat. This study is based on the assumption that the objective parameters, that can be used to predict comfort, are known. For this, parameters that are described in literature are used.

In this chapter, the term comfort has been used several times. The meaning of comfort as described in literature is very broad with very diverse definitions. It is often not difficult for a person to describe whether a seat sits fine or not. However,

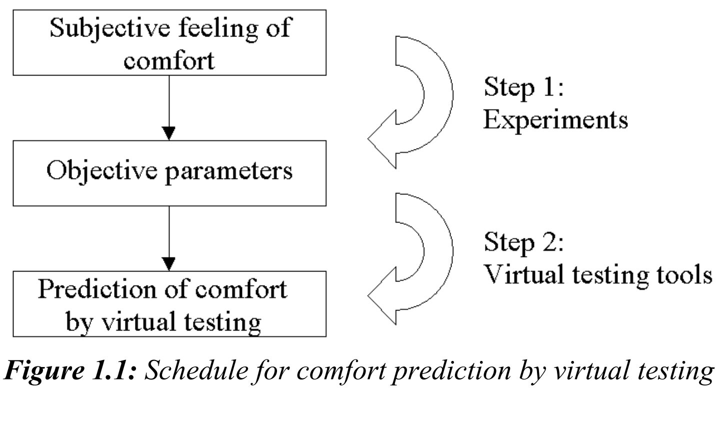


Figure 1.1: *Schedule for comfort prediction by virtual testing*

it is hard to define how or why something is comfortable. Hertzberg (1972) and Shen & Vértiz (1997) defined comfort by the absence of discomfort. Slater (1985) defined comfort by the state of pleasure influenced by psychological, physiological and physical factors. Some researchers go further: they state that comfort can be divided into levels and introduced comfort scales. Others state that comfort and discomfort may concern two sides of one scale, having various levels, not only for discomfort, but also for comfort (Delleman, 1999; Holmér *et al.,* 1995; Nilsson *et al.,* 1999; Park *et al.,* 1998). On the other hand, Zhang *et al.* (1996) and de Looze *et al.* (2003) state that comfort and discomfort may be associated with different factors and should be expressed on different scales. According to this definition, discomfort is underlied by physical factors. Exposure, dose and response are main factors. On the other hand, comfort concerns feelings of relaxation, pleasure and well-being. From this point of view it can be expected that the relationships between objective parameters with discomfort would be stronger than for comfort (first step Figure 1.1), as the link between discomfort and objective measures is more direct.

Therefore, there seems to be a diversity of views on comfort expressed in literature. One common view, however, is that comfort is a subjective parameter influenced by psychological, physiological and physical impressions of the environment on a person. In the present thesis, this has been the basic assumption when the term comfort is used. This definition of comfort suggests a number of contributory physical aspects like vision, noise, thermal factors, vibration, seating, and posture. In the current thesis, the focus is on mechanical parameters. Since these mechanical parameters are more related to discomfort than to comfort (Zhang *et al.,* 1996; de Looze *et al.,* 2003), it basically means that in this thesis the development and application of numerical tools for investigation of *discomfort* are described.

For prediction of automotive seating (dis)comfort a human model and a seat model are needed. This thesis starts with a literature review on two topics. Firstly, the relationship between objective mechanical parameters and the subjective feeling of comfort is discussed. Secondly, a review is given of published human body models. The choice of the human model used in this study is based on its suitability for (dis)comfort analyses. A search in literature for papers on seat models showed that hardly any have been reported on this topic. For that reason, no review is provided on this topic.

1.1 Literature review on objective parameters relating to comfort

There are a number of objective parameters relating to the subjective parameter of (dis)comfort in automotive conditions. This review is focused only on the mechanical parameters: pressure distributions, EMG, vibrations, posture and body motion and seat properties.

With respect to the subjective parameters, it should be noted that most studies treat comfort and discomfort as one variable on one scale from extreme comfort to extreme discomfort. Some studies do not make a distinction between discomfort and comfort at all. Due to this, in some cases the authors use 'comfort' while discomfort has been investigated. In this literature review studies are included investigating relations between objective parameters and both comfort and discomfort.

1.1.1 Pressure distribution

The contact interaction between the human body and the seat is one of the factors influencing the sensation of (dis)comfort for a subject. Measurement of pressure distributions is a means to express the stresses acting at the contact interface between the human and the seat.

Several studies have examined the relationship between (dis)comfort and pressure distributions. The studies vary in experimental set-up. The distinction between static and dynamic conditions is a first variable between the studies. Most studies describe static conditions (Kamijo *et al.*, 1982; Reed *et al.*, 1991; Yun *et al.*, 1992; Lee & Ferraiulo, 1993; Zhao *et al.*, 1994; Thakurta *et al.*, 1995; Porter *et al.*, 1997; Park *et al.*, 1997, 1998; Gyi *et al.*, 1999; Bubb *et al.*, 2000; Milivojevich *et al.*, 2000; Tewari *et al.*, 2000; Ebe *et al.*, 2001). Only a few studies involved dynamic conditions (Inagaki *et al.*, 2000; Uenishi *et al.*, 2000).

A second difference between the literature studies, is the ability for volunteers to adapt the seat to a preferred position. In the studies in which the experimental subjects were requested to sit in a driver's position, they were free to adapt the seat in their most optimal position (Reed *et al.*, 1991; Yun *et al.*, 1992; Lee & Ferraiulo, 1993; Porter *et al.*, 1997; Park *et al.*, 1997, 1998; Bubb *et al.*, 2000; Inagaki *et al.*, 2000). In the other studies, comparing several seats in a laboratory environment, this aspect was not considered (Kamijo *et al.*, 1982; Zhao *et al.*, 1994; Milivojevich *et al.*, 2000; Tewari *et al.*, 2000; Uenishi *et al.*, 2000).

In most studies, a relationship was established between (dis)comfort and seat pressure distributions (Kamijo *et al.*, 1982; Reed *et al.*, 1991; Yun *et al.*, 1992; Zhao *et al.*, 1994; Thakurta *et al.*, 1995; Park *et al.,* 1997, 1998; Inagaki *et al.*, 2000; Milivojevich *et al.*, 2000; Tewari *et al.*, 2000; Uenishi *et al.,* 2000; Ebe *et al.*, 2001). By contrast, the studies of Lee & Ferraiulo (1993), Porter *et al.* (1997), Gyi *et al.* (1999) and Bubb *et al.* (2000), who all measured discomfort in the subjective evaluation, did not report any relationship. Bubb *et al.* (2000) suggest that the measured values in the pressure distributions were too low to cause any discomfort feeling.

Parameters within the seat pressure distribution correlating to (dis)comfort in static conditions are:

- average pressure (Yun *et al.*, 1992; Park *et al.*, 1997, 1998; Tewari *et al.*, 2000)
- maximum pressure (Zhao *et al.*, 1994; Thakurta *et al.*, 1995; Ebe *et al.*, 2001)
- symmetry of the distribution (Kamijo *et al.*, 1982; Park *et al.*, 1997, 1998)
- thigh pressure (Zhao *et al.*, 1994; Park *et al.*, 1997, 1998)
- lumbar pressure (Zhao *et al.*, 1994; Thakurta *et al.*, 1995)

For evaluation of pressure distributions in static conditions, Inagaki *et al.* (2000) introduced the seat compliance, a combination of seat deformation and pressure distribution, which they considered to correlate with comfort. In dynamic conditions, Inagaki *et al.* (2000) established an association between the hold feeling, defined as the pressure distribution as a function of time and comfort. Uenishi *et al.* (2000) found a relationship between comfort and the root mean square of the pressure change rate.

1.1.2 EMG

Several studies regarded muscle fatigue as an important factor in the (dis)comfort sensation of subjects during driving manoeuvres. EMG is a way to measure the muscle activity during driving. The studies of Lee & Ferraiulo (1993), Reed *et al.* (1991) and Inagaki *et al.* (2000) focus on the relationship between (dis)comfort and EMG. Reed *et al.* (1991) investigated the relationship between seat design factors and long time driver (dis)comfort using EMG. EMG of muscles in the lower back and abdomen region was measured. They concluded that EMG was not suitable for (dis)comfort analysis. Lee & Ferraiulo (1993) investigated the relationship between EMG and (dis)comfort by measurement of the maximum generated muscle activity of muscles in the neck, shoulder, legs and lower back. The correlation between EMG and (dis)comfort was too weak to be considered as a basis for design decisions and the authors concluded that more tests are needed to test any such relationship. Inagaki *et al.* (2000) evaluated the relationship between EMG activity in the lumbar spine and (dis)comfort for long time driving. The results showed a good relationship between EMG and the subjective feeling of (dis)comfort.

1.1.3 Posture and body motion

Only a few studies have investigated the relationship between (dis)comfort and posture (static conditions) or body motion (dynamic conditions). Reed *et al.* (1991) reported that posture tracking can be regarded as a good measure for (dis)comfort analysis. Judic *et al.* (1993) described limits for angles of least discomfort. These angles exclude movements where muscular or ligament pain or discomfort could quickly arise. Bubb *et al.* (2000) investigated the association between joint angles and discomfort, based on dynamic experiments for long time driving with a research car. An equation was presented describing the discomfort change over time in the back region. Lee *et al.* (1995) discussed several objective measures for seating (dis)comfort, including body motion, defined as the amount of times a driver adjusts his/her position. However, Lee *et al.* (1995) raised doubts over the accuracy of the digital motion tracking systems.

1.1.4 Seat properties

Seat properties are assumed to have a large influence on the (dis)comfort feeling of a subject. No single property can be identified as the parameter relating to (dis)comfort, as reflected in the large number of seat parameters reported in the literature.

Kamijo *et al.* (1982) developed a method for objectively evaluating static and dynamic seating (dis)comfort. Static load/deflection characteristics and vibration characteristics were determined as objective parameters. Both the natural frequency and the static spring constant were revealed as useful objective measures for determining seating (dis)comfort. The authors concluded that the lower the natural frequency the higher the evaluation of vibration (dis)comfort. Relations between vibration comfort and the transmission ratio and vibration (dis)comfort and natural frequency were presented.

Gurram *et al.* (1997) performed dynamic experiments to investigate the relation between (dis)comfort and cushion stiffness. The subjects were seated with their hands on their laps and subjected to two random excitation levels by a hydraulic shaker. It was found that an increased stiffness of the cushion generally resulted in an increased (dis)comfort feeling.

Hughes *et al.* (1998) investigated the effects of regional seat compliance (the deformation level) and instantaneous stiffness (gradient in force-deflection characteristic of a seat) on the seat back (dis)comfort. The experiments included a test environment for static and transient conditions with each subject seated in the driving position. The study showed that the (dis)comfort feeling of the lumbar region correlates well with both the seat lumbar compliance and the seat lumbar stiffness. Moreover, the results showed that the amount and the stiffness of the lumbar support influence the perception of the overall seat back (dis)comfort.

Park *et al.* (1998) investigated the relationship between (dis)comfort and a range of physical parameters. Their analysis showed a statistically significant relationship between overall seating (dis)comfort and the deformation level of the seat back and seat cushion, dynamic spring constant and the hardness of the foam padding and seat back cover. The authors presented a regression equation describing this relationship.

1.1.5 Vibrations

In dynamic conditions the transfer of vibrations from seat to human is seat and car dependent. Dynamic parameters influence these transfers of accelerations, which affect the subjective perception of (dis)comfort. No studies have reported volunteer experiments on the influence of variations in seat parameters on the transmissibility of vertical vibrations from seat to human in relationship to (dis)comfort, although low back pain is often referred to in relationship to vertical vibrations (Hulshof & van Zanten, 1987; Griffin, 1990; Bovenzi & van Zanten, 1998). The International standard ISO 2631-1 (1997) combines the knowledge presented in literature on human behaviour in vertical vibrations in relation to (dis)comfort. It describes relationships between the loading, frequency and the maximum exposure limits for drivers. In addition, the vibration level is related to vibration sensation (discomfort) in this standard.

Most studies regarding vibration (dis)comfort are performed using lumped-mass models for investigation of seat parameters on transmission ratios. Only Kamijo *et al.* (1982), Gurram *et al.* (1997) and Park *et al.* (1998) performed an experimental analysis to establish any relationship between the subjective sensation of vibration (dis)comfort and critical dynamic parameters in vibrations. The influence of the vibration magnitude in this was not investigated.

1.1.6 Discussion

Table 1.1 provides an overview of the different objective measures for determination of (dis)comfort as described in the previous sections, highlighting the degree of correlation between the objective parameter and the subjective feeling of (dis)comfort.

Seat pressure distribution seems to be the objective parameter relating to (dis)comfort in quasi-static conditions. Most studies investigating this relation found a statistically significant relation. Average pressure, maximum pressure, the size and symmetry of the contact area are the parameters mostly reported in literature to relate to (dis)comfort. The studies that were not able to establish a relation, clearly described that they investigated discomfort as subjective rating. Probably, the measured pressures were too low to cause any discomfort feeling. For other objective parameters, like EMG, posture and body motion, the relation with (dis)comfort was less clear. Some studies found a relationship, but most of the studies failed to establish such a relationship. It seems that technical limitations associated with the current measuring systems (accuracy, sensitivity, resolution) restrict the application of these parameters as objective measures for (dis)comfort. These finding are confirmed by the literature review of de Looze *et al.* (2003) on the relationship between objective measures and (dis)comfort.

	Researchers	*Condition*	*Correlation subj/obj*	*Correlation coefficient*
Pressure distribution	Kamijo et al.(1982)	Static	Gen. trend	N/A
	Reed et al.(1991)	Static	Yes	N/A
	Yun et al. (1992)	Static	Yes	N/A
	Lee et al.(1993)	Static	No	N/A
	Zhao et al.(1994)	Static	Yes	0.79 – 0.95
	Thakurta et al. (1995)	Static	Yes	N/A
	Porter et al. (1997)	Static	No	N/A
	Park et al.(1997, 1998)	Static	Yes	0.62 – 0.97
	Bubb et al. (2000)	Static	No	N/A
	Inagaki et al.(2000)	Stat.+Dyn.	Yes	N/A
	Milvojevich et al.(2000)	Static	Yes	N/A
	Tewari et al. (2000)	Static	Yes	N/A
	Uenishi et al.(2000)	Stat.+Dyn.	Yes	N/A
	Ebe et al. (2001)	Static	Yes	N/A
EMG	Reed et al. (1991)	Static	No	N/A
	Lee et al.(1993)	Stat.+Dyn.	No	N/A
	Inagaki et al. (2000)	Long time	Yes	N/A
Body motion & subject posture	Reed et al. (1991)	Static	Yes	N/A
	Lee et al.(1993)	Stat.+Dyn.	No	N/A
	Bubb et al. (2000)	Dynamic	Yes	0.94-0.99
Static spring constant	Kamijo et al.(1982)	Static	Yes	0.65
	Park et al.(1997, 1998)	Static	No	N/A
Dynamic spring constant	Park et al. (1997, 1998)	Static	Yes	N/A
Damping ratio	Park et al. (1997, 1998)	Static	No	N/A
Force-deflection	Gurram et al.(1997)	Dynamic	Gen. trend	N/A
	Park et al. (1997, 1998)	Static	Yes	0.89
	Inagaki et al. (2000)	Static	Yes	N/A
Natural frequency	Kamijo et al.(1982)	Dynamic	Yes	0.71
Hardness foam padding	Park et al. (1997, 1998)	Static	Yes	0.73
Hardness seat cover	Park et al. (1997, 1998)	Static	Yes	0.80–0.85
Lumbar prominence	Hughes et al.(1998)	Static Transient	Yes	N/A
Regional compliance	Hughes et al. (1998)	Static Transient	Yes	N/A
Regional instant stiffness	Hughes et al. (1998)	Static Transient	Yes	N/A

Table 1.1: *Overview of measures for comfort analyses (N/A: not available)*

For dynamic conditions applies that the subjective sensation of (dis)comfort is associated with vertical vibrations. The International Standards Organisation (ISO 2631-1, 1997) describes the relations between discomfort and the acceleration level a driver is subjected to. Further, relationships between vibrations and exposure time are described.

Both static and dynamic seat properties relate to (dis)comfort. Significant relationships with (dis)comfort have been established for static and dynamic spring constants and the cushion stiffness. These seat properties are also closely related to seat pressure distributions and human behaviour in vibrations: a change in these seat properties will directly affect the seat pressure distribution at the contact interface between human and seat or the way accelerations are transmitted from seat to human body in vertical vibrations. Also, variations in posture directly influence the seat pressure distributions at the human-seat contact interface or seat-to-human transmissibilities of accelerations in vertical vibrations. Body motion is generally determined by the standard deviation of the body pressure distribution.

Based on the findings described above, it can be concluded that human behaviour in vertical vibrations and seat pressure distributions are most clearly related to (dis)comfort. Therefore they are used in the current thesis. The parameters seat properties, posture and body motion are indirectly accounted for in this study by their influence on the seat pressure distributions and human behaviour in vertical vibrations.

1.2 Literature review on human body models

This section reviews the human models for virtual testing of automotive seating comfort, associated with objective measures of static and dynamic comfort. A wide range of human models has been developed for ergonomic packaging. Generally these models can be divided into kinematic models that focus on static postures, which do not accommodate force considerations, and dynamic models that account for internal and external forces. To date, these models have been mainly used in analyses of voluntary movements and impact situations.

1.2.1 Kinematic human models

Several kinematic human models have been described in literature (Table 1.2). Judic *et al.* (1993) represented the human body skeleton by a two dimensional system of eight articulated links. Postural constraints were used to define the position of the human body with respect to the elements of the vehicle, namely seat, steering wheel and pedals, and the reaction of the body on constraints of prolonged driving. Further, vehicle, driver and seat characteristics are also taken into account.

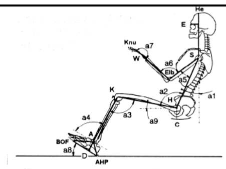
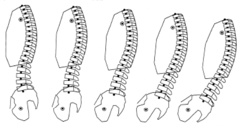
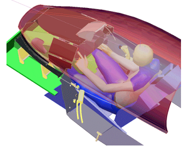
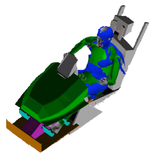
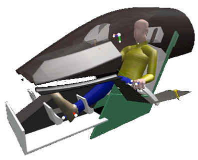
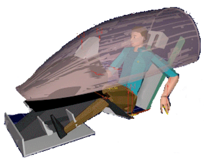
		Model characteristics	*Comfort tools*
Judic et al. (1993)		• 8 segments • Posture prediction based on postural constraints and seat characteristics	• Based on joint rotations (ranges of motion)
Reed et al. (1996)		• 18 segments • Posture prediction based on postural constraints	• Based on joint rotations (ranges of motion)
RAMSIS		• 91 segments (4 for spine) • Based on statistical analysis of results of mock-up experiments • Posture prediction by definition of constraints and H-point	• Based on joint rotations (ranges of motion)
BHMS		• 110 segments (17 for spine) • Posture prediction based on definition of constraints	• No comfort tool available
Safeworks		• 94 segments (17 for spine) • Posture prediction based on several points and definition of constraints	• Based on joint rotations (ranges of motions)
Jack		• 39 segments (17 for spine) • Posture prediction based on several points and constraints • Optimisation based on equilibrium	• Based on joint rotations (ranges of motions)
ERL		• 23 segments (17 for spine) • Posture prediction by design variables using optimisation techniques (body sizes: 5th, 50th, 95th percentile; postures: slumped, normal, erect) • Regression model for spinal curvature	• Based on joint rotations (ranges of motion)

Table 1.2: *Overview of the possibilities of kinematic human body models*

Reed *et al.* (1996) developed a kinematic model in which all spinal vertebrae were represented. The vertebrae were connected by revolute joints, allowing one rotational degree of freedom. The spine motion has been distributed over the lumbar spine and no thoracic spine mobility has been included. A validation was performed based on experimentally recorded postures. The model was still a two-dimensional model and based on a 50th percentile human male. Both the model from Judic *et al.* (1993) and Reed *et al.* (1996) allow a comfort analysis based on joint rotations.

RAMSIS (**R**echnergestutztes **A**nthropometerisches **M**athematisches **S**ystem zur **I**nsassen-**S**imulation), BHMS (**B**oeing **H**uman **M**odelling **S**ystem), Safework, Jack and ERL are commercially available ergonomic packages. In all packages a three dimensional human model can be defined and for a user-defined configuration, the most probable posture can be predicted.

The packages of RAMSIS, BHMS and Safework predict the most probable posture by definition of an H-point and postural constraints, sometimes in combination with seat and/or vehicle characteristics (ERL). The RAMSIS posture prediction is based on statistical analysis of results from mock-up experiments (Seidl, 1994). Jack and ERL use an optimisation technique for the posture prediction of the human body model. In ERL a regression model has been implemented for prediction of the spinal curvature.

In RAMSIS, the user can define a human model with any anthropometric characteristics he/she prefers. Similar applies for the human models in BHMS, Safeworks and Jack. In ERL, only three body sizes are available (5th, 50th and 95th percentile). The RAMSIS human models have a spine represented by 6 links. For all other human models applies that all vertebrae in the spine have been represented.

RAMSIS, Safework, Jack and ERL allow a comfort analysis based on joint rotations. BHMS does not.

1.2.2 Dynamic human models

The dynamic models can roughly be divided by lumped mass models, multi-body models and finite element models. Some packages allow a combined combination of multi-body and finite element techniques, most do not. Lumped mass models are usually one or two dimensional, multi-body models two or three dimensional and finite element model usually three dimensional.

1.2.2.1 Lumped mass models

Lumped mass models have been mainly used for analyses of human behaviour in vertical vibrations. The system is represented by one or more rigid elements often connected by mass-less elements, like springs and dampers. Zhao *et al.* (1994) studied the effects of dynamic parameters, such as eigenfrequency and damping ratio on frequency response characteristics of human-seat systems by means of a model with 3 degrees of freedom. This model reflects the frequency response characteristics of a human-seat system with real subjects sitting on a seat.

In a similar manner, Gurram *et al.* (1997) and Wu *et al.* (1999) used a lumped mass model to investigate the influence of seat cushion deflection on (dis)comfort and ride quality. The influence of the stiffness of the seat cushion on the occupant feeling, the influence of seat deflection on seat acceleration, and the influence of a non-linear stiffness on the natural frequency were determined. Amirouche *et al.* (1997) used lumped-mass models of the human and the seat to evaluate the behaviour of a seated subjected in vertical vibrations. Three seat models were developed to highlight the influence of a selection of seat design parameters on seat-to-human transmissibilities when subjected to a vertical input signal. Stiffness and damping coefficients were selected as variable parameters in order to minimise the transmissibility of the vibrations from floor to human body. Cho *et al.* (2000) determined the seat cushion properties based on a dynamic model with 9 degrees of freedom (DOF), representing seat and subject. Parameters such as mass, inertia and joint positions were validated with three experiments. According to the authors, the optimal seat properties are a result of the minimisation of the transmitted acceleration of floor, hip and seat back.

All lumped mass human body models mentioned have been validated for vertical vibrations based on experimental studies; the model seat-to-human transmissibilities have been compared with experimental values.

1.2.2.2 Multi-body models

In multi-body models elements in a chain can be connected by various joint types that constrain the number of degrees of freedom between the elements. The motion of the joint-connected elements in a multi-body model is caused by external forces generated, such as forces for accelerations, spring-damper elements, restraint models and contact models. Multi-body techniques also allow the definition of flexible bodies instead of rigid bodies. ALASKA, ADAMS and MADYMO are three examples of multi-body packages. In all packages, one or more human body models have been developed.

In ALASKA, a biomechanical human model has been developed (DYNAMICUS) allowing prediction of dynamic behaviour of a person whose size and posture has been modelled with RAMSIS (Jödicke, 2001). The human model contains 19 bodies, with 62 degrees of freedom. The human spine exists of three parts, while joints have been represented by ellipsoid-like forms. Ideal joints connect the bodies and ranges of motion have been based on Silva *et al.* (1997). Muscles have been implemented and elastic contact has been included to allow the interaction between human and seat. The use of wobbling masses, motion limits and damping is optional. Currently, no validation results of this model have been presented.

In ADAMS (Automatic Dynamic Analysis of Mechanical Systems) a FIGURE human modelling system is available (McGuan, 2001). The base human model (50^{th} percentile male) contains 15 bodies (head, neck, upper torso, middle torso, lower torso, upper and lower arms, upper and lower legs, feet) and 16 joints: detailed sub-models can be included. The human spine contains three bodies. The human model can be displayed as ellipsoids, skeletal or as a skin/clothed model. Interaction with the environment has been generated by ellipsoid-flat surface contact elements. The joints in the human model were three dimensional and created at anatomical locations. The forces in the joints might be passive or active. The segment mass properties and dimensions, joint stiffnesses, damping friction and limits were consistent with a Hybrid III crash dummy. Up till now, the model has not been validated for comfort applications.

In MADYMO, several multi-body occupant models have been developed (TNO Automotive, 2001); one of them is the 50^{th} percentile occupant model. This model was based on RAMSIS anthropometry. The human model consists of 92 bodies of rigid bodies connected by kinematic joints and the skin has been represented as a triangulated surface (triangular shells). All spinal and neck vertebrae have been represented by rigid bodies interconnected by spring-damper combinations. The surface description delivers a desired level of accuracy for the contact interaction with the seat. The model allows the inclusion of finite element parts in case of a detailed investigation on local mechanisms. The model has been validated for low and mid severity crash conditions (1-37 G).

1.2.2.3 Finite element models

The systems to be modelled in finite elements models, are divided in a number of finite volumes, surfaces or lines representing an assembly of finite elements. These elements are assumed to be interconnected at a discrete number of points: the nodes. In a displacements-based finite element formulation, the motion of the nodes within each finite element is defined as a function of the motion of the nodes. The stresses are derived from the deformations and the constitutive properties of the material modelled. ALASKA and PAM-CRASH are examples of finite element packages. MADYMO is a combined multi-body and finite element package. The human models developed by Hubbard et al. (1993), the CASIMIR model, ROBBY and the MADYMO finite element occupant model (van Hoof *et al.*, 2001) are examples of finite element human models.

Hubbard *et al.* (1993) developed a new 3D biomechanic computer model providing representations of human geometry and human movement. An average male (called JOHN), a small female (called JANE) and a large male (called JERRY) were developed. The models exist of the skull, the rib cage and the pelvis. These bodies have been represented as rigid structures and connected to each other by a flexible cervical and lumbar spine. Muscles have been incorporated in the legs, especially the gluteal, quadriceps and the calf muscles, and in the torso. The muscles between the back and the sides of the pelvis and the rib cage have been represented complemented by the major back muscles on either side of the spinal column. A thin layer acting as the skin covers the skeleton and muscles and represents the regional soft tissue thickness. In a subsequent article of the same group by Frost *et al.* (1997), a new back contour for all three models is presented for a variety of postures in the sagittal plane. The new contour had a solid object skin surface, based on a wireframe mesh from I-DEAS. This new contour was an anatomically more representative model of an undeflected contour. The human body models have been used for comfort analysis and for development of a new articulated seat for different body postures.

In ABAQUS, a dynamic finite element model of the sitting human has been developed (CASIMIR) that can be individualised to represent a specific person or a specific percentile group in a defined posture by its link to RAMSIS (Pankoke *et al.*, 2001). It has been based on human anatomy and its properties (inertia, stiffness, damping) were derived from experimental biomechanical data. The lumbar spine exists of rigid bodies connected by tangent stiffness matrices and discrete, frequency dependent dashpots. The remaining body has been represented by 9 rigid bodies. Further, a dynamic model of the viscera, back muscles and joints has been implemented. The outer surface (skin) has been roughly modelled. Pankoke *et al.* (2001) implemented a simplified linearised finite element model of the lumbar spine. The model has been verified for whole body human vibrational behaviour and showed reasonable correlation with experimental data.

In PAM-CRASH several finite element human models have been developed. The ROBBY model is a Human Articulated Rigid Body (HARB) representing a 50^{th} percentile occupant male. The model is built from rigid body segments that are linked together with non-linear joint elements. Each rigid body segment contains nodes of corresponding skeleton bones and the surrounding skin portions. The skin is modelled by shell elements. The model contains 15 segments (7 in the spine and neck). The masses, centres of gravity, principal axes of inertia and inertia moments, the joint locations and orientations, the joint ranges of motion and the mechanical resistances of motion have been derived from literature and anatomical text books. The model has been validated for crash applications. Recently, the ROBBY HARB model has appeared in ergonomic studies for the French military. No validation results have been presented up till now.

The finite element model developed in MADYMO (van Hoof *et al.*, 2001) has been based on the anthropometry of a 50^{th} percentile human male. The model has been specially developed for automotive applications. To ensure that all body parts, including the organs, were positioned correctly, the 50^{th} percentile male was digitised in a seated position. All major organs were included and contact interfaces were defined to represent the interaction of these organs with their environment. In the model, kinematic joints accommodated the articulations between various skeletal structures. The ranges of motion and resistance to motion in these joints were represented by non-linear stiffness and damping. The element size has been determined by a prescribed time step of 1 μs to ensure the industrial applicability of the model. The model has been validated in simulations of volunteer tests as well as PHMS impact tests.

The above described finite element human models are examples of full body human models. Several finite element models have been published focussing on a specific body part, so-called segment models. Brosh & Arcan (2000), Chow & Odell (1978), Dabnichki *et al.* (1994), Todd & Thacker (1994), Oomens *et al.* (2003) and Setyabudhy *et al.* (1997) developed finite element models of the human buttocks and/or thigh to investigate the interaction of human soft tissues with seats in relation with pressure sores. The models have in common that they have a simplified geometric description. Moens & Horvath (2002) developed a finite element model of the human buttocks for seat optimisation. None of these models have been validated for seat pressure distributions at the contact interface between human and seat.

1.2.3 Discussion

In the previous sections human body models have been described that have been or could be used for (dis)comfort analyses. As discussed in section 1.1.6, this thesis focuses on the development of human models that are able to predict seat pressure distributions at the contact interface between human and seat, and the human behaviour in vertical vibrations. Analyses of human behaviour in vertical vibrations is commonly based on investigations of the transfer of accelerations from seat to human and inside the human from pelvis to head. For that reason, realistic descriptions of translations and rotations of all spinal joints due to internal and external forces are required. A realistic description of the contact interaction between human and seat is also required to predict the transfer of accelerations from seat to human. Seat pressure distributions at the contact interface between human and seat usually show high stresses around the pelvic ischial tuberosities and lower stresses in the rest of the contact interface. Simulation of pressure distributions at the contact interface between human and seat requires a realistic description of the stresses and deformations acting at the contact interface. To enable the prediction of the stresses around the ischial tuberosities, a realistic geometric description of the pelvic bony structures and the soft tissues is required.

The above described requirements for the human model imply that kinematic human models, which focus on static postures and do not account for forces, are not suitable for this project and a dynamic model has to be used. The dynamic human models have been divided into lumped mass models, multi-body models and finite element human body models. Generally, it can be stated that lumped models are very useful for global analyses of human behaviour, but have a limited value for studies analysing e.g. spinal loading at vertebrae level or stresses at the contact interaction between human and seat.

Both multi-body human models and finite elements human models have their own advantages and disadvantages. Finite element models can accurately predict deformations but at high computational costs, while multi-body models can only globally describe the effects of deformations but with high computational efficiency. The multi-body technique enables the definition of rigid and flexible bodies. In MADYMO, for example, the deformations can be approximated through penetrations in the contact interfaces. The choice of which method to use is determined by the purpose of the study. In analyses of the human-seat interaction in (vertical) vibrations, the prolonged simulation times favour multi-body techniques. Analysis of the pressure distribution between human and seat requires an accurate prediction of the deformation of human and seat and, therefore, the finite element method has to be used.

In the selection of a human model to be used in this project, it is preferable to select a human model that satisfies both the requirements for the prediction of seat pressure distributions and seat-to-human transmissibilities in vertical behaviour. A simulation package allowing both the usage of multi-body techniques for vibration analyses and finite element techniques for seat pressure distribution analyses is preferred. Table 1.3 lists the described models with their advantages and disadvantages. Unfortunately, none of the described human body models already fulfils both requirements. The JOHN model of Hubbard *et al* (1993) is able to predict seat pressure distribution, but not suitable for analysis of human behaviour in vertical vibrations. While human models as DYNAMICUS (Jodicke, 2001), CASIMIR (Pankoke *et al.*, 2001), the ADAMS human model (McGuan, 2001) and the MADYMO multi-body occupant model (TNO Automotive, 2001) are able to predict human responses in vertical vibrations, they require adaptations for the prediction of seat pressure distributions.

The MADYMO-code has the best potential to fulfil the requirements for (dis)comfort prediction in future. In the code, both simulation techniques are available. For that reason, MADYMO has been selected as numerical simulation code for this project. The multi-body 50th percentile occupant model (TNO Automotive, 2001) forms a good basis for this study. This model is a whole body model, in contrast to the JOHN model from Hubbard *et al.* (1993). In the multi-body 50th percentile occupant model, all spinal vertebrae are represented enabling investigation of the loading in the whole spine in vertical vibrations. This is a main advantage over the other models that only contain a simplified representation of the

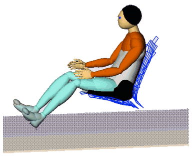
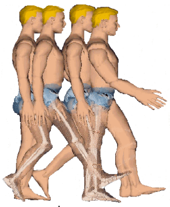
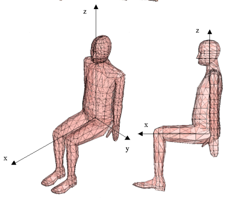
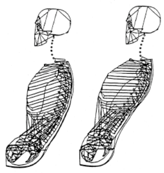
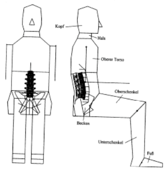
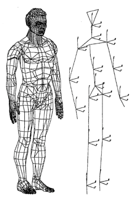
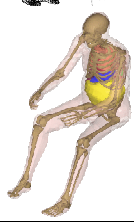
		Advantages	*Disadvantages*
ALASKA/ DYNAMICUS		• Suitable for analysis of human behaviour in vertical vibrations	• Human spine simplified represented • Skin roughly modelled
ADAMS/ FIGURE		• Suitable for analysis of human behaviour in vertical vibrations	• Human spine simplified represented • Skin roughly modelled • No finite element techniques
MADYMO/ 50th percentile male occupant model		• Suitable for analysis of human behaviour in vertical vibrations • All spinal and neck vertebrae included • Detailed surface description	• Lumped soft tissue properties • Finite element model of human buttocks has to be developed
Hubbard et al. (1993) & Frost et al. (1997)		• Suitable for prediction of back rest pressure distribution	• Rigid thorax • Rigid thoracic and cervical spine • Only a contour for back and thighs
ABAQUS/ CASIMIR		• Suitable for analysis of human behaviour in vertical vibrations	• Human thoracic spine simplified represented • Skin roughly modelled
PAMCRASH/ ROBBY		• Suitable for prediction of soft tissue deformation	• CPU time • No detailed spine model (7 segments)
MADYMO/ 50th percentile male finite element model		• Suitable for prediction of soft tissue deformation • Suitable for analysis of human behaviour in vertical vibrations	• CPU time • Mesh pelvis too rough for prediction of seat pressure distributions

***Table 1.3:** Overview of dynamic human body models for comfort prediction*

lumbar spine (DYNAMICUS, FIGURE), thorax (DYNAMICUS, CASIMIR and FIGURE) and neck (DYNAMICUS, CASIMIR and FIGURE). Further, the model has a realistic description of the outer contour, in contrast to DYNAMICUS, CASIMIR and FIGURE. Biofidelic translation and rotation characteristics have been included in the model allowing a vibration analysis. For prediction of seat pressure distributions, a finite element part of the human buttocks can be included in the base multi-body model.

1.3 Objectives

The previous sections showed there is a need to develop a numerical tool for (dis)comfort analyses of automotive seating. For this, objective parameters relating to (dis)comfort are required. The present study is limited to mechanical parameters, which have been adopted from literature. Section 1.1 showed that human behaviour in vertical vibrations and seat pressure distributions are the two objective mechanical factors most clearly relating to a subject's (dis)comfort sensation.

Currently, no human and seat models suitable for prediction of automotive seating comfort exist. This thesis concerns the development and application of human body models suitable for the prediction of human behaviour in vertical vibrations and seat pressure distributions. The objectives of this project are:

- The development and validation of a human body model that is suitable for realistic predictions of seat-to-human transmissibilities in vertical vibrations.
- The development and validation of a human buttocks model that is able to predict realistic seat pressure distributions at the contact interface between human and seat. It should be possible to include this model in the model validated for vertical vibrations.
- To evaluate the suitability of numerical human body and seat models in comfort analyses for seat designers in early stages of the development process of new car seats.

As described in Section 1.2.3, the objective on human behaviour in vertical vibrations favours a different simulation technique than the objective on seat pressure distributions. The prolonged simulation time of human behaviour in vertical vibrations, favours the usage of computationally efficient multi-body techniques. Therefore, for simulation of the human behaviour in vertical vibrations, the multi-body 50th percentile occupant model is used together with a multi-body seat model. For analyses of seat pressure distributions, realistic prediction of the deformations of the human soft tissues and the seat is required. Finite element techniques provide this, multi-body techniques do not. For that reason, a finite element model of the human buttocks is developed that is able to predict realistic deformation of the soft tissues. For prediction of realistic seat deformations, a finite element model of the seat is developed.

Figure 1.2 provides an overview of the strategy employed to achieve the objectives described above. For the realisation of the first two objectives, first a human model and a seat model have to be validated separately, before both models can be used in a combined simulation. More specifically, in case of analyses of human behaviour in vertical vibrations, a multi-body model of a standard car seat is developed and validated for its response based on experiments with a rigid loading device. The multi-body 50^{th} percentile occupant model is validated for its behaviour in vertical vibrations for rigid seat conditions. After the separate validation, the human model and the seat model are validated together for vertical vibrations with a standard car seat condition. Finally, the human model and the seat model are used in a sensitivity study on its suitability for seat designers in an early stage of the design process of new seats.

A similar approach is applied to realise the objective on prediction of seat pressure distributions. Firstly, the finite element model of the human buttocks region is validated for a rigid seat condition. A finite element seat model is first validated using rigid loading devices. Thereafter, the two models are combined in one simulation and validated for the prediction of seat pressure distributions on soft cushions. A sensitivity study has been performed to show the suitability of the models for prediction of seat pressure distributions at the contact interface between human and seat.

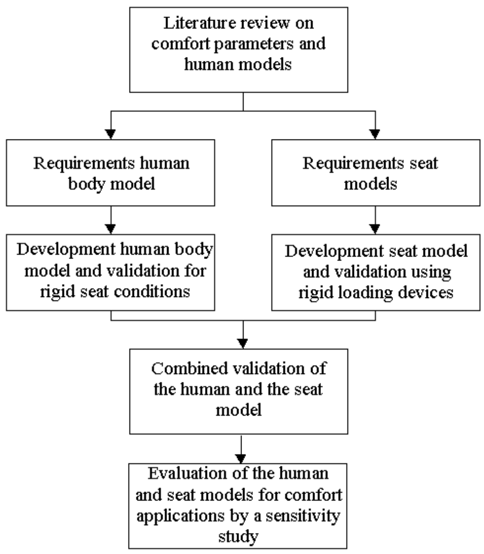


Figure 1.2: *Research strategy*

1.4 Thesis outline

Chapter 2-4 focus on the realisation of the objective on vertical vibrations. Chapter 2 concerns the development of a seat model for the analyses of human behaviour in vertical vibrations. A methodology based on multi-body techniques is outlined. Seat experiments are described providing the mechanical properties of several seat components. These data serve as input for the numerical seat models. This chapter includes the description of both methodology and seat experiments. The process is exemplified for one standard car seat. The chapter finishes with a validation of the seat model.

Chapter 3 describes the human behaviour in vertical vibrations based on volunteer experiments with a rigid seat and a standard car seat. These experiments have been used for the validation of the multi-body 50^{th} percentile male occupant model for its behaviour in vertical vibrations, as outlined in Chapter 4. In Chapter 4, first the model is validated for the rigid seat condition. Thereafter, the human model and the seat model, described in Chapter 2, are validated together for the standard car seat condition. Further, human spinal loading in vertical vibrations is estimated by numerical simulation for both the rigid seat and the standard car seat condition. The spinal local forces provide insight in the mechanics acting between vertebrae in the human spine when subjected to vertical vibrations.

Chapter 5 focuses on the realisation of the objective on seat pressure distributions. Chapter 5 deals with the prediction of seat pressure distributions. The development of a finite element model of the human buttocks is described. The buttocks model has been validated for static conditions using volunteer experiments. First, the cushion model is validated based on experiments with a rigid loading device, while the finite element model of the human buttocks is validated on rigid seat volunteer experiments. Thereafter, both models are validated together based on soft cushion volunteer experiments. A parameter study has been performed to investigate the influence of human soft tissue and seat cushion properties on human-seat interaction.

Chapter 6 focuses on the suitability of the numerical models, developed in the Chapters 2-5, for seat designers in an early stage of the design process. A sensitivity study is performed to investigate whether the models are able to predict the influence of variations in seat parameters, that are relevant for seat developers in the design phase of a new seat, on the human-seat interaction.

Finally, Chapter 7 includes discussions, conclusions and recommendations.

Chapter 2

Aspects of seat modelling for comfort analysis[1]

The development of more comfortable seats is an important issue in the automotive industry. However, the development of new car seats is very time-consuming and costly, since it is typically based on experimental evaluation using prototypes. Computer models simulating the human-seat interaction could accelerate this process. This chapter describes a protocol for the development of seat models using numerically efficient simulation techniques. The methodology has been outlined (Section 2.2) and experiments have been defined to characterise the mechanical properties required as input for the seat model for comfort applications (Section 2.3). The protocol is exemplified using a standard car seat. The validation of the seat model is discussed in Section 2.4 and 2.5. The presented seat model is used for vibration analyses in Chapter 4 in combination with the multi-body human model.

2.1 Introduction

Safety and comfort are two factors that seat and car manufacturers use to distinguish their products from their competitors. Its is well established that the mechanical properties and shape of the seat influence the head and torso movements in impact situations, especially in rear and side impact (Szabo *et al.*, 2002; Prasad *et al.*, 1997; Benson *et al.*, 1996; Warner *et al.*, 1991). These seat characteristics are also important in comfort analyses since they determine the contact interaction between human and seat, e.g. the transmission of accelerations from seat to driver (Amirouche *et al.,* 1997; Zhao *et al.*, 1994; Pope *et al.*, 1990) and pressure distributions at the contact interface between human and seat (e.g. Ebe *et al.*, 2001; Park *et al.*, 1998; Hughes *et al.*, 1998; Kamijo *et al.*, 1982). The

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[1] Adapted from: M.M. Verver, R. de Lange, J. van Hoof, J.S.H.M. Wismans, *Aspects of seat modelling for comfort analysis.* Submitted to Applied Ergonomics

development and design of new car seats and interiors is very time consuming and expensive, since this process is mainly based on trial and error using prototypes. The use of numerical seat models could accelerate this process.

Two types of modelling techniques can be considered for seat models involving multi-body and finite element analyses, each with their own advantages and disadvantages. Finite element models can accurately predict deformations but at high computational costs, while multi-body models can only globally describe the effects of deformations but with high computational efficiency. The multi-body technique enables the definition of rigid and flexible bodies. In MADYMO e.g., deformations are approximated through penetrations in the contact interfaces. The choice of which method to use is determined by the purpose of the study. In analyses of the human-seat interaction in (vertical) vibrations, the prolonged simulation times favour multi-body techniques (Chapter 4). Analysis of the pressure distribution between human and seat requires an accurate prediction of the deformation of human and seat and therefore the finite element method has to be used (Chapter 5).

In literature, few studies were found describing an approach for the development of a numerical model of a car seat. In published vibration analyses, the seat was often simply represented as a lumped mass model (Amirouche, 1997; Cho, 2000; Smith, 1997). These models enabled the prediction of impedance and the transmissibility from seat to head, but not the prediction of a realistic human-seat interaction. Van der Horst (2002) briefly described the seat models used in the study of human head neck responses in impact loading. Only multi-body techniques were used, but no validation of the seat model was presented. Marshall *et al.* (1999, 2000) described the usage of both multi-body and finite element techniques for the development of (crew) seats in aircrafts. Applications with large longitudinal accelerations were investigated with the model. The seat was mainly modelled by beams, only areas subjected to compressive loads by the occupant were modelled in detail with (reduced integration) shell elements for the seat base and (reduced integration volume) elements for the seat foam. Multi-body joints were used to connect the seat cushion and seat back to each other. No validation results of the seat model were presented. Kondo *et al.* (2002) used finite element techniques to develop a seat model with all parts represented separately: the frame by shell elements, the cover by membrane elements, the foam by volume elements and the springs by beam elements. No comprehensive validation results of the complete seat model were presented, only the foam model was validated. Further, the application of the seat model with a finite element model of the human in vertical vibrations was described, also without any validation.

This chapter describes a method for the development of efficient seat models. In a first approach only multi-body techniques have been used and the focus is on comfort applications. The simulations have been performed with the combined multi-body-FE code MADYMO. The set-up of the seat models in MADYMO, selection and experimental characterisation of seat properties are detailed, followed by a validation of the model. Finally, the resulting data is discussed and conclusions are drawn.

2.2 Methods

The seat model has been established from three bodies, i.e. seat cushion, seat back and head restraint. These bodies have been connected to each other by three joints: one for the connection between seat cushion and its surroundings, one for the connection between seat cushion and seat back, and one for the connection between seat back and head restraint. These joints allow adjustment in the seat back angle and head restraint angle, but, in addition, represent the stiffnesses of the connections between seat cushion - seat back and seat back - head restraint. The joint choice for the connection between seat cushion and its surroundings depends on the application of the seat model and is, therefore, arbitrarily set to a translational joint. The seat back and seat cushion have been connected to each other by a revolute joint to allow rotations around the y-axis. A similar connection applies between the seat back and the head restraint. In this seat model the height of the head rest can not be adapted. For seats that have an adaptive head restraint, this aspect can be included in the model by a definition of an extra translational joint.

The geometry of the seat has been accurately represented by arbitrary surfaces, involving triangular shells (TNO Automotive, 2001). The mesh was based on data points measured with the 3D measuring system. The data points were

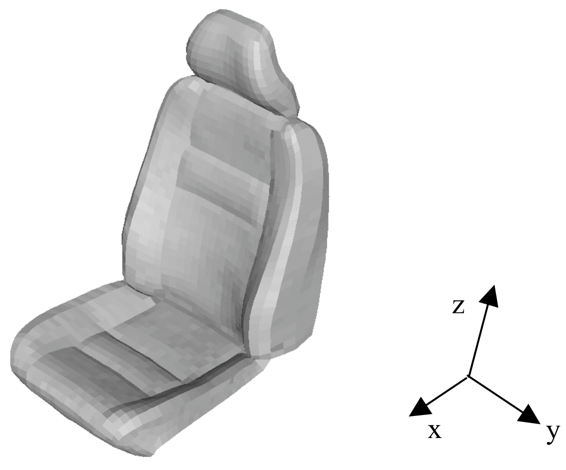


Figure 2.1*: The surface representation of the seat model*

measured every 2 centimetres while tracking over the outer surface and the joint locations were also measured. The mesh, generated in Hypermesh (Altair, 2002), is symmetrical with respect to the sagittal plane (Figure 2.1). Several sections have been defined: the seat cushion and the seat back consist of five parts: the seat cushion has been divided by the two wings, a front part, a mid part and a back part (Figure 2.2).

The seat back has been modelled in a similar way and exists of two wings, a lower part, a mid part and an upper part. The head restraint is also one section. Each part has it's own properties, specific for that location. The elements of the seat cushion have been attached to the seat cushion body, the elements of the seat back to the seat back body and the elements of the head restraint to the head restraint body. Two reference vertices have been added to define the location of the seat back joint and the head restraint joint.

The following properties are required as input for a multi-body seat model in MADYMO:

- Mass of head rest, seat back and seat cushion.
- Moments of inertia of head rest, seat back and seat cushion
- Location of the centre of gravity of the head rest, seat cushion and seat back

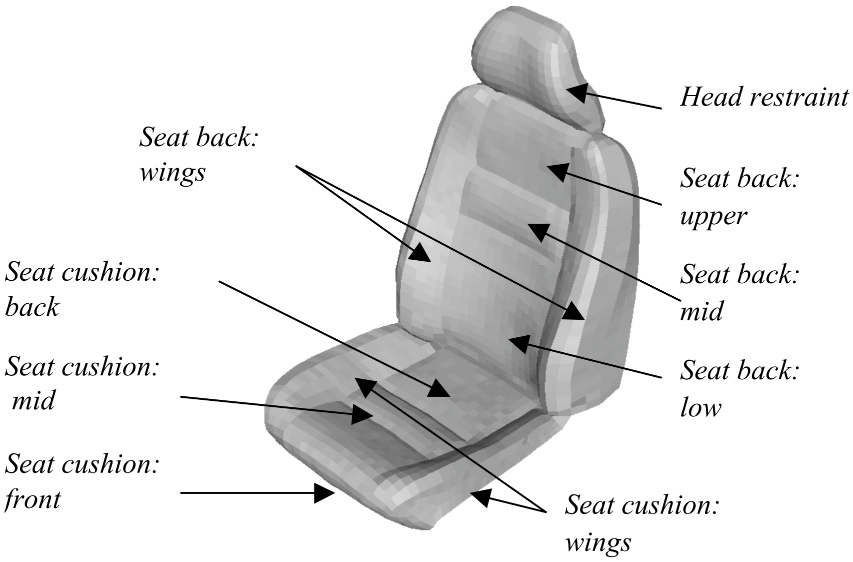


Figure 2.2: *Overview of the division of the seat in several parts*

- The lumped frame-foam-stiffnesses (loading and unloading) of the different parts in the seat cushion, seat back and head restraint
- The damping properties of the lumped frame and foam
- The joint properties (loading and unloading)
- Friction coefficient of the seat cushion and seat back

2.3 Determination of required input by experimental testing

This section describes the experiments performed to obtain the mechanical properties required as input for a multi-body seat model in MADYMO. The experiments can be divided in tests to determine the frame-foam properties, joint properties, friction coefficient and mass. In the experiments for determination of the frame-foam properties and the joint properties, the seat parts have been loaded up to a maximum force as defined by a realistic loading of that component. As the focus of these experiments was on comfort applications of the seat models, the experiments were performed at relatively low severity and velocity. It was also decided not to measure the velocity dependent behaviour of the lumped foam-frame properties, since the velocity-dependency of the foam at these low loading rates has been assumed to be negligible. Hysteresis has been included by measuring loading and unloading force-displacement functions. The locations of the body's centres of gravity and the moments of inertia have been defined approximately, since no major influence on the seat response characteristics was expected at the low loading rates applied.

2.3.1 Frame-foam properties

The seat was divided in the same sections as the model and all sections were tested separately. The parts of the seat cushion and seat back were loaded by a flat rectangular loading device, dimensions 150 x 150 mm, as illustrated in Figure 2.3a.

The head restraint was loaded by a half cylinder loading device representing the back of a head (Figure 2.3b). The loading devices were mounted on a hydraulic cylinder, the sample frequency was 10 Hz. The seats were loaded up to a maximum force of 500 N and then unloaded back to the starting position, which was close to the seat. As soon as the loading device contacted the seat, a trigger started the measurement of the applied force and the displacement of the loading device. All loading devices were positioned such that the contact area was as large as possible during the tests. In the experiments with the flat plate loading device (Figure 2.3a), the plate approached the seat part surface perpendicular. The velocity of the loading device was 0.90 mm/s. Some tests were performed twice to check reproducibility.

Flat plate loading device

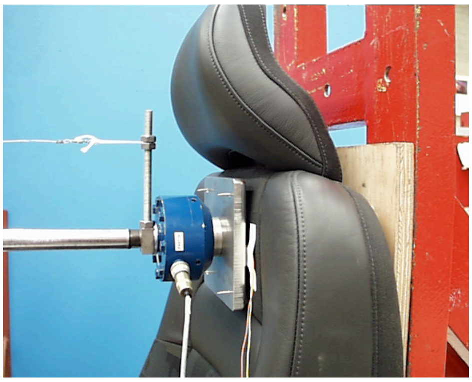
Half cylinder loading device

Wooden buttocks

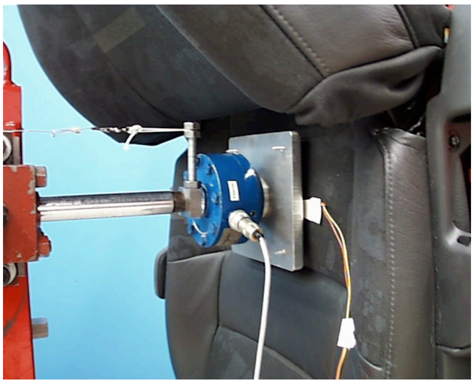
Wooden back

Friction test plate

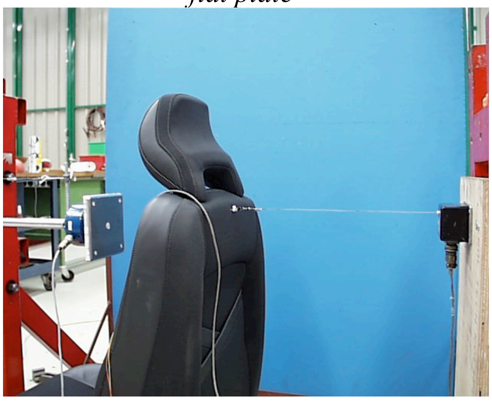
Figure 2.3: *Overview of the loading devices*



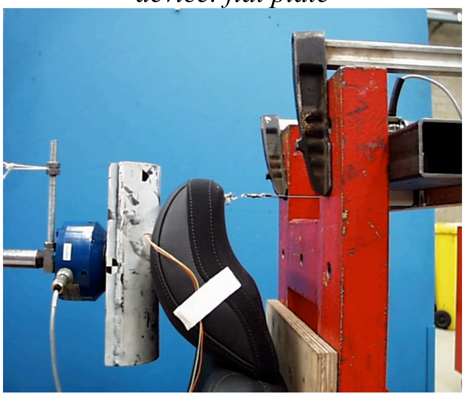
(a) Seat back – high; Loading device: flat plate



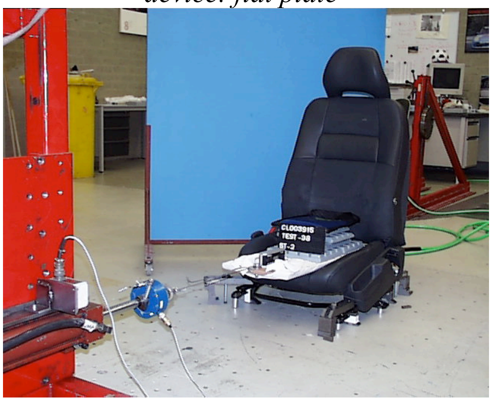
(b) Seat cushion – back; Loading device: flat plate



(c) Seat back recline joint; Loading device: flat plate



(d) Head restraint joint: Loading device: half cylinder



(e) Friction test seat cushion

Figure2.4: *Overview of the experiments performed to gain input for the numerical seat model*

For all seat back experiments, the seat was rigidly mounted. In the experiments performed to determine the lumped foam-frame stiffness properties (seat back low, mid, high and wings), the seat back was blocked by a wooden plate, such that no rotation was possible between seat cushion and seat back. Figure 2.4 provides an impression of the tests incorporating the range of the loading devices (Figure 2.3).

2.3.2 Joint properties

The properties of the joint between seat cushion and seat back were obtained by tests with the flat plate loading device mounted on the hydraulic cylinder (sample frequency 10 Hz). The seat was mounted on the floor and the seat back was free to rotate. The flat plate was positioned just in front of the seat back such that no initial penetrations occurred and the contact area would be as large as possible in the test. The seat back was loaded up to 750 N. This force was based on an assumption for realistic body masses and acceleration loading on the seat back (Figure 2.4c).

The properties of the joint between seat back and head restraint were obtained by tests with the half cylinder loading device. The seat back was locked and the head rest was free to rotate. The head restraint was loaded up to 500 N (Figure 2.4d).

2.3.3 Friction

The friction tests were performed with a flat plate (dimensions: 70x40 cm, radius edges 15 mm). This flat plate was covered with a piece of cotton to simulate the clothing worn by an occupant (Figure 2.3e). To investigate whether the friction coefficient was mass or/and velocity dependent, the tests were performed with different masses (24.2 kg, 35.2 kg, 62.2 kg, and 84.2 kg) and at two different velocities (0.9 mm/s, 8.0 mm/s). The mounting of the seat for the friction experiments was similar to the seat mounting in the test for determination of the seat back properties. Figure 4e provides an illustration of the experimental set-up associated with the friction tests.

2.3.4 Mass

The mass of the seat was determined by a balance. For that, the seat was divided into three components, namely, the seat cushion, the seat back and the head restraint. Since in the standard car seat, the head restraint could not be removed from the seat back, the masses of the seat back and head restraint have been added.

2.4 Set-up of seat model validation

The validation of the seat model was divided in two parts, a validation of the seat cushion and a validation of the seat back. The validation has been based on experiments with rigid loading devices with a more human-like geometry, namely a wooden buttock and a wooden back. The test conditions were similar to the experiments described above. The loading devices were mounted on a hydraulic cylinder (sample frequency 10 Hz) and positioned such that the contact area was maximal during the tests. The loading device velocity was 0.9 mm/s and the seat was loaded up to 1000 N. In the test with the wooden back, the seat back was not restrained (Figure 2.6 and 2.10).

The geometry of the wooden back and wooden buttocks was also measured with the 3D measuring system. Data points were collected every two centimetres and used to generate the mesh surface in Hypermesh. The mesh of the wooden back and wooden buttocks were symmetrical in the sagittal plane. In MADYMO the loading devices have been modelled as separate systems. This system contained three bodies to represent the hydraulic cylinder and the loading device combined: the base, the probe and the wooden back or buttocks. The base has been rigidly connected to the surroundings. The base and the probe have been connected to each other by a translational joint, which describes the displacement of the hydraulic cylinder. The connection between the probe and the loading device has been defined by a bracket joint that simulates the load cell in the experiment. In the simulation, the initial position of the loading device in the experiments has been approached as much as possible by comparing the initial positions in simulation and experiments using the pictures of experiments (Figure 2.7 and 2.11).

2.5 Results

In Section 2.5.1, the results of the experiments for the definition of the model input, as described in Section 2.3, are plotted. Section 2.5.2 presents the results of the validation for the seat cushion and the seat back, based on the experiments described in Section 2.4.

	m = 35.2 kg	m = 62.2 kg	m = 84.2 kg
v = 0.9 mm/s	0.4423	0.3217	0.4073
v = 8.0 mm/s	-	-	0.4605

Table 2.1: *The values of the friction coefficient at the various conditions*

	Mass kg)
Seat cushion	11.68
Seat back & head restraint	9.18

Table 2.2: *The masses of the seat components*

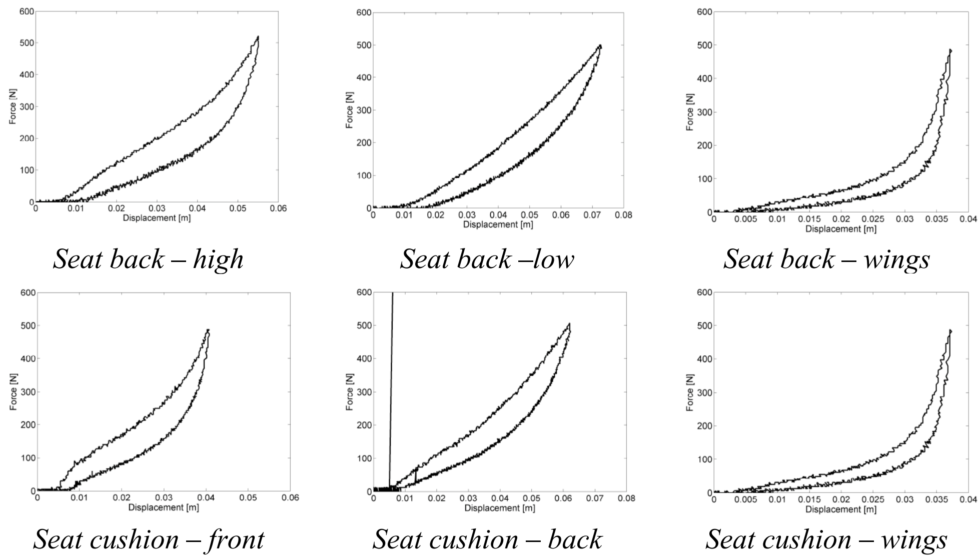


Figure 2.5: *The lumped frame-foam properties*

2.5.1 Experimental results for definition model input

Figure 2.5 shows the results of the experiments for determination of the lumped foam-frame properties (Section 2.3.1). The loading and unloading characteristic is plotted as a force-displacement relation. The properties for the seat back parts high, low and the wings and the seat cushion parts front, back and wings have been presented. The friction coefficients of the various tests, as described in Section 2.3.3, are listed in Table 2.1. Table 2.2 lists the mass of the various seat parts.

2.5.2 Results validation seat model

Figure 2.8 and 2.9 show the results of the validation of the seat cushion based on the wooden buttocks experiments. In Figure 2.8 the force through the loading device is plotted against time and in Figure 2.9, the force is plotted as function of the displacement. Both figures show that the numerical seat model approaches the seat characteristics, as derived from the experimental tests, well and that the maximum force is accurately described. The loading function approximates the experimental loading curve, whereas the unloading function shows small differences.

Figures 2.12 and 2.13 show the results of the validation of the seat back based on the wooden back experiment. In Figure 2.12 the force is plotted versus time and in Figure 2.13 the force is plotted as function of the displacement. The figures show that the model response approaches the experimental response well

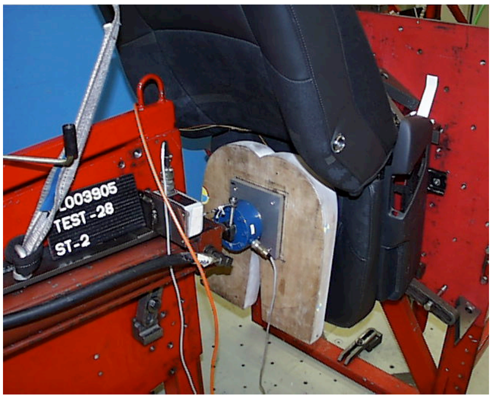


***Figure 2.6**: The initial position of the wooden buttocks in the experiment*

***Figure 2.7**: The initial position of the wooden buttocks in the simulation*

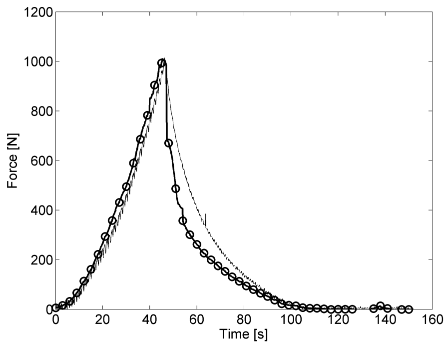


***Figure 2.8**: Validation of the seat cushion with the wooden buttocks as loading device (force-time response); (-) experimental results; (o) response seat model*

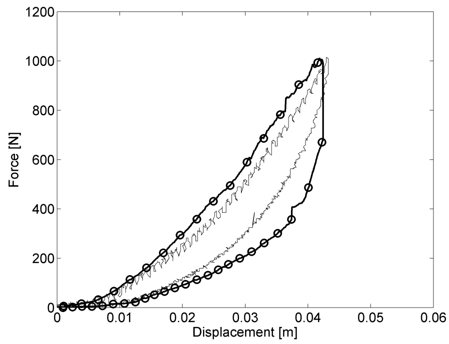


***Figure 2.9**: Validation of the seat cushion with the wooden buttocks as loading device (force-displacement response); (-) experimental results; (o) response seat model*

and that the maximum force is accurately predicted. The loading function increases at a slightly faster rate than the experimental loading function, but the unloading function approaches the experimental curve very well.

2.6 Discussion

This chapter describes a set-up for the development of seat models using multi-body techniques in MADYMO. The latest developments in multi-body techniques, like arbitrary surfaces, have been used. The methodology has been

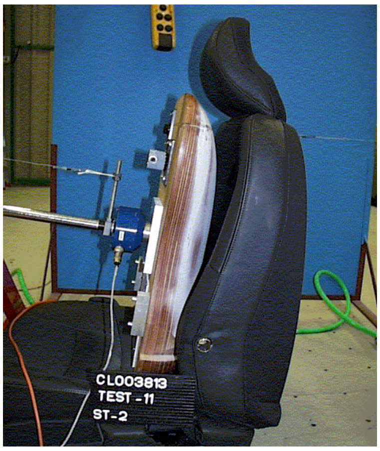


***Figure 2.10**: The initial position of the wooden back in the experiment*

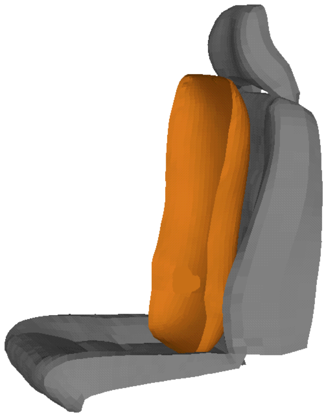


***Figure 2.11**: The initial position of the wooden back in the simulation*

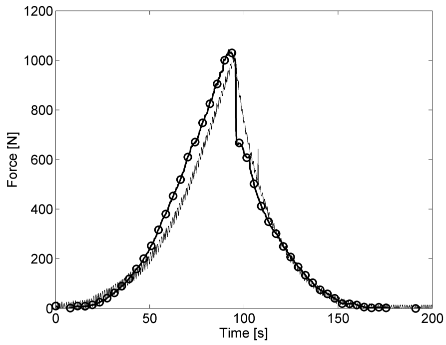


***Figure 2.12**: Validation of the seat back with the wooden back as loading device (force-time response); (-) experimental results; (o) response seat model*

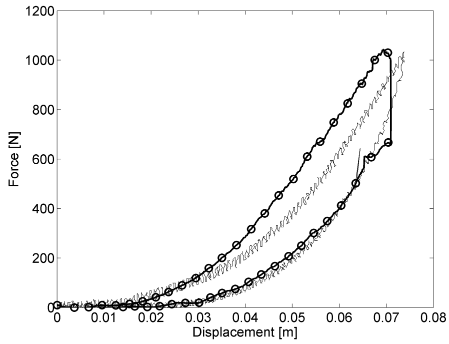


***Figure 2.13**: Validation of the seat back with the wooden back as loading device (force-displacement response); (-) experimental results; (o) response seat model*

outlined and required input parameters have been defined. Additionally, experiments have been described to determine the required model input parameters. For one specific seat, this whole process was evaluated through and the resulting seat model has been validated.

The validation of the seat model is based on low velocity tests using loading devices with human-like shapes. The response of the seat model agreed well with the experimental results. For the seat cushion simulation, the initial stiffness, as measured from the flat plate loading device tests, was found to too low for the simulation. The presented test methodology, during which the loading of one component of the seat would be influenced by the stiffness of the surrounding sections, normally over-estimates the total cushion stiffness. However, during the pushing of the buttocks in the seat, the buttocks reach the tubes underneath the seat, while the forces in the flat plate loading device tests were too small to reach these tubes. The influence of these tubes on the stiffness is larger than the over-estimation of the total stiffness by summation of the test results of the separate flat loading devices. And therefore, the summation of stiffnesses of the small plate loading devices is too small for the tests compared with the wooden buttocks loading device. Therefore the initial stiffness inputted in the model was increased, although the ratio of the stiffnesses of the front, mid and back parts of the cushions and the wings were kept constant. In the seat back simulation, the stiffness had to be slightly adapted, due to the over-estimation of the total stiffness by the sum of all flat plate loading devices. The ratio between the low, mid, high parts and the wings of the seat back were again kept constant.

This chapter describes the usage of multi-body techniques for the development of seat models. This method is an efficient way of seat modelling and very attractive for efficient parameter variation in an early stage of the design process and for simulations that require long simulation time, e.g. simulation of human behaviour in vertical vibrations. The next step in the process of development of seat models would be the usage of finite element techniques, since finite element seat models allow a more accurate simulation of the deformation of the seat components. Experiments for definition of the material properties would be required to develop an accurate finite element seat model. Main advantage of this method over the method presented in this chapter is that the problem described above, caused by the summation of properties of various seat parts, would be rectified. However, the CPU time of simulation with a finite element seat model increases drastically.

The focus of this chapter is on the development of seat models for comfort applications. The same methodology can be applied for development of seats for impact applications. However, seat models suitable for impact analyses require some other experimental input. This would involve implementation of velocity-dependent behaviour of the seat components and, therefore, associated experiments would be required to determine this behaviour. Further, a more accurate definition of the locations of the centres of gravity and inertia is necessary for the various components of the seat models (van der Horst, 2002).

2.7 Conclusions

A method for the development of numerically efficient seat models, applicable for usage in the development process of comfortable seats has been presented. Additionally, experiments providing appropriate input for the seat model have been described. As an example, the method has been evaluated for one standard car seat: a virtual model of this seat has been created containing the mechanical properties obtained from the real seat. The following can be concluded:

- A method has been outlined for the development of seat models, showing realistic prediction of the human-seat interaction, by usage of numerically efficient simulation techniques.
- The method proved to enable the prediction of realistic responses in human seat interaction: the model responses agree well with the results obtained from experiments at low velocity with human like loading devices on the real seat.

The usage of multi-body techniques for seat modelling is an efficient method in terms of computational time, for development of seats. This strongly affirms the proposition that seat models are attractive for parameter variation at an early stage of the design process. The presented method is attractive for simulations with long computational times, but that do not require a detailed analysis of deformations. In future, further development of seat models should focus on the usage of finite element techniques for prediction of seat component deformations.

Chapter 3

Human body resonance behaviour in vertical vibrations

ISO 2631-1 (1997) describes the relation between vertical vibrations measured at the human-seat contact interface and (dis)comfort. Vertical vibrations are also often considered to be related to low back pain. The causes of these low back pains are not well understood. However, they occur often and cause increasing social costs. This chapter investigates the human behaviour in vertical automotive vibrations and provides insight in the interaction between human and seat. The transfers of vibrations from seat to human body and inside the human body (from pelvis to head) are investigated experimentally. Human responses are separated from responses caused by seat parameters. The results of the experiments form the basis for the validation of the MADYMO human body model for vertical vibrations in Chapter 4.

3.1 Introduction

Complaints about pain in the lower back are quite common by professional drivers of trucks, buses and off-road vehicles. The social costs related to low back pain are increasing. Previous studies have shown a relation between exposure to whole-body vibration and low back pain (Bovenzi & Hulshof, 1998; Griffin, 1990; Hulshof & van Zanten, 1987). The cause of this low back pain is not well understood, but it is clear that a better understanding of the spinal movement in automotive vertical vibrations is necessary to solve this problem.

Literature reports several investigations on human responses in vertical vibrations. These analyses are commonly performed in the frequency domain. Some studies investigated impedance or apparent mass variation at various frequencies (Kitazaki & Griffin, 1995, 1997, 1998), where others focused on seat-to-human transmissibility (Griffin, 1990; Kitazaki & Griffin, 1998; Mansfield & Griffin, 2000; Panjabi *et al.*, 1986; Pope *et al.*, 1990; Zimmerman & Cook, 1997). The use of transfer functions is only allowed when the system of human and seat behaves in a linear manner. Several experimental studies showed a consistent pattern in human behaviour during vertical vibrations, but none reported a confirmation of linear behaviour. Griffin (1990) reported frequency response functions of seat to head. Mansfield & Griffin (2000) reported the ratio of responses at several places in the lower abdomen and the input signal, while Panjabi *et al.* (1986) reported a similar study investigating frequency response functions from seat to the sacrum and lumbar vertebrae. The ISO 5892 document (2001) presented ranges of idealised values to characterise seated-body biodynamic response under vertical vibrations; the seat-to-head transmissibility represented the ratio of acceleration transmitted to the head to the acceleration measured at the interface between human buttocks and seat. However, no studies to date have reported the response within the human body during vertical excitations. Investigation of the pelvis-to-head transmissibility, in addition to seat-to-human transmissibility, can help to separate mechanisms due to human responses like spinal movement from mechanisms caused by seat parameters.

Virtual testing is considered to be a tool that can provide insight in the mechanics acting in the human spine. Numerical biomechanical human models can help to explain forces and moments that act in the spinal column during various exposures. The combination of human models with seat models enables an investigation of the interaction between human and seat prior to production of a prototype seat. Validation of these human and seat models requires knowledge and experimental data of human response when exposed to vertical excitations.

This chapter investigates the human response in vertical vibrations based on frequency response functions. The frequency range in which the use of linear transfer function theory is allowed is determined. Resonance frequencies are studied in the linear domain. This study focuses of both seat-to-human transmissibility and the responses inside the human body by studying pelvis-to-head transmissibility. The influence of seat parameters on the human response is investigated by comparison of rigid seat experiments with standard car seat experiments. An analysis with analytical models is used to provide insight into the differential response between these seats.

3.2 Materials and methods

Experiments were performed at the Catholic University of Leuven (Belgium). Two types of seats were used, namely, a rigid seat and a standard car seat as illustrated in Figure 3.1. The rigid seat was used to gain insight in the behaviour of the human body in vertical vibrations without any influence of seat parameters. The standard car seat was used to investigate the influence of the seat parameters on the human vibrational response. The seat back and the seat panel of the rigid seat had an inclination with the vertical of 7.3° and an inclination with the horizontal of 9.8° respectively. The rigid seat had no head restraint included. In the experiments with the standard car seat, the angle of the seat back was set to 20° with respect to the vertical. In both experiments the same protocol was used.

The seats were mounted on an electro-hydraulic shaker with six degrees of freedom. This platform was excited by a continuous swept sine waveform applied in vertical direction. The frequency ranged from 0.5 Hz to 15 Hz as illustrated in Figure 3.2 with the input signal plotted in decibels. The acceleration varied over time with a r.m.s. of 2.35 m/s^2 and the peak acceleration of 0.4 G. At least five periods of the swept sine wave were recorded per experiment.

Linear accelerations were measured in the sagittal plane by linear accelerometers (Kistler 3803A/2G). Accelerations of the platform frame and between the seat cushion and the buttocks were recorded. The acceleration between seat cushion and buttocks was measured using a sitbar. For investigation of human behaviour, accelerations of the pelvis, T1 and head were measured. Pelvis accelerations were measured by accelerometers attached to a belt, which was tied such that they were positioned at the iliac wings. The T1-accelerometer was attached to the skin by elastic tape at the position of the spinous processes. Head accelerations were measured by accelerometers attached to a stiffened water polo cap which was tied around the head (Figure 3.1). In separate measurements the accelerometer mountings were evaluated. It was found that no resonance frequencies below 15 Hz were introduced by the mounting methods. The sample frequency was 200 Hz (the Nyquist frequency was 100 Hz). In a few studies in literature methods were proposed for correction of bone accelerations measured on the skin (Hinz *et al.*, 1988; Kitazaki &Griffin, 1995). However, there are no relevant international standards and therefore no correction method was employed in the present study.

(a) Rigid seat *(b) Standard car seat*

Figure 3.1: *Illustration of the experimental set-up: (a) rigid seat, (b) standard car seat*

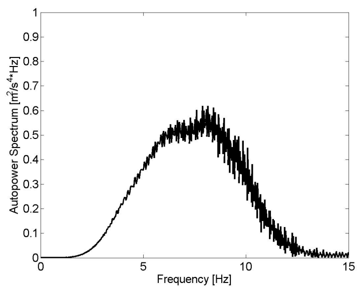


Figure 3.2: *The power spectral density of the vertical input acceleration of the seat.*

	Sex	*Body mass (kg)*	*Body height (cm)*
Subject 1	Female	57	169.5
Subject 2	Male	80	173
Subject 3	Male	68	178
Subject 4	Male	80	186
Subject 5	Male	71	174
Subject 6	Male	70	181
Subject 7	Male	80	187
Subject 8	Male	94	180
Subject 9	Male	80.5	187
Subject 10	Male	76.5	193
Subject 11	Male	75	182
Mean (±STD)	-	74.6 (±9.4)	181 (±7.1)

Table 3.1: *Anthropometric data of the volunteers*

Eleven healthy subjects participated in the experiment that was approved by the Ethics Committee of the Medical Faculty of the Catholic University of Leuven (Belgium). Before the experiments, anthropometric measurements of the volunteers were made including body weight and height, sitting height, head dimensions and chest dimensions, pelvis-knee and pelvis-heel distance. Only body mass and body length are listed in Table 3.1.

The subjects were not restrained. The volunteers were asked to sit relaxed and not to resist the vibrations. The initial posture was photographed (Figure 3.1) and the experiments were recorded on video. All volunteers participated in the experiments with both the rigid seat and the standard car seat.

3.3 Data analysis

The frequency response functions from seat to pelvis, T1 and head were calculated. Also the transmissibilities from pelvis to head were analysed. These transmissibilities were calculated using the cross spectral density method:

$$H_{io}(f) = \frac{G_{io}(f)}{G_{ii}(f)}$$

where $G_{io}(f)$ is the cross spectral density between the input acceleration (seat or pelvis) and the acceleration of the human body. $G_{ii}(f)$ is the power spectral density of the input acceleration (seat or pelvis). $G_{ii}(f)$ is defined by:

$$G_{ii}(f) = \int_{\tau=-\infty}^{\infty} R_{ii}(\tau) e^{-2\pi j f \tau} d\tau$$

with $R_{ii}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)x(t+\tau)dt$ the auto correlation function, with $x(t)$ the input signal in the time domain. The cross spectral density, $G_{io}(f)$, is defined by:

$$G_{io}(f) = \int_{\tau=-\infty}^{\infty} R_{io}(\tau)e^{-2\pi jf\tau}d\tau$$

with $R_{io}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)y(t+\tau)dt$ the cross correlation function, and $y(t)$ the output signal.

A limitation for the use of frequency response functions is that they can only be used for systems that behave linearly. To check the linear domain of the human-seat system under vertical vibration conditions, the coherence functions were calculated:

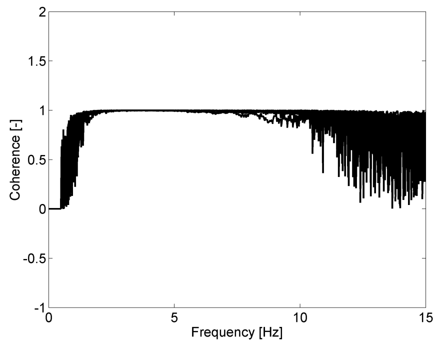
$$\gamma_{io}^{2}(f) = \frac{|G_{io}(f)|^2}{G_{ii}(f)G_{oo}(f)}$$

where $G_{oo}(f)$ is the power spectral density of the output acceleration. If a system behaves linearly and measurement noise is absent, the coherence function equals one. In literature, no coherency values are reported describing a limit above which a system can be regarded as linear. For that reason, in this study a value of 0.90 was used.

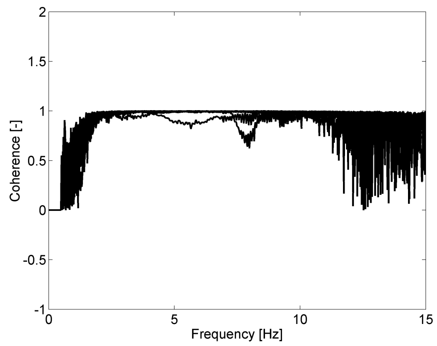
3.4 Experimental results

Figures 3.3 and 3.4 show the coherence functions relating to the frequency response functions from seat to human body for the rigid seat experiments and the standard car seat experiments. The graphs represent the pooled data for all experimental volunteers.

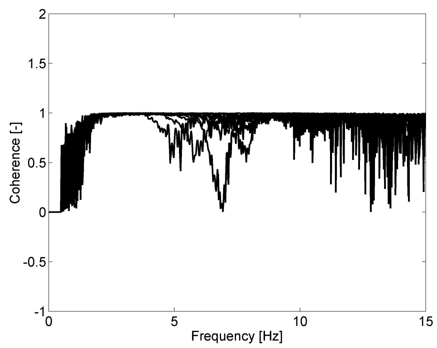
Though a large diversity was found between the different volunteers in the rigid seat experiments, the transfer of accelerations from seat to pelvis of most volunteers is linear from 2-10.5 Hz (Figure 3.3). For the volunteers seated on the standard seat linear behaviour is found between 2-10 Hz for the seat-to-pelvis transmissibility (Figure 3.4). For most volunteers, the transfers of accelerations from seat to T1 can be considered linear between 2–11 Hz for the volunteers seated on the rigid seat and for the standard seat experiments between 2-10 Hz. The transfer of accelerations from seat to head in the rigid seat experiments is linear at



(a) Seat to pelvis

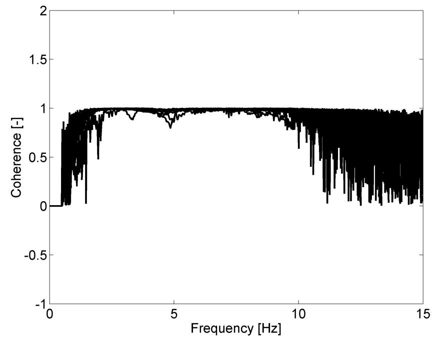


(b) Seat to T1

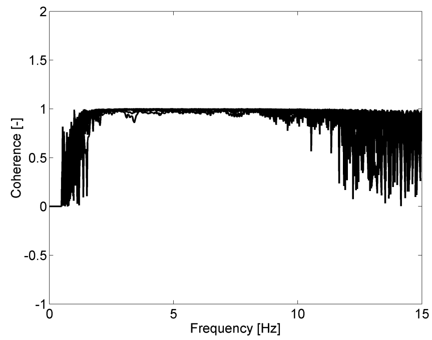


(c) Seat to head

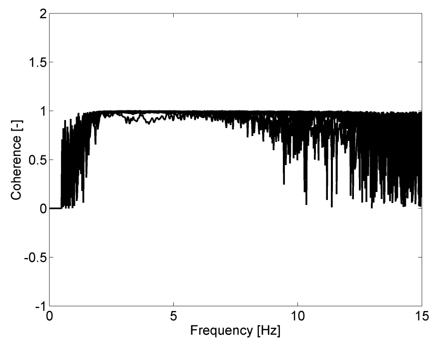
Figure 3.3: *Coherency function for the transfer of accelerations from seat to human body in the rigid seat experiments*



(a) Seat to pelvis

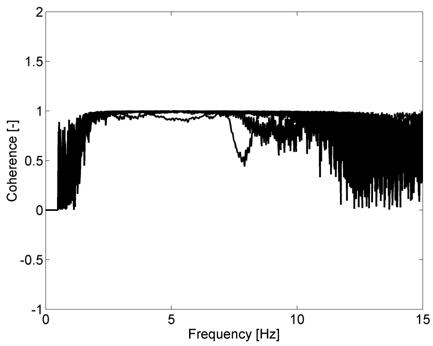


(b) Seat to T1

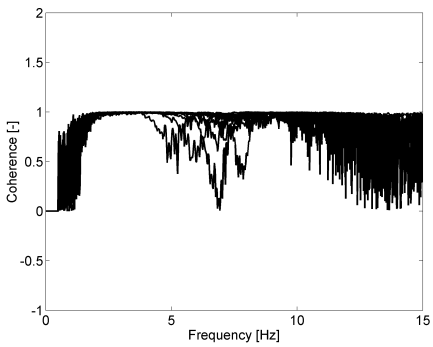


(c) Seat to head

Figure 3.4: *Coherency function for the transfer of accelerations from seat to human body in the standard seat experiments*

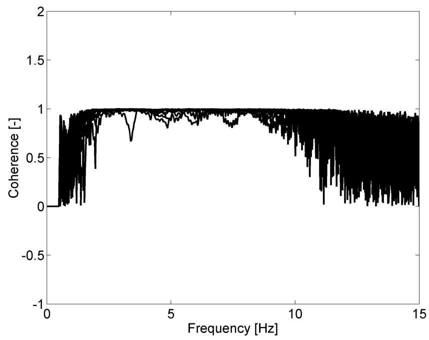


(a) Pelvis to T1

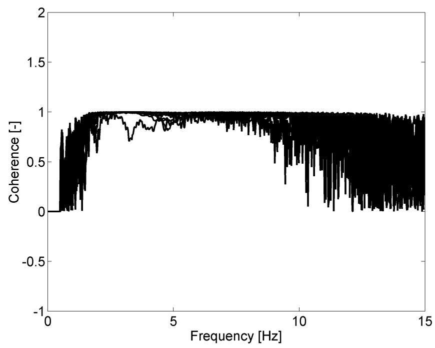


(b) Pelvis to head

Figure 3.5: *Coherency function for the transfer of accelerations in the human body in the rigid seat experiments*

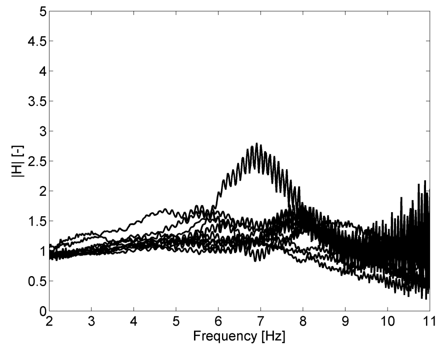


(a) Pelvis to T1

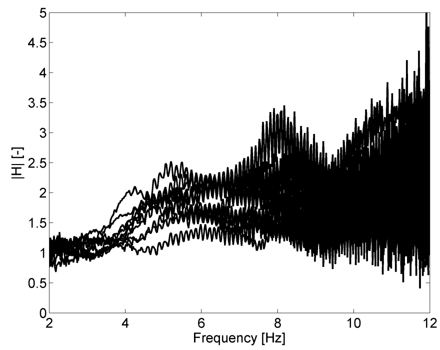


(b) Pelvis to head

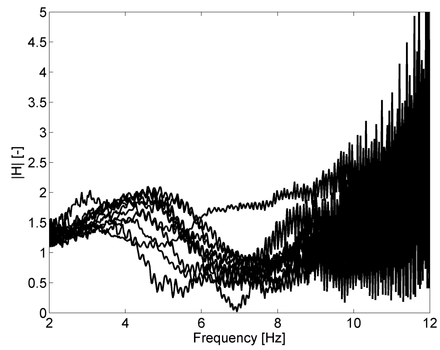
Figure 3.6: *Coherency function for the transfer of accelerations in the human body in the standard seat experiments*



(a) Seat to pelvis

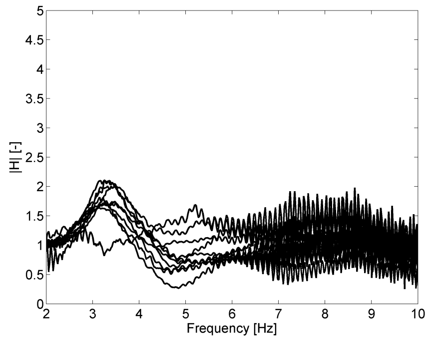


(b) Seat to T1

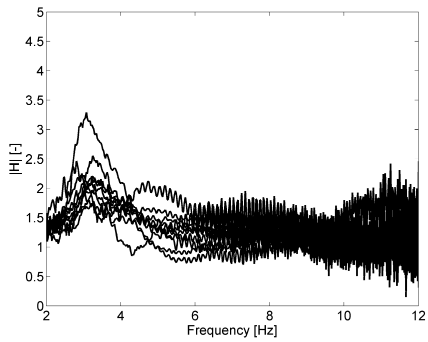


(c) Seat to head

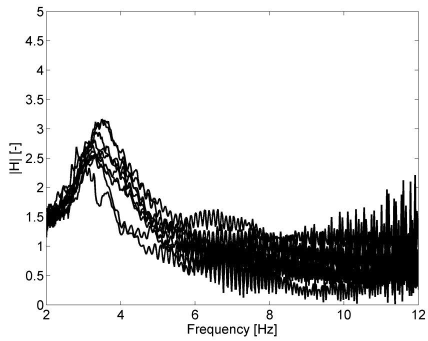
Figure 3.7*: Frequency response functions from seat to human body in the rigid seat experiments*



(a) Seat to pelvis

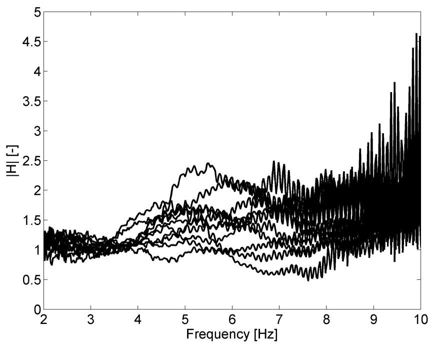


(b) Seat to T1

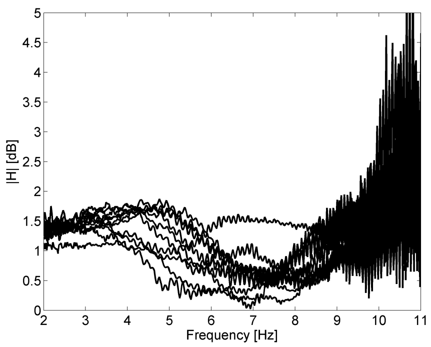


(c) Seat to head

Figure 3.8*: Frequency response functions from seat to human body in the standard seat experiments*

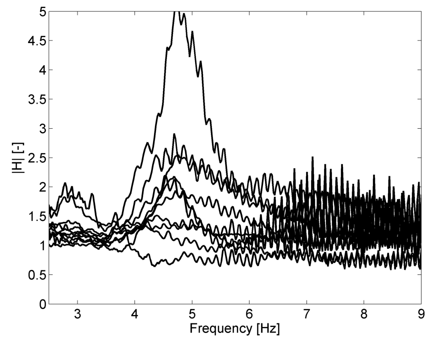


(a) Pelvis to T1

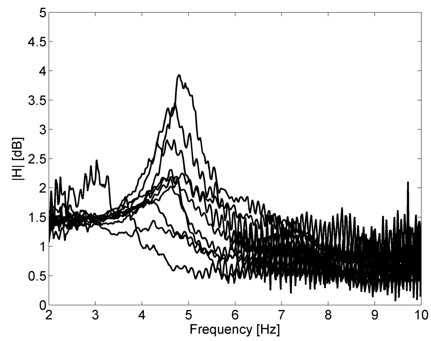


(b) Pelvis to head

Figure 3.9: *Frequency response functions inside the human body for the rigid seat experiments*



(a) Pelvis to T1



(b) Pelvis to head

Figure 3.10: *Frequency response functions inside the human body for the standard car seat experiments*

most frequencies between 2-10 Hz. Low coherence values appear between 5-8 Hz. The seat-to-head transmissibility in the standard car seat experiments shows linear behaviour from 2-9 Hz.

Figures 3.5 and 3.6 illustrate the coherence functions related to the transfer of accelerations from pelvis to T1 and pelvis to head on the rigid seat and the standard car seat, respectively. For most volunteers the transfer of accelerations from pelvis to T1 is linear from 2-10 Hz and 2.5-9 Hz on the rigid seat and the standard car seat, respectively. For volunteers seated on a rigid seat the transfer of accelerations from pelvis to head is linear between 2-5 and 8-11 Hz and for volunteers seated on a standard car seat between 2-9 Hz. Generally, the coherency values for the seat-to-T1 and seat-to-head transmissibilities in the rigid seat experiments are smaller than in the standard car seat experiments. The decrease of the coherence function between 5-8 Hz presumably acts inside in the human body: both the seat-to-head transmissibility (Figure 3.3c) in the rigid seat experiments and pelvis to head transmissibility (Figure 3.5b) depict the low coherency values between 4-8 Hz, while the seat-to-pelvis transmissibility (Figure 3.3a) does not show this.

Figures 3.7 and 3.8 indicate the absolute values of the frequency response functions from seat to human body within their linear domain. Like the coherency results, a large variability is found between the volunteers. Most frequency response functions from seat to pelvis for volunteers on the rigid seat have one resonance frequency between 4.5 and 9 Hz. On the standard car seat two resonance frequencies are found, at approximately 3.5 Hz and 8 Hz. The transfers of accelerations from seat to T1 in the rigid seat experiments do not show a clear resonance frequency, whereas the seat-to-T1 transmissibility of standard seat experiments has a resonance frequency at approximately 3 Hz (Figure 3.8b). The transfer of accelerations from seat to head in the rigid seat experiments shows two resonance frequencies at approximately 5 Hz and 12 Hz and for some volunteers an anti-resonance frequency in between 6-8.5 Hz. The standard seat experiments have one resonance frequency for the transfer of accelerations from seat to head at 3.5 Hz; after 5 Hz the transmissibility is very low.

Figures 3.9 and 3.10 depict the absolute values of the frequency response functions within the human body, from pelvis to T1 and from pelvis to head within their linear domain. The pelvis-to-T1 results of both seat experiments have a resonance frequency at approximately 5 Hz, although this is particularly marked with the standard car seat. The pelvis-to-head results show for the rigid seat experiments two resonance frequencies, namely at approximately 5 and 10-11 Hz. In the standard seat experiments just one resonance frequency is found, namely at 5 Hz.

Close examination of Figure 3.7-3.10 shows that the frequency response functions of the standard seat experiments seem to be mainly determined by the seat properties. Generally in the rigid seat more high frequencies are transmitted than in the standard car seat experiments. Indeed the frequency response functions relating to the standard car seat experiments depict low transmissibility above 5 Hz. Furthermore, all transmissibilities from seat to human body in the standard car seat experiments have a similar trend: a clear resonance frequency at 3.5 Hz. This 3.5 Hz resonance frequency does not appear inside the human body (Figure 3.10). In the rigid seat experiments the dynamics of the human body is most important. Indeed the rigid seat experiments do not show a similar trend in the seat-to-pelvis, seat-to-T1 and seat-to-head transmissibility. The seat-to-human transmissibilities are comparable with the pelvis-to-T1 and pelvis-to-head responses.

3.5 Analytical analysis of experimental results

The experimental work showed several differences between the frequency response functions in the rigid seat experiments and the standard car seat experiments. Investigation of Figure 3.7 and 3.8 showed that the standard car seat experiments resulted in a lower resonance frequency with a higher amplitude than the rigid seat. Analytical models of human and seat have been employed to explain the differences in frequency response functions between the rigid seat experiments and the standard car seat experiments.

Figure 3.11 shows the analytical model of the human on a rigid seat for analysis of transfer functions from seat to the pelvis. The human body is modelled as a single mass-spring-dashpot system, where, m_{sh} represents the mass of the shaker and seat and, m_p the mass of the pelvis and upper body. The stiffness and damping properties of the buttocks and upper legs are represented by k_p and c_p, respectively. The transfer function in the frequency domain of this system is determined by Laplace transformation of the equations of motions of each body. The transfer function of signals from the shaker and the rigid seat to the pelvis of the human body *$H_{rigid}(s)$* is:

$$H_{rigid}(s) = \left.\frac{X_p}{X_{sh}}(s)\right|_{rigid} = \frac{c_p \cdot s + k_p}{m_p \cdot s^2 + c_p \cdot s + k_p}$$

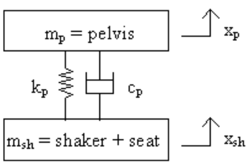


Figure 3.11: *Analytical model of the human body on a rigid seat*

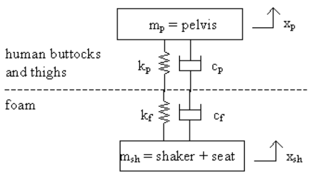


Figure 3.12: *Analytical model of the human body on a standard car seat*

	Parameter value	
m_p	75	kg
k_p	$1 \cdot 10^4$	N/m
k_f	$4.7 \cdot 10^3$	N/m
c_p	1000	N·s/m
c_f	200	N·s/m

Table 3.2: *Parameter values for analytical models*

Figure 3.12 depicts an analytical model of the human body on a standard car seat. The mass of the foam of the seat can be neglected when compared to the mass of the human body and the seat frame. The properties of the seat foam and the occupant buttocks and thighs are represented by springs and dashpots. The transfer function of signals from the standard car seat to pelvis of the human body $H_{standard}(s)$ is:

$$H_{standard}(s) = \left.\frac{X_p}{X_{sh}}(s)\right|_{standard} = \frac{c_{tot} \cdot s + k_{tot}}{m_p \cdot s^2 + c_{tot} \cdot s + k_{tot}}$$

with $k_{tot} = \dfrac{k_p \cdot k_f}{k_p + k_f}$ and $c_{tot} = \dfrac{c_p \cdot c_f}{c_p + c_f}$.

Realistic spring and damping properties are used (Table 3.2), based on mean values reported in literature (Cho *et al.*, 2000; Smith, 1997; Zhao *et al.*, 1994). In Figure 3.13 and 3.14 the absolute value of the analytical frequency response function in the rigid and the standard car seat situation are plotted. Both figures show that the general trend of the frequency response function predicted with the analytical model approaches that of the experimental data. The graph shows one resonance frequency at a low frequency with a peak value similar to the experimental values for both the rigid seat (Figure 3.7a) and the standard car seat experiments (Figure 3.8a). Comparison of both figures confirms the conclusions of the experimental data with reference to the influence of seat properties on the seat-to-human transmissibility. In particular, the model predicted a shift of the first resonance frequency in the seat-to-pelvis frequency response function to a lower

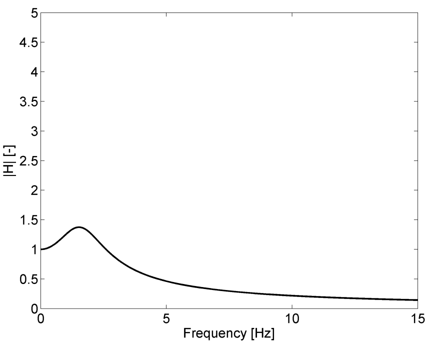


Figure 3.13: *Frequency response function from seat to pelvis of an analytical model of the human body on a rigid seat (see Figure 3.11)*

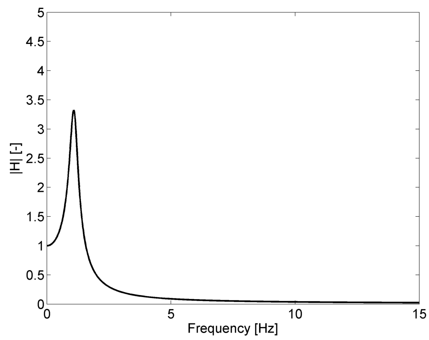


Figure 3.14: *Frequency response function from seat to pelvis of an analytical model of the human body on a standard car seat (see Figure 3.12)*

value in the standard car seat situation and an increasing peak value, which could be attributed to the soft properties of the standard car seat.

3.6 Discussion

The human behaviour in vertical vibrations has been investigated by transmissibility and non-linear behaviour. Previous studies reported in literature, only investigated the transfer of signals from seat to human. In this study human responses have been separated from influences of seat parameters by distinguishing seat-to-human transmissibility from the behaviour inside the human body, i.e. pelvis-to-head transmissibility.

The responses of the different volunteers show large variations. Other studies (Griffin, 1990; Hinz & Seidel, 1987; Mansfield & Griffin, 2000; Panjabi *et al.*, 1986) in which the transmisibilities of accelerations from seat to the human body are investigated show similar variations. These were mainly caused by differences in the initial posture and anthropometry: a small change in initial posture results in another transfer function (Griffin, 1990; Kitazaki & Griffin, 1998; Pope *et al.*, 1989; Zimmerman & Cook, 1997). Zimmerman and Cook (1997), Kitazaki and Griffin (1998) and Pope *et al.* (1989) reported on the influences of initial posture on the frequency response functions by changing the pelvis orientation and spine posture (erect versus relaxed) respectively. Griffin (1990) described that testing one volunteer several times did not result in equal responses. Hinz *et al.* (2001) doubted in their article to what extent mean values reflect individual patterns of biodynamics: the study showed that the maximum of the seat-to-head transmissibility and the frequency of its occurrence is influenced by the posture of a subject in a dominant way and shows an individual variability of considerable extent.

The present study shows small coherency values for seat-to-human transmissibility below 2 Hz and at frequencies higher than 10 Hz. Probably, the environmental disturbances were too large compared to the small input signal at these frequencies. The seat-to-head and pelvis-to-head frequency response functions show also small coherency values between 4-8 Hz in the rigid seat experiments. This effect could possibly be caused by mechanisms inside the human body or effects from the seat back (Figure 3.3a). The fact that also the frequency response function shows a decrease at these frequencies (Figure 3.7c) can be regarded as an indication for anti-resonances. Mansfield & Griffin (2000) reported non- linearities in the frequency range between 3-16 Hz. Their study focussed on an analysis of the apparent mass of a seated person and the transmission of vibrations to the abdominal wall, the lumbar spine and the pelvis. Kitazaki & Griffin (1998) report generally high coherence levels up to 10 Hz, but decreasing values after 10 Hz. In literature no study was found describing an investigation of coherency for frequency response functions inside the human body, from pelvis to T1 and pelvis to head.

In the present study clear resonance frequencies in all frequency response functions appear. Mansfield & Griffin (2000) reported transmissibilities from seat to the iliac crest of 12 subjects sitting unsupported on a platform. Their results showed a resonance frequency at 4 Hz and a larger peak at 8-9 Hz. The 8-9 Hz resonance frequency was also observed in this study, but the 4 Hz resonance was not found. However, due to differences in test conditions and anthropometry of the volunteers, a comparison between this study and the study of Mansfield & Griffin (2000) is hard. Mansfield & Griffin (2000) measured accelerations while the volunteers were not supported by a back rest. Further, the anthropometry of the volunteers participating in this study differs from the volunteer data of the Mansfield & Griffin (2000) study: average weight of the volunteers was 74.6 kg in the present study versus 68.3 kg in Mansfield & Griffin (2000).

No studies are found in literature reporting on seat-to-T1 transmissibility. Panjabi *et al.* (1986) reported only sacral and lumbar vertebral vertical ratios (i.e. vertical sacral or lumbar acceleration divided by the vertical input acceleration) for volunteers on a plywood seat without back rest. They attached accelerometers directly into the spinous processes. Panjabi *et al.* (1986) reported a resonance frequency of 4-5 Hz for both the transmission of acceleration to the sacrum and the lumbar vertebrae. Zimmerman & Cook (1997) published the transmissibilities from seat to trunk (T5): the results did not show a clear trend and the trunk transmissibility values remained relatively unchanged within various pelvic orientations. In this present study, no clear T1 resonance frequencies can be seen in the rigid seat experiments, while the standard car seat experiments show one at 3.5 Hz. Comparison of T1 transmissibility results presented in this paper with the results of the studies of Panjabi *et al.* (1986) and Zimmerman and Cook (1997) is difficult; the properties of the spine and the seat back influence the results too much.

A couple of studies in literature presented seat-to-head transmissibilities in rigid seat experiments. Griffin (1990) reported transmissibility of accelerations from input to head for 12 subjects using bite boards: he described resonance frequencies at approximately 5 and 12 Hz. Zimmerman & Cook (1997) reported also seat-to-head transmissibilities. They showed a clear resonance frequency at approximately 5 Hz, followed by decreasing values up to 10 Hz and after 10 Hz an increase in seat-to- head transmissibility. The present study shows similar results in the rigid seat experiments as Griffin (1990) and Zimmerman & Cook (1997): a

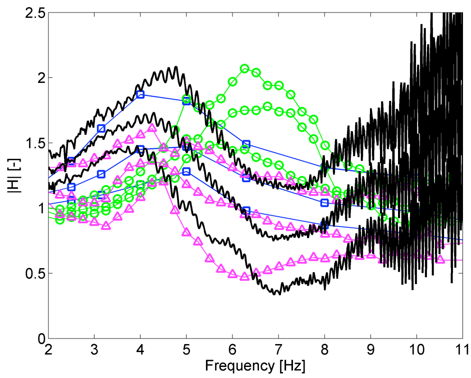


Figure 3.15: *The mean value and the mean value plus and minus the standard deviation of the seat-to-head transmissibility of present study (-) together with the results reported in Griffin (1990) (with backrest: o; without backrest: △) and ISO 5892 (2001) (□).*

resonance frequency at approximately 5 Hz and an increase in seat-to-head transmissibility after 10 Hz. In ISO 5892 (2001) seat-to-head transmissibilities have been described: corridors representing the upper and lower limiting values encompass the mean values of all the data sets selected. ISO 5892 (2001) described one resonance frequency in the seat-to-head transmissibility at 5 Hz. However, these values only apply for seated subjects in an erect seated posture without backrest. Figure 3.15 shows the mean value and the mean value plus and minus the standard deviation of the seat-to-head transmissibility of present study together with the results reported in Griffin (1990) and ISO 5892 (2001). It seems that the subjects did not or almost not use the back rest in the present study, since the data are almost similar with the results of ISO 5892 and the results of Griffin (1990), in which no backrest was used. Hinz & Seidel (1987) described seat-to-head and seat-to-trunk transmissibilities with a rigid but anatomically shaped seat. The seat-to-head and seat-to-trunk transmissibility both showed a resonance frequency at 4-5 Hz; at higher frequencies no amplification appeared any more. Due to the shaped form of the seat, the contact area between human and seat was larger than in the rigid seat experiments of the present study and so the results of the study of Hinz & Seidel (1987) approach the standard car seat experiments of the present study better.

Some studies found in literature (Kitazaki & Griffin, 1997, 1998) reported on the transmissibility of accelerations from seat to human trunk and head by means of the vibration mode shapes. These studies described a resonance frequency for the whole body at approximately 5 Hz. A second resonance frequency appeared at approximately 8-9 Hz which is contributed to pelvis rotation. These two principal resonance frequencies also appear in the pelvis and head signals of the present study.

In literature, no studies are found describing the frequency response functions within the human body, i.e. from pelvis to T1 and head, respectively. Therefore, it was not possible to compare the results of this study to others. This study shows clear resonance frequencies within the human body. The pelvis-to-head transmissibility shows resonance frequencies at 5 Hz and 10-11 Hz for volunteers sitting on the rigid seat and at 5 Hz for volunteers on the standard car seat. The pelvis-to-T1 transmissibility in the standard car seat experiments shows a resonance frequency at 5 Hz, but the rigid seat experiments do not show a clear resonance frequency.

This study also shows the large influence a seat can have on the vertical vibration of the human body when subjected to vertical excitations. Within the linear domain, the frequency response functions from pelvis to T1 and head differ between volunteers seated on a rigid seat and on a standard car seat. These differences can be caused by several aspects, such as posture, contact area and foam properties. The influence of posture was discussed before (Griffin, 1990; Kitazaki & Griffin, 1998; Pope et al, 1990; Zimmer & Cook, 1997). Generally, a more backward postures cause lower transmissbilities (Griffin, 1990). In the present study the peak values at the resonance frequencies of the standard car seat (more backward posture) are higher than the values of the rigid seat (upward posture). So, probably the frequency response function from seat to human body is more influenced by other factors, like e.g. the foam properties and contact area.

In literature, little is reported on the influence of seat properties on human behaviour during vertical vibrations. Only Pope *et al.* (1990) reported on this aspect: in a vertical impact the influences of three different foams (varying from hard to soft) on the transmissibility of accelerations from seat to lower lumbar vertebra L3 were investigated. Pope *et al.* (1990) showed in this study that the soft foams lower the first principal frequency and increase the gain at the first principal frequency. The present study shows a similar result: for all volunteers, the first principal resonance frequency appears at lower frequencies in the standard car seat experiments than in the rigid seat experiments and the gain values of the transfer functions at the first resonance frequency are larger in the standard seat experiments than in the rigid seat experiment.

The human-seat interaction is another aspect that can have a large influence on the seat-to-human transmissibilities. The interaction between human and seat is mainly determined by the contact area between human and seat. In explaining the effects of posture on seat-to-human transmissibilities, Kitazaki & Griffin (1998) referred to their previous work and a study by Payne & Band (1971), describing that an increase in contact area between e.g. buttocks and seat results in a decrease of the total axial stiffness under the pelvis due to the non-linear force-deflection relationship of the buttocks tissue. A more reclined posture increases the horizontal difference between the excitation point at the buttocks and the mass centre of the body. This increases the excitation moment and shear deformation of the buttocks tissue at the entire body mode, resulting in a decrease in the natural frequency with much lower shear stiffness of the tissue than the axial stiffness. The same theory can be used to explain the differences in transmissibilities inside the human when seated on the rigid seat and seated on the standard car seat. In the standard car seat experiments, the contact area between the buttocks and the seat is much larger than in the rigid seat experiments, which result in larger shear deformations of the buttocks tissue and a smaller first principal frequency. The present study does show this phenomenon. The standard car seat experiments show for all volunteers a first resonance frequency at lower frequencies than in the rigid seat experiments. Also the influence of the larger contact area between the human back and the seat back in the standard car seat experiments contributes to the differences between both experiments.

3.7 Conclusions

This chapter describes volunteer experiments to investigate human behaviour in vertical vibrations. The frequency range, in which the use of the linear transfer function theory is allowed, is determined. Resonance frequencies are studied in the linear domain. The experiments were performed on two seats, a rigid seat and a standard car seat, to investigate the influence of seat parameters. The transmissibility inside the human body, pelvis to T1 and head, is studied to separate human responses from responses influenced by seat parameters. The experimental frequency response functions are analysed with analytical models. The following can be concluded:

- Most frequency response functions show linear behaviour between 2 and 11 Hz. The low coherency of the seat-to-head transfer and pelvis-to-head transfer in the rigid seat experiments between 5-8 Hz combined with the small seat-to-head and pelvis-to-head transmissibility values indicate anti-resonances.
- The frequency response functions depict clear resonance frequencies, only frequency response functions from seat to T1 in the rigid seat experiments do not. The rigid seat experiments show a resonance frequency between 6-8 Hz for the seat-to-pelvis transmissibility and two resonance frequencies for the seat-to-head transmissibility at 5 and 12 Hz. In the standard car seat resonance frequencies at 3.5 and 8 Hz appear in the seat-to-pelvis frequency response function; the seat-to-T1 and the seat-to-head frequency response function shows a resonance frequency at 3.5 Hz.

- The human responses have been separated from the responses caused by the seat. In the rigid seat experiments the dynamics of the human body is dominant in the frequency response functions, while in the standard car seat experiments the frequency response functions from seat-to-human are mainly determined by the seat properties.
- The response of the human body differs between the rigid seat experiments and the standard car seat experiments. The foam properties of the standard car seat cause an increase in the peak value of the seat-to-human transmissibility at this first resonance frequency and cause a larger contact area, resulting in a shift of the first resonance frequency to lower values.
- Analysis with analytical models of human and seat confirms that the differences in seat-to-human transmissibility between both experiments can be contributed to the soft foam properties of the standard car seat.

Chapter 4

Estimation of spinal loading in vertical vibrations by numerical simulation[2]

In order to solve the problem of whole body vibration related injuries, knowledge about the interaction between human spinal vertebrae in vertical vibrations is required. This interaction cannot be measured in volunteer experiments. This chapter describes the application of the numerical 50th percentile occupant model developed in MADYMO for prediction of spinal forces, that could be used as a basis for derivation of hypotheses regarding low back pain disorders. This chapter starts with a validation study for vertical vibrations. The validation study has been based on the volunteer tests, presented in Chapter 3. After the validation, the spinal forces have been estimated.

4.1 Introduction

Low back pain and vertical vibrations are often related to each other (Bovenzi & Hulshof, 1998; Griffin, 1990). In recent years, an increasing part of the population is exposed to whole body vibration in vehicles at work, like truck and bus drivers. These professions introduced new complaints related to whole body vibrations at work, e.g. low back pain, resulting in increasing social costs. However, the causes of these low back pains are not well understood. Numerical models of human and seat can be used to provide insight in the interaction between human and seat in vertical vibrations and can help to explain the mechanisms that act in the human spinal column. These models allow for the estimation of tissue loading, which can not be measured in vibration experiments with volunteers.

In literature, several numerical models are described to predict the human behaviour in whole body vibrations. Most of these models are two-dimensional

[2] Adapted from: M.M. Verver, J. van Hoof, C.W.J. Oomens, N. van de Wouw, J.S.H.M. Wismans. *Estimation of spinal loading in vertical vibrations by numerical simulations*, **Clinical Biomechanics**, Vol. 18, No. 9, pp 800-811, 2003.

(2D) lumped mass models (e.g. Amirouche *et al.*, 1997; Cho *et al.*, 2000; Matsumoto & Griffin, 2001; Smith, 1994; Wu *et al.*, 1999; Zhao *et al.*, 1994). These models are applicable for a global prediction of impedance and transmissibility from seat to human body. However, these models are not valid for prediction of the local forces and moments acting on the human spine, which are assumed to be related to the cause of low back pain. Fritz (2000) presented a human model consisting of 16 rigid bodies representing the upper body, allowing the prediction of forces in the lumbar spine and neck. Kitazaki & Griffin (1997) developed a two-dimensional finite element model of human biomechanical responses to whole-body vibration. Beam, spring and mass elements were used to model the spine, viscera, head, pelvis and buttocks tissue in the mid-sigittal plane. The model was validated by comparison of vibration mode shapes of the model with those measured in a laboratory. For both the model of Fritz (2000) and Kitazaki & Griffin (1997) applies that the outer surface of the human body was not modelled and, therefore, the prediction of the interaction of the human body with the seat was not included.

Buck & Woelfel (1998) developed a dynamic three-dimensional finite element model with a detailed representation of the lumbar spine and back muscles. The model comprised non-linear ligament models, a non-linear contact model in the articular facets and dynamic properties of passive as well as active muscle tissue. The complete model of a sitting human was formed by adding relatively simple dynamic models of the upper trunk with arms, neck, head, pelvis and legs using rigid bodies. Pankoke *et al.* (2001) presented a simplified linearised version of the model of Buck & Woelfel (1998). However, in both studies the outer surface of the human body was modelled roughly and, therefore, the possibility for analyses of human behaviour in vertical vibrations due to the interaction between human and seat in various postures is limited.

In this chapter, the multi-body 50th percentile occupant model develop din MADYMO (TNO Automotive, 2001) is used for vibration analysis. The model consists of a set of rigid bodies connected by kinematic joints and the outer surface is presented as a triangulated surface (triangular shells). All spinal and cervical vertebrae are represented by rigid bodies interconnected by 3D-spring-damper combinations allowing a detailed analysis of the local loading acting in the spine. The geometric description of the outer surface together with the lumped mechanical properties of the soft tissues (muscles, ligaments, intervertebral discs) delivers the desired level of accuracy for the contact interaction with the seat in both static and dynamic conditions.

The objective of this chapter is to estimate the local spinal forces acting on the human spine under vertical vibrations in automotive conditions by numerical simulation using the MADYMO 50th percentile occupant model. A validation of the model is presented based on a comparison of measured transmissibilities from seat to human to corresponding modelled transmissibilities. Volunteer experiments on a rigid seat and a standard car seat are used for this validation. Using this model, the simulated spinal forces at each segment level are investigated in detail for these conditions.

4.2 Methods

This section describes the MADYMO human model and the experiments used for the verification of the human model. In addition, the set-up of the simulations is outlined.

4.2.1 Human body model

A mathematical human body model representing a 50th percentile male was developed in MADYMO (a combined multi-body and finite element package using an explicit time integration method) at TNO Automotive (Figure 4.1) (Happee *et al.*, 1998; Happee *et al.*, 2000). The dynamic multi-body human body model was based on the RAMSIS anthropometry of the 50th percentile male with 1.74 m standing height and 75.7 kg total mass (Tecmath AG, 2000). The RAMSIS model was converted to MADYMO providing joint locations, joint ranges of motion, segment masses and centres of gravity, and a triangulated outer surface connected to various body segments.

In the resulting spine and neck model all vertebrae are represented by rigid bodies, connected to each other by joints in which translational and rotational resistances are implemented. Since the MADYMO model contains more bodies in the spine than the RAMSIS model, the mass distribution in torso and neck has been

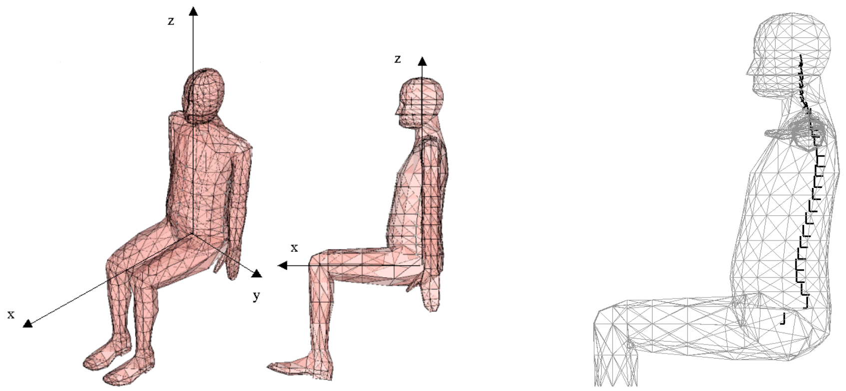


Figure 4.1: *The MADYMO human model with the definition of global orientation (left) and local orientations of the vertebrae (right).*

reassigned. Figure 4.1 shows the spine model in the neutral position that has been defined according to the RAMSIS model and thereby represents the mild spinal curvature of a standing person. The joint resistances represent the static and dynamic response and include effects of soft tissues like intervertebral discs, muscles and ligaments in a global manner by lumping their properties. The implemented spine and neck translational and rotational resistance are non-linear, based on literature data (Prasad & King, 1974; Kapanji, 1974; Yamamoto *et al.*, 1989; Schultz *et al.*, 1979; Berkson *et al.*, 1979; Markolf *et al.*, 1972; Panjabi *et al.*, 1994; de Jager, 1996). The spine model has been validated statically and dynamically (Happee *et al.*, 1998; Happee *et al.*, 2000). The limbs have been modelled as rigid bodies connected by joints.

The outer surface of the human model is described by 2174 triangular elements connecting 1068 nodes. This outer surface is supported by the rigid bodies; the contact algorithm describes local deformations. In the contact algorithm, the compliance of materials is taken into account by allowing penetrations in the contacting surfaces. For each node, the local stress is calculated applying a user-defined penetration function. The contact force is obtained by multiplying the calculated contact stress by the area around the node. This contact force is transferred from the surface model to the applicable rigid body or flexible body. In the thorax area the outer surface is supported by flexible bodies (Koppens *et al.*, 1993). The flexible bodies describe global deformations. This combination allows the thorax surface to continuously deform in response to contact loading and spinal deformation.

Energy dissipation has been implemented using hysteresis (in the contact interaction) and damping (in the spine and the contact interaction) (Happee *et al.*, 1998; Happee *et al.*, 2000).

4.2.2 Experiments

Experiments were performed at the Catholic University of Leuven (Belgium), using both a rigid seat and a standard car seat. The rigid seat was used to gain insight in the behaviour of the human body in vertical vibrations without any influence of seat parameters. The rigid seat back and the seat panel had an inclination with the vertical of 7.3° and an inclination with the horizontal of 9.8°. The selected rigid seat had no head restraint. In the experiments with the standard car seat, the angle of the seat back was set to 20° with respect to the vertical. Both experiments were set up based on the same protocol. The seats were mounted on an electro-hydraulic shaker with six degrees of freedom. The electro-hydraulic platform was excited by a swept sine applied in vertical direction. The frequency ranged from 0.5 Hz up to 15 Hz; the acceleration varied over time with a r.m.s. of 2.35 m/s^2 and the peak acceleration of 0.4 G. At least five periods of the swept sine were recorded per experiment. Figure 3.2 shows the power spectral density of the input acceleration.

Eleven healthy young subjects (age 20-30) participated in the experiment that was approved by the Ethics Committee of the Medical Faculty of the Catholic University of Leuven (Belgium). Table 4.1 provides some information about the volunteers (age, sex body mass, standing height). The subjects were instrumented with linear accelerometers (Kistler 3803A/2G) on the head, the upper thoracic vertebra (T1) and the pelvis (Figure 4.2 and 4.3). The pelvis acceleration was measured by accelerometers attached to a belt that was tied such that the accelerometers were positioned at the iliac wings. The T1-accelerometer was attached to the skin by elastic tape at the position of the spinous processes. Head accelerations were measured by an accelerometer attached to a stiffened water polo cap which was tied around the head. Furthermore, the acceleration was measured on the shaker and between the seat cushion and the buttocks. Vertical and frontal accelerations were measured. In separate measurements the accelerometer mountings were evaluated: it was found that no resonance frequencies below 15 Hz were introduced by the mounting. The sample frequency was 200 Hz, the Nyquist frequency was 100 Hz. In a few studies in literature methods were proposed for correction of bone accelerations measured on the skin (Hinz *et al.,* 1988; Kitazaki & Griffin, 1995; Pankoke *et al.*, 2001). Since no international standard exists on this topic, the authors did not use any correction method. The subjects were not restrained; they were requested to look forward fixating on a point in space having their hands on their lap and not to withstand the vibration. The initial posture was photographed. The experiments were recorded on video. All volunteers participated in both the experiments with the rigid seat and the standard seat.

	Sex	*Body mass (kg)*	*Standing height (cm)*
Subject 1	Female	57	169.5
Subject 2	Male	80	173
Subject 3	Male	68	178
Subject 4	Male	80	186
Subject 5	Male	71	174
Subject 6	Male	70	181
Subject 7	Male	80	187
Subject 8	Male	94	180
Subject 9	Male	80.5	187
Subject 10	Male	76.5	193
Subject 11	Male	75	182
Mean (±STD)	-	74.6 (±9.4)	181 (±7.1)

Table 4.1: *Anthropometric data of the volunteers*

Figure 4.2: *Experimental set up (left) and simulation set-up in MADYMO (right) of the rigid seat experiments.*

The results of the experiments agree with responses of the human body in vertical vibrations published before in literature (Figure 4.5 and 4.6). Some variations within the curves at frequencies above 9 Hz can be accounted to the disturbances already present in the input signal. The rigid seat experiments show a resonance frequency between 6-8 Hz for the seat-to-pelvis transmissibility. Similar results were measured by Mansfield & Griffin (2000) for transmissibilities from seat to iliac crest in a rigid seat condition. The seat-to-head transmissibility shows resonance frequencies between 4-5 Hz and 10-11 Hz. Griffin (1990) and Zimmerman & Cook (1997) published corresponding results for seat-to-head transmissibilities on a rigid seat.

Figure 4.3: *Experimental set up (left) and simulation set-up in MADYMO (right) of the standard seat experiments.*

4.2.3 Simulation set-up

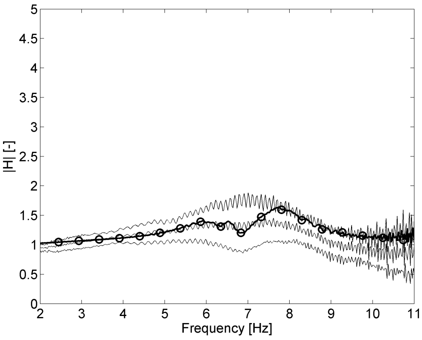
In the simulations of the experiments, the outer surfaces of the seats were represented by triangular and quadrangular shell elements, which were supported by rigid bodies. Kinematic joints between the bodies representing seat cushion and seat back and between the bodies of seat back and head restraint were introduced to represent the bending of the seat back and head restraint. The mechanical properties of the foam and frame were lumped. These lumped foam-frame properties, expressed as stress-strain curves, and the joint properties, expressed as moment-angle curves, were based on quasi-static tests with rigid loading devices. For that the seat cushion and seat back were each divided in several parts to account for foam thickness differences and foam-support by the frame. Hysteresis is included by definition of different loading and unloading curves. No strain-rate dependency is included in the model. The seat cushion and seat back were validated separately by quasi-static tests with rigid loading devices; the use of rigid loading devices allows for the analysis of the seat behaviour without any disturbances of the loading device. The loading devices had human like forms (Chapter 2).

The initial position of the human body model was based on photographs of the experiments. The human model was set just above the seat model and left to sink into the seat due to gravitational forces to reach an equilibrium between human model and seat model, and within the human body. In reality, the muscles are slightly activated to maintain the initial position of the body while the body settles and during the experiments. This active muscle behaviour is simulated by additional rotational stiffnesses in the articulations (spine and neck), based on muscle reflex stiffnesses of Brouwn (2000). This final position of the model after the settling process, i.e. the initial position in the vibration simulation, was checked with photos of the experiments (Figure 4.2 and 4.3).

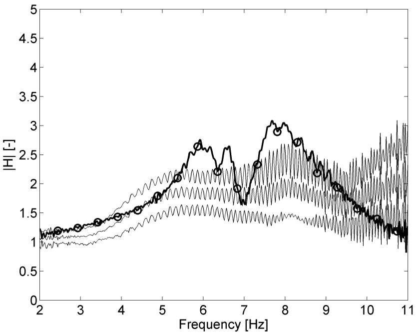
4.3 Results

Figure 4.4 and 4.5 show the absolute values of the seat to human frequency response functions of the human model compared to the volunteer responses in the linear domain, i.e. the frequency domain in which the coherency function is close to one. The mean values and mean value plus and minus the standard deviation of the experimental results are depicted. Figure 4.4 presents the rigid seat experiments, Figure 4.5 the standard car seat experiments.

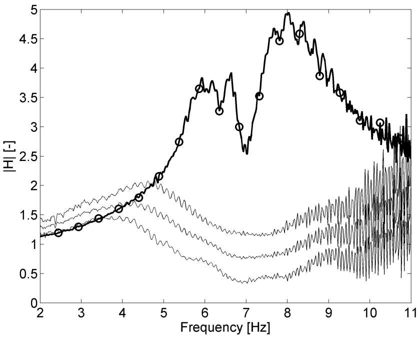
For the rigid seat experiments, the seat-to-pelvis transmissibility of the human model has one resonance frequency at 8 Hz, like most volunteers (Figure 4.4a). The transmissibility from seat-to-T1 of the human model contains two peaks: a small one at 6 Hz and a larger one at 8 Hz (Figure 4.4b). This response agrees with the volunteer responses. The simulated seat-to-head transmissibility shows



(a) Seat to pelvis

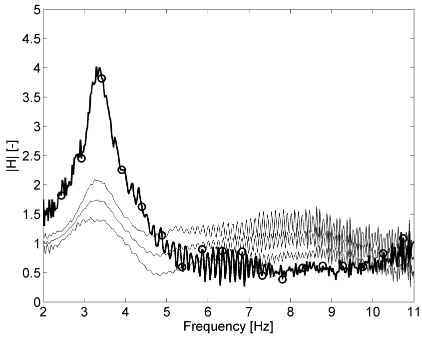


(b) Seat to T1

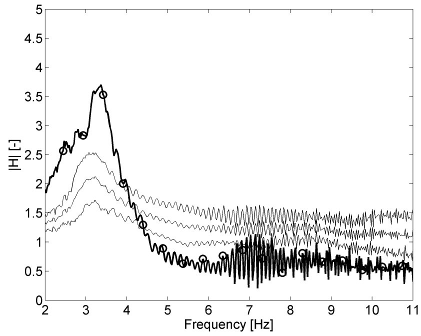


(c) Seat to head

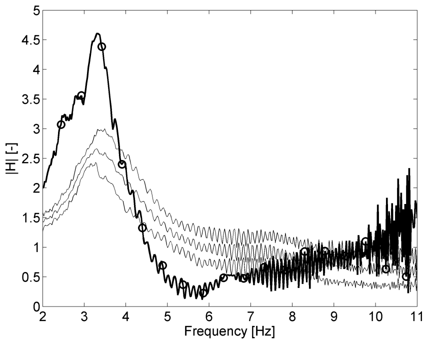
Figure 4.4: *The seat-to-human transmissibility of the human model (o) compared to the volunteer responses (mean (-), mean plus and minus standard deviation (-)) for the rigid seat experiments.*



(a) Seat to pelvis



(b) Seat to T1



(c) Seat to head

Figure 4.5: *The seat-to-human transmissibility of the human model (o) compared to the volunteer responses (mean (-), mean plus and minus standard deviation (-)) for the standard car seat experiments.*

two resonance frequencies at 6 Hz and one at 8 Hz (Figure 4.4c). The amplification of this seat-to-head transmissibility of the human model is larger than the amplification values of the seat-to-head transmissibilities of the volunteers.

In the standard car seat experiments, the volunteers show a resonance frequency at 3.5 Hz in all seat-to-human frequency response functions (Figure 4.5a-c), followed by a decrease at higher frequencies. The human model shows this resonance frequency as well in all seat-to-human frequency response functions. The predicted amplification of the frequency response function at this resonance frequency is too large for the seat-to-pelvis transmissibility and the seat-to-head transmissibility.

Figure 4.6 depicts the seat-to-pelvis transmissibility of the human model compared to two volunteers with similar mass (75.0 kg and 76.5 kg respectively) as the human model (75.8 kg) for both the rigid seat (left) and the standard car seat experiments (right). For the rigid seat experiments, the human model response approaches the volunteer response very well: both the volunteers and the human model show a resonance frequency at 7.5 Hz. Also for the standard car seat experiments the human model predicts the resonance frequency at 3 Hz of the seat-to-pelvis transmissibility of the volunteers well, the amplification of the seat-to-pelvis transmissibility of the human model is overestimated compared to the volunteer responses.

Investigation of the spinal forces can provide insight in the mechanisms acting in the human spine during vertical vibrations. Figure 4.8 depicts the minimum and maximum values of the tension-compression forces at each vertebra level for the rigid seat (Figure 4.8a) and the standard car seat simulations (Figure 4.8b). See also Figure 4.7 for definition of the loads. As can be expected, the tension-compression forces in both the rigid seat and the standard car seat experiments gradually

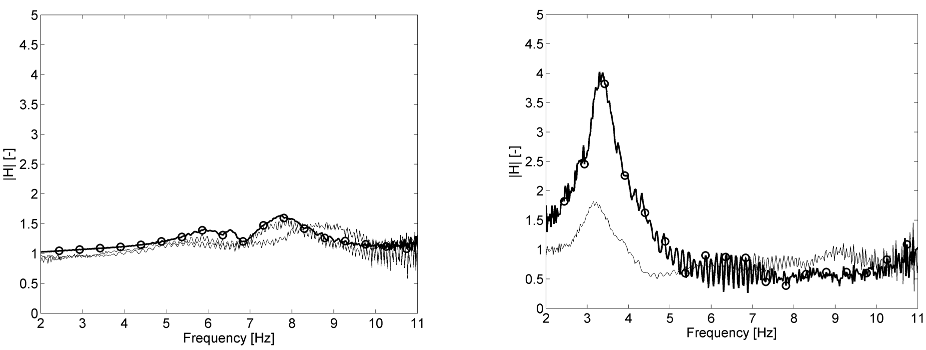
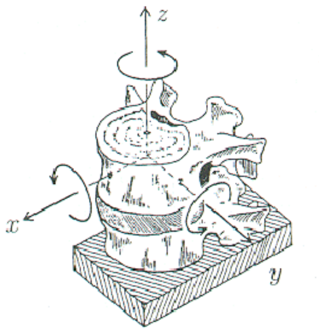


Figure 4.6: *The seat-to-pelvis transmissibility of the human model (o) compared to the responses of two volunteers (-) with similar mass as the human model. Left: rigid seat experiments. Right: standard car seat experiments.*



Load	Name
$+F_x$	*Anterior shear*
$-F_x$	*Posterior shear*
$+F_y$	*Lateral shear*
$+F_z$	*Tension*
$-F_z$	*Compression*

Figure 4.7: *Definition of the loads*

decrease from lumbar spine to cervical spine. The maximum compressive forces in the standard car seat experiments are much larger than the forces in the rigid seat experiments, especially in the lumbar region. In Figure 4.9 and 4.10 the maximum and minimum values of the anterior-posterior shear forces are plotted at each vertebra level for the rigid seat (Figure 4.9) and the standard car seat simulations (Figure 4.10). For the rigid seat simulation, the maximum shear forces appear in the lumbar spine and the lower thoracic spine. Generally, the anterior shear is larger than the posterior shear. For the standard car seat simulation, the maximum posterior shear forces appear in the lumbar spine while the maximum anterior shear forces appear in the thoracic spine. Comparison of the spinal shear forces in the rigid seat simulation with the standard car seat simulation shows that generally the posterior shear forces in the standard car seat simulation are larger than shear forces in the rigid seat simulation, while the anterior shear forces are larger in the rigid seat condition.

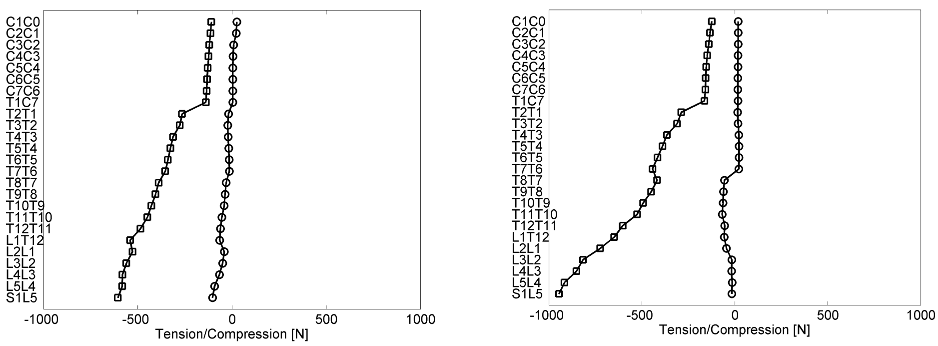


Figure 4.8: *The maximum (o) and minimum (□) spinal loading in tension-compression. Left: Rigid seat experiments. Right: Standard car seat experiments. Plus: tension. Minus: compression.*

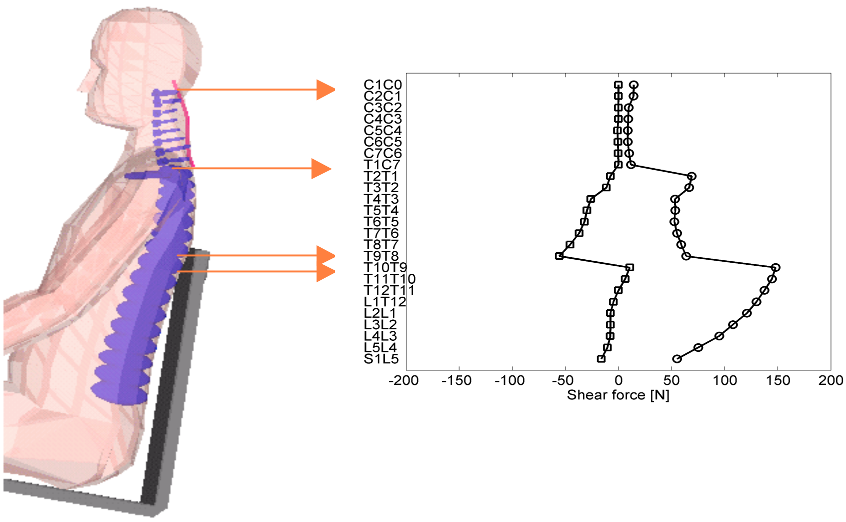


Figure 4.9: *The maximum spinal shear loading for the rigid seat simulations (right) together with the position of the vertebrae in the human model with respect to the seat (left). o = anterior, □ = posterior.*

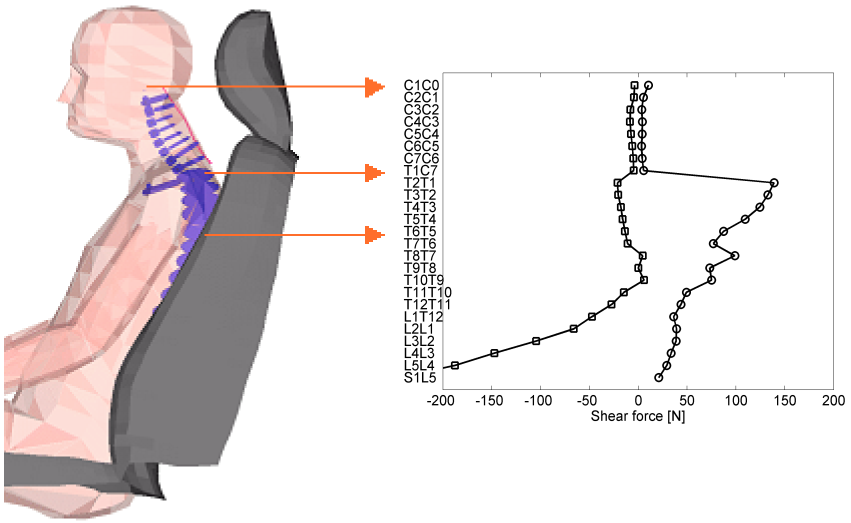
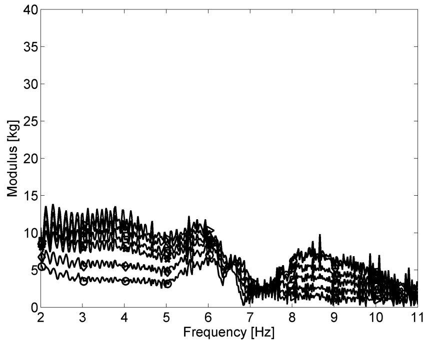
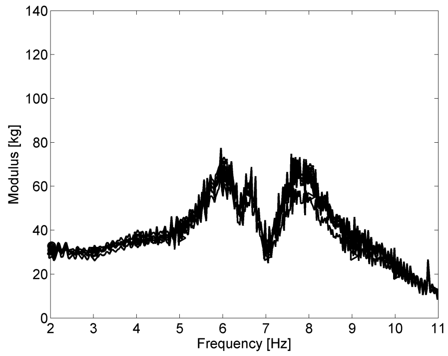


Figure 4.10: *The maximum spinal shear loading for the standard car seat simulations (right) together with the position of the vertebrae in the human model with respect to the seat (left). o = anterior, □ = posterior*

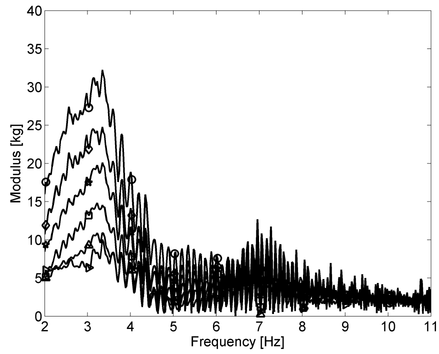


(a) Anterior-Posterior Shear

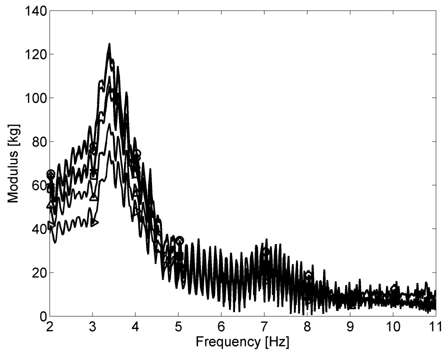


(b) Tension-Compression

Figure 4.11: *The transfer from seat acceleration to lumbar forces as function of the frequency for the rigid seat experiments. o = S1L5, ◊= L5L4, ⬠ = L4L3, □ = L3L2, △= L2L1, ▷=L1T12*



(a) Anterior-Posterior Shear



(b) Tension-Compression

Figure 4.12: *The transfer from seat acceleration to lumbar forces as function of the frequency for the standard car seat experiments. o = S1L5, ◊= L5L4, ⬠ = L4L3, □ = L3L2, △= L2L1, ▷=L1T12*

Figure 4.11 and 4.12 illustrate the relation between the exposure and loads on the spine: the frequency response function from the input acceleration to the compressive and shear forces in the spine is depicted as function of the frequency for the rigid seat (Figure 4.11) and the standard seat simulation (Figure 4.12). The rigid seat simulation shows no clear peak in the loading in shear. The tension-compression loading shows two peaks at 6 Hz and 8 Hz, and the maximum values are larger than the shear loading (Figure 4.11b). For both shear and compressive loading applies that the loading of the various lumbar intervertebral discs are close to each other. The standard car seat simulation shows for both the shear and the tension-compression loading a maximum at 3.5 Hz, i.e. the resonance frequency in the seat-to-human frequency response functions, followed by a decrease of the signals at higher frequencies (Figure 4.12). The loading levels at the various intervertebral discs differ significantly around the peak value.

4.4 Discussion

In this chapter, the human behaviour in vertical vibration has been simulated numerically. The MADYMO 50th percentile occupant model response has been compared to volunteer responses based on rigid seat and standard car seat experiments by means of seat-to-human transmissibility. Additionally, spinal shear and compressive loading have been investigated by maximum and minimum forces at all vertebral levels and the ratio of the autopower spectra of the lumbar forces and the input acceleration.

To the author's knowledge, in literature only a few studies are available describing the validation of numerical models for rigid seat experiments. Matsumoto & Griffin (2001) developed lumped mass models to obtain insight into resonance phenomena observed at about 5 Hz in the dynamic responses of the seated human body exposed to vertical whole-body vibration. The validation of the model was based on apparent mass and seat-to-head transmissibility data published in literature with which the model showed good agreement. Fritz (2000) presented a biomechanical model with 16 rigid bodies representing upper body and arm of a sitting person. Validation was performed using ISO 7962. The pelvis-to-head transmissibility predicted the resonance frequency well, but overestimated the mean amplification at this resonance frequency, although it stayed within the upper and lower range. Also, the peak value in the apparent mass response of the model was larger than the volunteer responses described in ISO 5982. Kitazaki & Griffin (1997) presented a two-dimensional finite element model of the spine, viscera, head, pelvis and buttocks. The vibration mode shapes predicted by the model agreed with the shapes measured in a laboratory. The results of the apparent mass and the seat-to-head transmissibility of the model showed good agreement with data published in literature in the range from 0-10 Hz. Pankoke *et al.* (2001) introduced a simplified version of the finite element human model of Buck & Woelfel (1998) adaptable to body height, body mass and posture of a specific subject. The validation was based on mechanical impedance and the transmissibility from seat to L4 and head. The impedance of the model predicted the experimental impedance well till 6 Hz, but differs from volunteer data for higher frequencies ($f > 6$ Hz). The model transmissibility from seat to head and L4 predicted the resonance frequency well, but overestimated the amplification at this resonance frequency.

Amirouche *et al.* (1997) and Zhao *et al.* (1994) do not describe a validation of their model, but only focused on the influence of seat parameters on seat-to-human transmissibility. Cho *et al.* (2000), Smith (1994) and Wu *et al.* (1999) described a validation of their models for soft seats. The 9 degree of freedom (DOF) model presented by Cho *et al.* (2000) predicted the resonance frequencies in the seat-to-human transmissibility well, while the amplification at the resonance frequency was a little overestimated. Smith (1994) used a 3 DOF and 5 DOF model to investigate human behaviour in vertical vibration by variation of seat parameters. These models were validated based on mechanical impedance and showed good responses.

The response of the MADYMO human model agrees reasonably with the volunteer responses in the seat-to-human transmissibilities: the resonance frequencies are predicted well in the transmissibilities from seat to pelvis and T1 in the rigid seat experiments and seat to pelvis, T1 and head in the standard car seat experiments. In the standard car seat simulation, the amplification of the seat-to-human transmissibilities is overestimated. The seat-to-human frequency response function is highly influenced by several factors like the mass and length of a person and the posture. These factors can explain the differences between the volunteer responses and small differences between human model responses and the volunteer responses in the experiments. The seat-to-pelvis transmissibility of the human model agrees well the response of the volunteers, having similar mass as the human model. The seat-to-head transmissibility of the human model in the rigid seat experiments requires some further improvement: the differences with the volunteer responses are too large.

The amplification of seat-to-human transmissibility in the standard car seat simulation is slightly overestimated. Similar trends can be observed in other models (both lumped mass models and more detailed models) reported in literature (Cho *et al.*, 2000; Smith, 1994; Wu *et al.*, 1999; Fritz, 2000; Pankoke *et al.*, 2001). The overestimation of the amplification of the seat-to-human transmissibilities in this chapter could probably be accounted to the model of the standard car seat: the damping properties of the foam and frame are only represented by hysteresis. No strain-rate dependent behaviour of foam is included in the model.

The response of the MADYMO human model has only been compared with the experimental results in the frequency domain between 2-11 Hz, i.e. the linear domain. The linear domain has been defined as the frequency range in which the coherency functions approach the value one. For all transmissibilities, the coherency functions showed small values below 2 Hz and between 11-15 Hz. These small values have been caused by the low input signal: probably, the environmental disturbances were too large compared to the low input signal at these frequencies.

After validation of the MADYMO human model for vertical vibrations, the spinal local forces and moments were investigated. In contradiction to most models described above, the human model allows the calculation of spinal forces and moments at all vertebral levels. Figure 4.8 shows that the maximum compressive loading occurs in the lumbar spine for both the rigid seat experiments and the standard car seat experiments. For the rigid seat experiments (Figure 4.9), the maximum shear force appears in the lumbar spine and the lower part of the thoracic spine, while for the standard car seat simulations the maximum shear forces act in the upper thorax (Figure 4.10). The maximum shear force in the rigid seat condition and the standard seat condition contain some large transitions around T1-C7. These large transitions are partly affected by the contact interaction between human and seat and partly by the spinal properties of the human model. In the rigid seat condition, the human model contacts the seat back only at T9 level (Figure 4.10). In the standard car seat condition, the contact area between human and seat is much larger than in the rigid seat situation. Consequently, the changes in spinal shear forces are smaller in the standard car seat situation than in the rigid seat situation. Some minor peaks are found at T7 level (Figure 4.10). At this level the human back releases contact with the seat back. For both the rigid seat and the standard car seat simulation, the maximum shear forces decrease rapidly from T2-T1 to T1-C7. This decrease is produced by a change in function of the shear properties from the thoracic spine to cervical spine. These functions are based on different literature sources describing spinal properties. Figures 4.8, 4.11 and 4.12 depict larger compressive and shear loading of the lower back vertebrae in the standard car seat simulation than in the rigid seat simulation. The overestimation of the amplitude of the frequency response functions of accelerations from seat to human in the standard car seat simulation could be an important factor influencing these results.

Comparison of the results of the present study with other studies reported in literature is hard since a limited number of articles is published describing models suitable for analyses of spinal loading. In addition, the differences in experimental set-up and loading conditions make a comparison between models difficult. To the author's knowledge, no models are reported allowing prediction of spinal forces at all vertebral levels. Fritz (2000) determined maximum loading at L3-L4 level for the experiments described in ISO 5982 and 7962 with the biomechanical model described before for frequencies between 0–30 Hz. Hinz *et al.* (1993) developed a biomechanical model for determination of compressive loading at L3-L4 level using the effective mass of the human body above the disc L3-L4 and the relative accelerations between the L3-L4 vertebrae. These accelerations were determined by volunteer experiments on a rigid seat. Hinz *et al.* (1993) tested several conditions, including a sinusoidal waveform in the frequency range from 0.5-7 Hz with a maximum seat acceleration of 0.3 G. Table 4.2 provides a summary of the maximum loading at L3-L4 level predicted by the human model of the present study, the model of Fritz (2000) and the model of Hinz *et al.* (1993). Keeping the differences between the maximum accelerations of different studies in mind, the maximum shear forces and compressive forces at L3-L4 are within the same range. The present study shows a maximum shear force of 95 N at a maximum acceleration of 0.4 G, while Fritz (2000) predicts a maximum shear force of 31 N at a maximum acceleration of 0.4 G. The maximum compressive force at L3-L4 determined in the present study is 581 N at a maximum acceleration of 0.4 G, while Fritz (2000) predicts a compressive force of 634 N for experiments between 0.1-0.5 G and Hinz *et al.* (1993) predicts a maximum compressive force 657 N for sinusoidal waveform of 500 ms with a maximum acceleration of 0.3 G.

Investigation of the transfer of the input acceleration to the lumbar local forces shows that the response of the individual compressive forces on the lumbar intervertebral joints do not differ much from each other in the rigid seat simulation (Figure 4.11b and 4.12b). This could be regarded as an indication that the magnitude of the displacements at all lumbar vertebral levels is comparable. The standard car seat simulation shows more variation between the various vertebra levels. The transfer of the input acceleration to the lumbar shear forces shows differences between the individual lumbar levels. The lumbar vertebrae seem to move with respect to each other (see also Figure 4.9 and 4.10). Whereas for the rigid seat simulation, the largest relative displacements between vertebrae occur in the upper part of the lumbar spine, in the standard car seat simulations the largest relative displacements of vertebrae occur at the lower vertebral levels (Figure 4.9, 4.10, 4.11, 4.12). Furthermore, the maximum shear force in the rigid seat simulation is posterior (negative), while the maximum shear force in the standard car seat simulation is anterior (positive). The differences in contact interaction between human and the seat back between the rigid seat and the standard car seat situation seem to influence the spinal forces. The trends and magnitude of

	Seat	*Freq. range*	*Max. acc.*	*Anterior/ Posterior shear*	*Compression*
Present study	Rigid seat	0.5-15 Hz	0.4 G	95 N (anterior)	581 N
	Standard car seat	0.5-15 Hz	0.4 G	147 N (posterior)	852 N
Fritz (2000)	Rigid seat	0-30 Hz	0.1-0.5 G	31 N	634 N
Hinz *et al.* (1993)	Rigid seat	0.5-7 Hz	0.3 G	-	657 N

Table 4.2: *The L3-L4 loading in vertical vibrations calculated in the current study by the MADYMO model compared to the L3-L4 loading determined by Fritz (2000) and Hinz et al. (1993).*

transmissibility from seat input acceleration to lumbar forces predicted by the model is similar with the results presented by Seidel *et al.* (2001). Seidel *et al.* (2001) used the model developed by Pankoke *et al.* (2001) as basis to predict static and dynamic compression and shear forces acting on the S1-L5 segment during whole body vibration by determination of transfer functions from seat acceleration to lumbar forces. Their study showed maximum values in the transmissibility from input acceleration to shear forces at the higher frequencies, while the maximum values in the transmissibility to compressive forces showed two peaks at the lower frequencies. An extension of the validation of the model used in present study for spinal loading, e.g. based on studies of El Khatib & Guillon (2001), Wilke *et al.* (1999) and Nachemson & Morris (1964), would be desired.

4.5 Conclusions

This chapter describes the application of numerical simulations with the MADYMO human model for the prediction of spinal loading in vertical vibrations. The model is validated for vertical vibrations based on volunteer experiments on a rigid seat and a standard car seat. The validation is performed by means of seat-to-human transmissibility. The local spinal forces are investigated for both the rigid seat and the standard car seat condition. The following can be concluded:

- The human model shows reasonable correlation with the volunteer responses for the rigid seat experiments. The resonance frequencies of seat-to-human transmissibility correspond well with the volunteer responses. Particularly, the correspondence between the human model and the two volunteers with similar mass as the volunteer is very good. The seat-to-head transmissibility of the human model requires further improvement.
- The seat-to-human transmissibility of the human model agrees reasonable with the volunteer responses for the standard car seat experiments. The resonance frequencies are predicted well by the human and seat model, but the amplification is overestimated. It would be recommended to further investigate the definition of the damping properties of the seat foam.
- For the rigid seat simulation, the maximum shear forces occur in the lumbar spine and the lower thoracic spine at the lower frequencies (2-5 Hz) and are in anterior direction. For the standard car seat simulation, the upper thoracic spine is subjected to the largest shear forces in posterior direction. This maximum loading occurs at 3.5 Hz. These differences in shear forces between the rigid seat condition and the standard car seat condition can be explained by the difference in interaction between human back and seat back rest.

- The maximum compressive forces act in the lumbar spine around 6 Hz in the rigid seat simulation. For the standard car seat simulation, the maximum compressive forces act in the lumbar spine at 3.5 Hz.
- The frequency response functions of the input acceleration to the lumbar shear and compressive forces indicate that the lumbar vertebrae move with respect to each other in both vertical and horizontal direction.

Chapter 5

A finite element model of the human buttocks for prediction of seat pressure distributions[3]

The contact interaction between human and seat is an important factor in the comfort sensation of subjects. This chapter presents a finite element model of the human buttocks, which is able to predict the seat pressure distribution at the contact interface between human and seat by its detailed and realistic geometric description of bony structures. Section 5.2 details the model description. A validation study is performed based on seat pressure distributions measured in volunteer experiments with a rigid and a soft cushion. A parameter study has been performed to investigate the influence of variations in human soft tissues and seat cushion properties on the seat pressure distribution at the interface between human and seat. Section 5.3 describes the cushion models used in both studies. Section 5.4 and 5.5 focus on the simulation set-up of both the validation study and the parameter study and the data analysis. The results are presented in Section 5.6. Section 5.7 discusses the results and in Section 5.8 conclusions are drawn.

5.1 Introduction

Seating comfort is becoming increasingly important. Higher demands on the performance of vehicles and the comfort-related physical complaints by professional drivers have led to an increasing demand for more comfortable cars. Car manufacturers use comfort as an item to distinguish themselves from their competitors. However, the development and introduction of a new, more-comfortable car seat or interior is time consuming and costly. The use of computer

[3] Adapted from: M.M. Verver, J. van Hoof, C.W.J. Oomens, J.S.H.M. Wismans, F.P.T. Baaijens. *A finite element model of the human buttocks for prediction of seat pressure distributions*. Submitted to Computer Methods in Biomechanical and Biomedical Engineering.

models of human and seat could facilitate this process. In the early stages of the design process a new design can be tested for its degree of comfort by computer simulations with models of the human and the seat. This allows manufacturers to speed up the design process of a new (car) seat or interior and reduce costs. To bridge the gap between the subjective feeling of comfort and the prediction of the comfort level of new designs by virtual testing, a relation has to be defined between that subjective feeling and objective parameters. Pressure distribution was proposed as an objective measure for (dis)comfort prediction (Ebe *et al.*, 2001; Inagaki *et al.*, 2000; Kamijo *et al.*, 1982; Lee *et al.*, 1995; Milvojevich *et al.*, 2000; Park & Kim, 1997; Park *et al.*, 1998; Reed *et al.*, 1991; Tewari & Prasad, 2000; Thakurta *et al.*, 1995; Uenishi *et al.*, 2000; Yun *et al.*, 1992; Zhao *et al.*, 1994). Pressure distribution represents a measure of the load pattern in the contact interaction between human and seat. Several studies showed the relation between a subject's personal sensation of comfort and seat pressure distributions (Ebe *et al.*, 2001; Inagaki *et al.*, 2000; Kamijo *et al.*, 1982; Lee *et al.*, 1995; Milvojevich *et al.*, 2000; Park & Kim, 1997; Park *et al.*, 1998; Reed *et al.*, 1991; Tewari & Prasad, 2000; Thakurta *et al.*, 1995; Uenishi *et al.*, 2000; Yun *et al.*, 1992; Zhao *et al.*, 1994). Average pressure, maximum pressure, the size and symmetry of the contact area are parameters most widely reported in the investigation of seating (dis)comfort. On the other hand, several authors describe the limitations of measurement of pressure distributions (Bader & Hawken, 1990; Oomens *et al.*, 2003): it is hard to perform reproducible and accurate measurements of the interface pressure between the human and the seat. Furthermore, pressure distributions do not provide information about internal stresses and deformations of the soft tissues. Finally, seat pressure distributions provide only information about the normal stress at the contact interface, while several studies in literature (Bader & Hawken, 1990; Bennett *et al.*, 1979; Chow & Odell, 1978; Krouskop *et al.*, 1990; Reichel, 1958; Scales, 1982) indicate the additional presence of shear stresses at the contact interface, which have a significant influence on the contact interaction between human and seat.

Despite these limitations, a combination of measurements of seat pressure distributions with virtual testing tools can be very useful and any established relation between (dis)comfort and pressure distribution can be used as a basis for prediction of (dis)comfort by virtual testing. A finite element model of the human buttocks can be used to predict the deformations of the soft tissues. Measurements of seat pressure distributions can be used for verification of the model for interface pressures. In combination with a finite element model of a seat, both models could provide insight into changes in contact interaction between human and seat due to variations in posture and seat properties. Further, use of finite element models of human and seat allows investigation of both normal stresses and shear stresses at the contact interface.

The main limitations of models published in literature are the simplified geometric description of the bony structures and soft tissues, the coarseness of the mesh and the need to combine several sources to create a model. Brosh & Arcan (2000), Chow & Odell (1978), Dabnichki *et al.* (1994), Todd & Thacker (1994) and Oomens *et al.* (2003) developed finite element models of the human buttocks for investigation of pressure sores. The geometry of their models was similar involving a hemisphere with a rigid core. As explained before, the maximum pressure in a pressure distribution is considered to correlate with comfort. These maximum pressures occur under the ischial tuberosities. So for an accurate prediction of the maximum pressure in a pressure distribution an accurate geometric description of the bony structures is required. For this reason, the aforementioned models have a limited value for detailed (dis)comfort predictions. Dalstra *et al.* (1995) and Besnault *et al.* (1998) developed finite element models of the pelvis with an accurate geometric description, although these models did not account for soft tissues. A number of finite element models of the entire human body have been introduced to study impact for automotive conditions (e.g. Lizee *et al.* (1998) and van Hoof *et al.* (2001)). The number of elements in these human models is limited to prevent long computation times and for that reason, the geometric description of the pelvis region is relatively coarse. Moens & Horváth (2002) developed a finite element model of the human buttocks for shape optimisation of seats. Limitation of this model is that it is a combination of two sources: the data of the bones is obtained from the Visible Human Data set (1997), i.e. a cadaver (average male) in the lying position, while the skin was generated from measurements on a living subject in a standing posture with flexed knee. The paper mainly focused on the model description and showed a few results, but no validation.

The objective of the present chapter is the development of a finite element model of the human buttocks suitable for prediction of realistic seat pressure distributions. A finite element model of the human buttocks is presented obtained from a sitting subject. The geometry of the bony structures has been modelled in detail to be able to predict realistic maximum stresses in the contact area between human and seat. Geometries of bones, soft tissues and skin have all been obtained from one source (Robin *et al.*, 2001) (Section 5.2). The model has been validated for static conditions, using volunteer subjects on a rigid surface and a soft surface (Section 5.6). A parameter study has been performed to show the sensitivity of the buttock model for changes in human soft tissues and seat cushion properties (Section 5.6).

5.2 Model description FE buttocks

A numerical model was developed using MADYMO 6.0, a simulation program that combines finite element and multi-body techniques (TNO Automotive, 2001). MADYMO uses explicit numerical integration methods to solve the equations of motion. The model includes a detailed anatomical description of the bony structures, like iliac wings including the ischial tuberosities, sacrum, coccyx and femora. The soft tissues, muscles, fat, ligaments, are lumped together and the skin is modelled separately (Figure 5.1).

5.2.1 Geometry

The description of the geometry is based on data obtained from a European project (Robin *et al.*, 2001). The 3D shape of the bony structures and the soft tissues of the model is based on a 78 year old male Post Mortem Human Subject (PMHS) with a weight of 80 kg and standing and sitting height of 1.73 m and 0.92 m respectively. The geometry of the iliac wings, sacrum, coccyx, femora and skin was used to define a mesh for the presented model.

The skin and bony structures have been modelled with triangular shells. The lumped soft tissues have been modelled by 4 node tetrahedron elements. Equivalent nodes have been used to model the connection between the FE parts of the skin with the soft tissues and the connection of the bony structures with the soft tissues: i.e. the same node has been used for definition of an element in e.g. the skin and the soft tissues. The element size was set to 10 mm. The model contains 158,310 elements and 29,661 nodes.

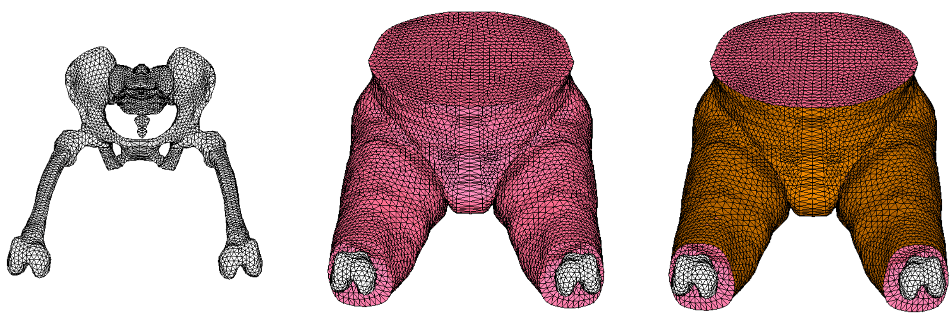


Figure 5.1: *The finite element model of the pelvis and thighs. Left: the bony structures. Middle: the bony structures and the human soft tissues. Right: the complete model - bony structures, human tissues and skin.*

5.2.2 Bodies and joints

Multi-body techniques have been used for definition of the joints. Joints have been modelled between the iliac wings and the upper body, between the iliac wings and both femora, representing the hip-joints, and between the femora and the lower legs, the knee-joints. The hip-joints allow the model to be used in studies with various pelvis angles. The masses of the upper body (torso, neck, head and arms) and the lower legs have been represented by multi-body bodies, with values based on those of an average male (TNO Automotive, 2001).

5.2.3 Material models

The bony structures are assumed to be rigid. The skin is described with a linear elastic isotropic material model. The material properties are defined by E = 0.15 MPa, ρ = 1100 kg/m^3, ν = 0.46. Similar values have been reported by Hendriks *et al.* (2003) and Lizee *et al.* (1998).

Literature does not report much about lumped properties of human soft tissues, i.e. combined properties of fat and muscles. Chow & Odell (1978) and Lizee *et al.* (1998) reported consistent values. However, the studies of Bader & Bowker (1983) and Adams *et al.* (1999) reported much lower values, while Todd & Thacker (1994) described larger values. In their studies, Setyabudhy *et al.* (1997), Bosboom (2001), Oomens *et al.* (2003) used the elastic Ogden material model to describe the non-linear behaviour of the human soft tissues; parameters for muscles and fat were defined separately. In the present study, the non-linear human soft tissues properties have been included within a Mooney-Rivlin hyperelastic isotropic material model. The strain energy function is defined by:

$$W = A_1(J_1 - 3) + A_2(J_2 - 3) + A_3(J_3^{-2} - 1) + A_4(J_3 - 1)^2$$

with J_1, J_2 *and* J_3 the invariants of the right Cauchy-Green strain tensor. The right Cauchy-Green strain tensor is defined by:

$$\underline{C} = \underline{F}^T \cdot \underline{F}$$

with $\underline{F}$ the deformation tensor. J_1, J_2 *and* J_3 have been defined as:

$$J_1 = trace(\underline{C})$$

$$J_2 = \frac{1}{2}\left(trace^2(\underline{C}) - trace(\underline{C}^2)\right)$$

$$J_3 = \det(\underline{C})$$

The second Piola-Kirchhoff stress tensor is obtained by differentiating the strain energy function W with respect to the right Cauchy-Green strain tensor:

$$\underline{S} = 2\frac{\partial W}{\partial \underline{C}}$$

The material parameters A_3 and A_4 are functions of the coefficients A_1 and A_2:

$$A_3 = \frac{1}{2} A_1 + A_2 \text{ and } A_4 = \frac{A_1(5\nu - 2) + A_2(11\nu - 5)}{2(1 - 2\nu)}$$

The values for A_1, A_2 and ν have been set to: A_1 = 1.65 kPa, A_2 = 3.35 kPa and ν = 0.49. These values fall in the range for human soft tissues properties reported in literature (Adams *et al.*, 1999; Bader & Bowker, 1983; Bosboom *et al.*, 2001; Chow & Odell, 1978; Lizee *et al.*, 1998; Oomens *et al.*, 2003; Setyabudhi, 1997).

5.3 Cushion models

Different cushion models have been used in the validation study and the parameter study. In the validation study, the cushion size and the element size of the cushion model have been adapted to the used cushion and pressure mapping system. In the parameter study, it has been chosen to define a surface covering the whole buttocks model.

5.3.1 Cushion model in validation study

In the validation study on the rigid surface, the seat cushion has been modelled by a flat surface of (430 x 430) mm^2. The model comprises three layers of 8-node hexahedron (brick) elements with a size of 26.875 mm, i.e. the size of the pressure sensors used in the experiments. A linear isotropic material model has been used to describe the cushion properties. In the simulation for the validation of the buttocks model on a rigid surface, the material properties have been set to: E = 2.0 GPa and ρ = 100 kg/m^3.

In the simulations for the validation of the buttocks model on the soft cushion, the cushion size has been modelled by a flat surface of (376 x 376) mm^2. The material properties of the cushions used in the volunteer experiments have been implemented, i.e. ρ = 56.1 kg/m^3 and a force–deflection characteristic of the cushion as depicted in Figure 5.2. The foam material model available in MADYMO has been used (TNO Automotive, 2001). The foam material model works with stresses and strains in the principal directions. The model is based on the assumptions that there is no coupling between stresses and strains of different principal directions (Poisson effects are neglected). The principal stresses and strains are fitted on single axis experiments, which are defined by an experimental stress-strain curve. For that reason, the force-deflection characteristics in Figure 5.2 have been converted to a stress-strain relation.

The cushion model has been validated based on the certification tests (ASTM 3574-01) performed with the foam cushion. In order to get good validation results, the element size had to be reduced to half of the sensor size.

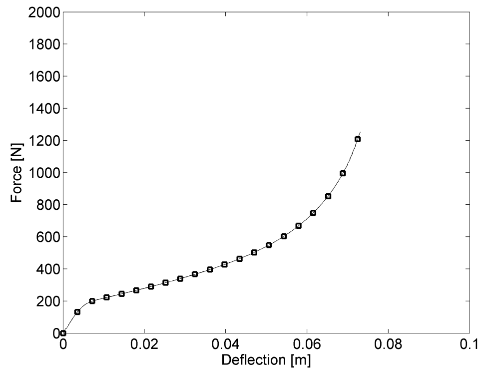


Figure 5.2: *The material properties of the soft cushion used in the validation study.*

5.3.2 Cushion model in parameter study

The seat cushion has been modelled by a flat surface of (500 x 600) mm^2 with a thickness of 60 mm. The model contains three layers of 8 node hexahedron (brick) elements with a size of 20 mm. A linear elastic isotropic material model has been used to describe the cushion properties. In the simulations, the material properties of the rigid surface have been set to: E = 2.0 GPa and ρ = 100 kg/m^3. In the simulation with a soft cushion in the parameter study, the stiffness is decreased to E = 0.2 MPa.

5.4 Simulation set-up

In both the simulations for the parameter study and the validation study, the FE-pelvis model was positioned just above the cushion (rigid or soft) and left to settle on the cushion due to gravity forces. Contact interfaces were defined to simulate the contact interaction between human and seat. This contact interaction was modelled by a penalty based model, in which the bulk modulus of the contact segment (i.e. cushion) was used in the calculation of the contact force. In the present study, only quasi-static conditions have been examined.

In the validation study, the conditions of the volunteer experiments were simulated. In these experiments, the volunteers were requested to sit on the cushions (rigid and soft stiffnesses) with a straight back and their feet unsupported. A FSA pressure mapping system was used (16 x 16 sensors; sensor size 26.875 mm; sample rate 3072 sensors per second; calibrated pressure range 0 - 200 mmHg). Although a rigid seat condition is not a realistic seating condition, it is a very suitable condition for validation of the FE buttocks model, since no disturbances are introduced by a cushion model.

The properties of the cushion used in the experiments have been used in the simulations (ASTM 3574-01). For the results of the validation study, the maximum stresses depicted in the pressure distribution have been set to 26.7 kPa (200 mmHg), corresponding to the maximum stress recorded by the pressure mapping system.

In the parameter study, the validated FE buttocks model has been used as reference model. The stiffness of the human soft tissues and the stiffness of the cushion have been varied. The stiffness of the human soft tissues was increased and decreased by a factor 10 with respect to the reference model, i.e. similar with the variation in human soft tissue properties reported in literature (Adams *et al.*, 1999; Bader & Bowker, 1983; Bosboom *et al.*, 2001; Lee *et al.*, 1995; Moens & Horváth, 2002; Scales, 1982). The stiffness of the cushion was decreased a factor 10^4 from 2.0 GPa to 0.2 MPa for simulation of a soft cushion with respect to the rigid seat simulation.

5.5 Data analysis

Examination of related studies have indicated that the average pressure, the maximum pressure, the size and symmetry value of the contact area are parameters commonly used to study the relation between pressure distributions and (dis)comfort. These parameters have also been used in the present study. The contact stresses acting on the cushion have been generated as output for evaluation of the pressure distribution. These values were also used to calculate the average pressure and the maximum pressure.

In the validation study, the pressure distribution predicted by the buttocks model has been compared with the pressure distribution of a male volunteer of 75 kg weight and 1.75 m standing height. Each of the selected parameters predicted by the buttocks model have been compared to the volunteer results. The distributions predicted by the FE buttocks model are plotted with same resolution as the experimentally measured distributions. For the simulation on the soft cushion, this meant that the resolution has to be resampled. The experimental values of the maximum pressure, average pressure and contact area are the mean values of four tests, representing two volunteers tested on two occasions in each condition.

In the parameter study, the influence of variations in stiffness of human soft tissues and cushion on the selected parameters has been investigated. The use of a symmetrical FE model and the examination of static conditions for normal sitting has precluded the inclusion of symmetry considerations in both the validation and the parameter study.

Measurements of seat pressure distributions have the limitations that only normal stresses at the seating interface can be measured. Several studies, however, have indicated that shear stresses on the contact interface have a significant influence on the contact interaction between human and seat (Bader & Hawken, 1990; Bennett *et al.*, 1979; Chow & Odell, 1978; Krouskop *et al.*, 1990; Reichel, 1958; Scales, 1982). Further, seat pressure distributions do not supply information about the internal stresses and deformations of the soft tissues of the human buttocks. The use of a finite element model of the human buttocks for research on the contact interaction between human and seat, does permit examination of these parameters. Therefore, these parameters have been generated as output in the present study.

5.6 Results

First, the results of the validation study are presented (Section 5.6.1), followed by the results of the parameter study (Section 5.6.2). In Section 5.6.3, the shear stresses at the contact interface and von Mises stresses in the soft tissues are presented.

5.6.1 Validation study

Figure 5.3 depicts the pressure distribution predicted by the buttocks model on a rigid surface with the pressure distribution of the volunteer on a rigid surface. The FE buttocks model predicts the maximum pressure located under the bony structures, the location also recorded for the volunteer studies. In both cases, the maximum pressure exceeds 26.7 kPa, the maximum pressure that could be recorded by the pressure map. Figure 5.4 & 5.5 compare the values of the maximum pressure, average pressure and contact area predicted by the FE buttocks model with the volunteer data. The average pressure approaches the experimental value well, while the contact area in the simulation is a little smaller than in the experiment (Figure 5.4 & 5.5). Furthermore, in the simulation some higher stresses

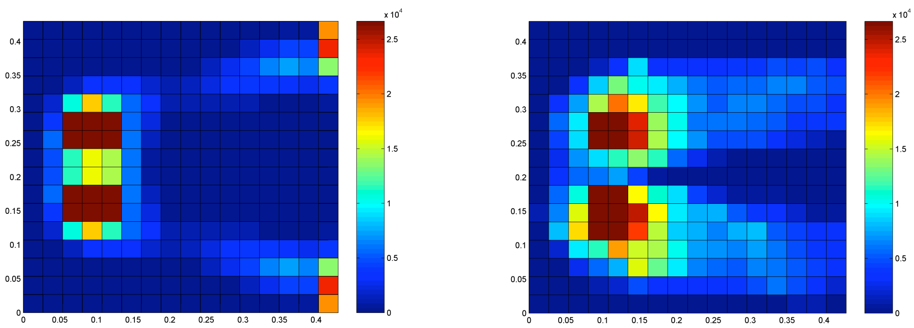


Figure 5.3: *The pressure distribution (Pa) for the rigid surface condition. Left: prediction by the FE buttocks model. Right: measurement of a human male.*

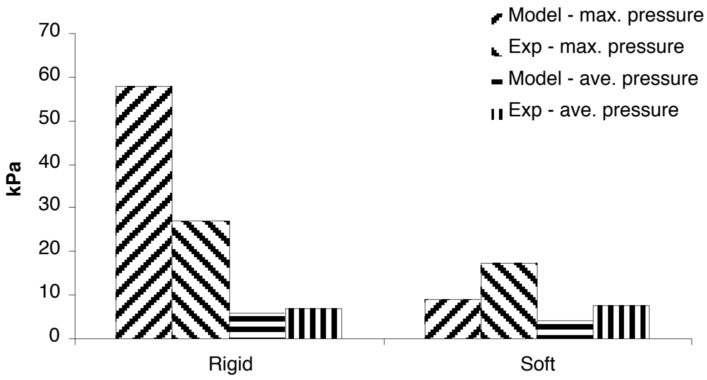


Figure 5.4: *Overview of the validation results: the values for maximum and average pressure predicted by the FE buttocks model with the volunteer results.*

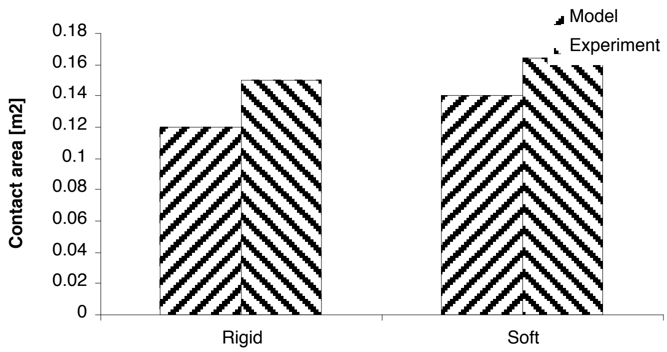


Figure 5.5: *Overview of the validation results: the values for the contact area predicted by the FE buttocks model with the volunteer results.*

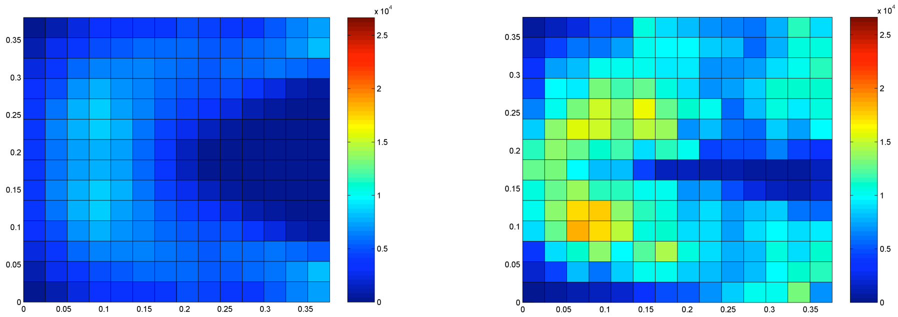


Figure 5.6: *The pressure distribution (Pa) of the FE buttocks model (left) compared to the pressure distribution of a human male (right) while seated on the soft cushion.*

at the front of the cushion, under the legs, are predicted (Figure 5.3).

In Figure 5.6 the pressure distribution predicted by the buttocks model and the volunteer pressure distribution are compared for the condition with the soft cushion. In Figure 5.4 & 5.5 also the selected parameters predicted by the FE buttocks model are compared with the volunteer data for the soft cushion condition. The values for the maximum pressure and the average pressure predicted by the FE buttocks model are some smaller than the values measured in the experiments but in the same order of magnitude. The contact area agrees well with the contact area measured in the experiments. Generally, it can be summarised that the FE buttocks model shows reasonable correlation with the volunteer response for both the rigid and the soft cushion condition.

5.6.2 Parameter study

Figure 5.7 provides an overview of the results of the parameter study. The properties of the human soft tissues and the cushion properties have been varied. The maximum pressure, average pressure and contact area have been normalised, i.e. the values have been defined as a ratio of the values of the reference model on the rigid seat. Figure 5.8 provides an overview of all conditions together with the corresponding seat pressure distributions.

In all simulations, the maximum pressure occurs underneath the ischial tuberosities. In the soft seat simulation, the maximum pressure decreases to 39%

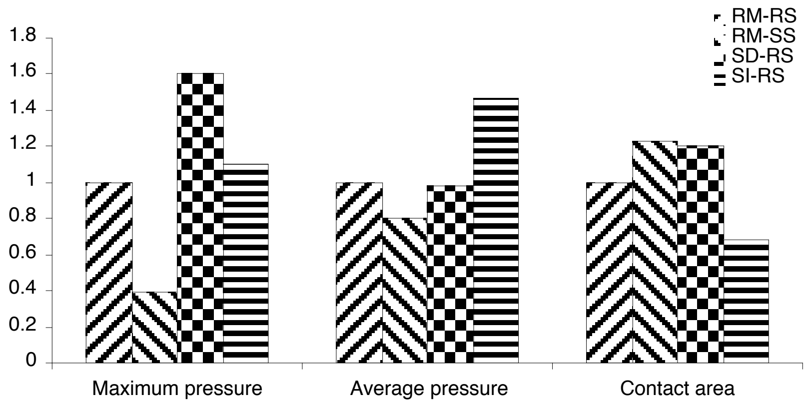


Figure 5.7: *Overview of results of the parameters study: the values of the maximum pressure, the average pressure and the contact area have been normalised with respect to the results of the reference model on a rigid surface.* ***RM-RS****: reference model, rigid surface.* ***RM-SS****: reference model, soft surface.* ***SD-RS****: stiffness human soft tissues decreased, rigid surface.* ***SI-RS****: stiffness human soft tissues increased, rigid surface.*

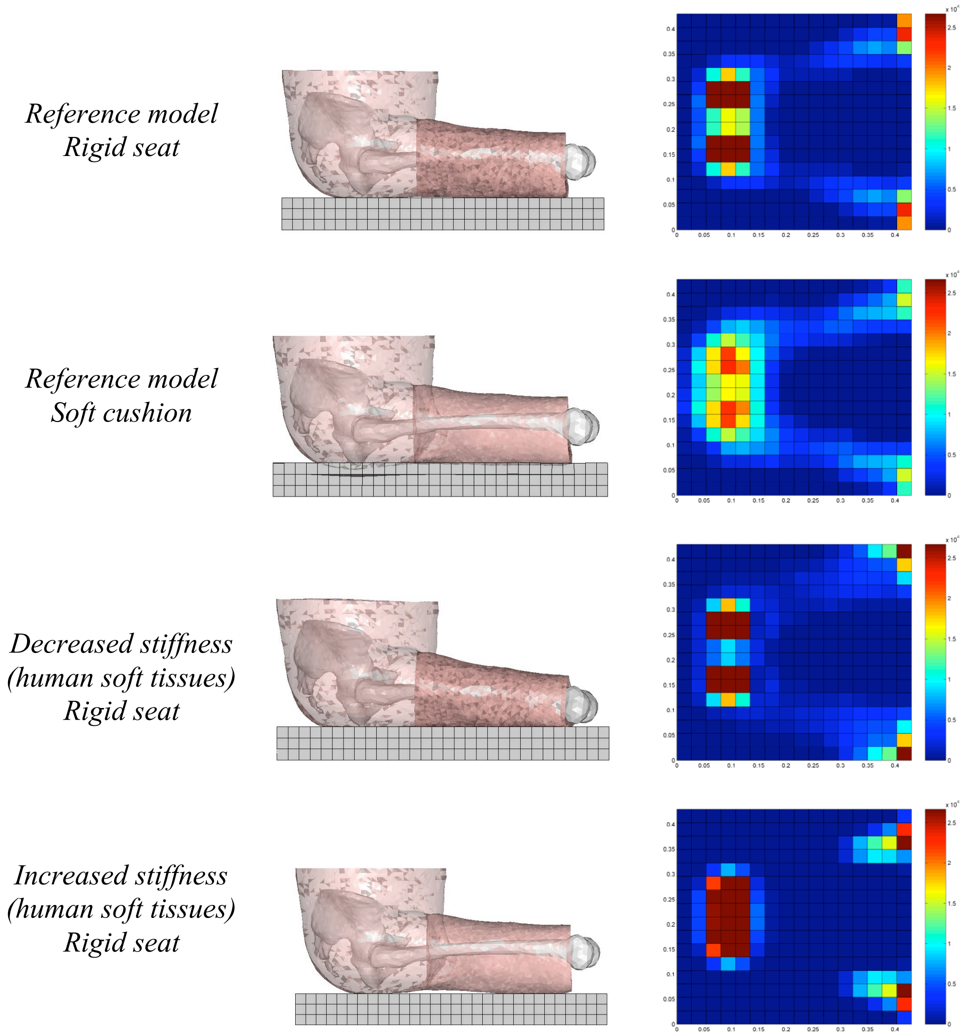
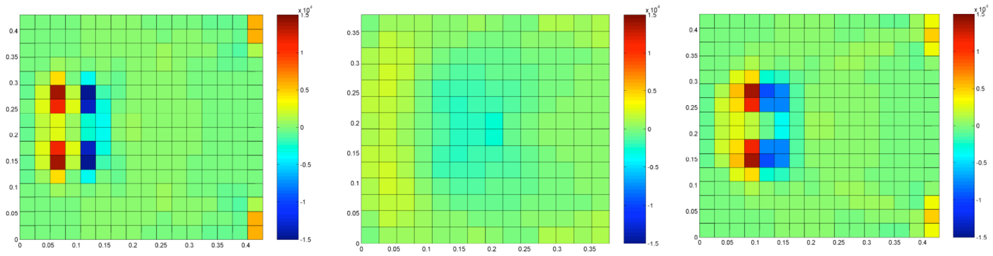


Figure 5.8: *Overview of the results of parameter study*

with respect to the rigid seat situation. The average pressure decreases to 80% due to an increase in the contact area up to 123%. Also, the forces under the thighs are lower than in the rigid seat situation (Figure 5.8).

In the simulations with the decreased and increased human soft tissue stiffness, the maximum pressure increases in both situations, to 160% and 110% respectively. In case of the decreased human soft tissue stiffness, the average pressure decreases to 98% while the contact area increases to 120% with respect to the reference model. The maximum stress occurs in a very small area, where the



(a) (b) (c)

Figure 5.9: *The shear forces (Pa) acting on the contact interface between human and seat for the validated model. Left: rigid surface, pelvis angle 0 degrees. Middle: soft surface, pelvis angle 0 degrees. Left: rigid surface, pelvis angle 5 degrees*

bony structure comes in contact with the rigid surface. It seems that the tissue stiffness is so low that the model is mainly supported by the ischial tuberosities and the soft tissues are compressed or pushed sideward. In the other part of the contact area the stresses are small. In case of the increased human soft tissue stiffness, high local stresses occur in the region underneath the ischial tuberosities and coccyx. The contact area is smaller than the contact area of the reference model: due to the high soft tissue stiffness a small rigid-rigid contact has been created supporting the buttocks model.

5.6.3 Shear stresses at the contact interface and von Mises stresses in the soft tissues

Figure 5.9 shows the shear stresses of the FE buttocks model on the rigid surface (Figure 5.9a) and the soft cushion (Figure 5.9b). The shear stress depicted is the shear stress on the interface in the sagittal plane in anterior-posterior direction (i.e. forward sliding). In all pictures the location of the ischial tuberosities is visible (zero stresses). In the simulation of the model on a rigid surface the maximum shear stress is 19.5 kPa. In the simulation with the soft cushion (Figure 5.9b), the area where shear stresses act increases while maximum shear stress decreases to 6.3 kPa.

Figure 5.10 shows the von Mises stresses of the soft tissues along a sagittal plane through the ischial tuberosities and the coccyx in the rigid cushion simulation. High stresses occur in the soft tissue layers around and underneath the bottom of the ischial tuberosities and the coccyx due to the weight of the upper body. Maximum stresses of 40-50 kPa act in the soft tissues under the ischial tuberosities, a value comparable with the maximum stress acting on the surface. Maximum stresses of 105 kPa act in the soft tissues around the coccyx.

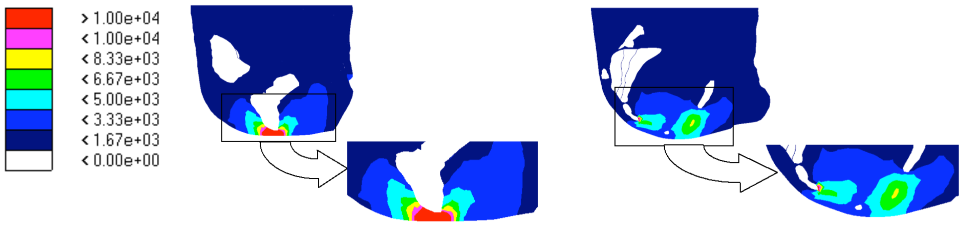


Figure 5.10: *The von Mises stresses (Pa) in the soft tissues along a sagittal plane through the ischial tuberosities (left) and the coccyx (right) for a simulation with the FE buttocks model on a rigid surface.*

5.7 Discussion

This chapter describes the development and the validation of a finite element model of the human buttocks. The main advantage of the present geometry, over models described in literature, is its detailed and realistic representation of the soft tissues and bony structures (in contrast with Chow & Odell, 1978; Dabnichki *et al.*, 1994; Oomens *et al.*, 2003; Todd & Thacker, 1994). The model is based on a seated average male, with equivalent geometry of skin and bony structures, in contrast to Moens & Horváth (2002).

The validation of the FE buttocks model with volunteer experiments on a rigid surface shows that the FE buttocks model predicts realistic seat pressure distributions. The results of the FE buttocks model agree reasonably with the volunteer results and the stresses of the model are of the same order of magnitude as the measured data. The difference in maximum pressure between the predicted value by the FE buttocks model and the experimental value can be contributed to the fact that the pressure mapping system used in the experiments was not able to measure higher stresses than 26.7 kPa. This limits a comparison between the results of the FE buttocks model and the experimental data. Differences in geometry between the model and the volunteers might also cause differences in maximum pressure and contact area.

The geometry is based on the geometry of an old man. This man had, typically for his age, a rounded stomach and thin upper legs. The dimensions of a healthy young average male and the amount of fat and muscles underneath the ischial tuberosities will be different. Further, the geometry of the PMHS was obtained while seated on an automotive seat. The curvature of the seat cushion, visible in the geometry of the lower side of the upper legs, required some manual adaptations. A small indentation between the pelvis and the thighs is still visible in the mesh (Figure 5.8). This caused the separation between the pelvis and the thighs in the seat pressure distributions predicted by the FE buttocks model in simulations on a rigid seat.

As mentioned before, a rigid seat condition is not a realistic seating condition. In daily seating conditions, a mechanical compliance of the seat cushion is present. However, a rigid seat condition is very suitable for the validation of the FE buttocks model, since no disturbances are introduced by a cushion model. The presented FE buttocks model predicts a maximum pressure of 57 kPa on the contact interface with a rigid surface. Similar values are reported in literature (Figure 5.11). It should be noted that comparison between several studies is limited since it is hard to perform reproducible and accurate measurements of seat pressure distributions. Brienza *et al.* (1996) reported a maximum pressure of 76 kPa for subjects on a rigid surface. This value is an average over eight subjects; the values were ranging from 45-86 kPa (i.e. upper limit of the system). Brosh & Arcan (2000) published values of 40 kPa for maximum pressure while seating on a rigid surface. The values reported by Wu *et al.* (1998) and Bader & Hawken (1990) were smaller: Wu *et al.* (1998) reported values of 36 kPa for healthy people sitting on a rigid, flat surface. Bader & Hawken (1990) presented maximum pressures of 18 kPa under the ischium. These values were based on tests with a plywood seat. However, in the studies of Wu *et al.* (1998) and Bader & Hawken (1990) the weight of the volunteers participating in the experiments is less than the weight of the FE buttocks model. This explains the larger maximum pressure predicted by the FE buttocks model than the values reported in the studies of Wu *et al.* (1998) and Bader & Hawken (1990). Further, Bader & Hawken (1990) mentioned that the

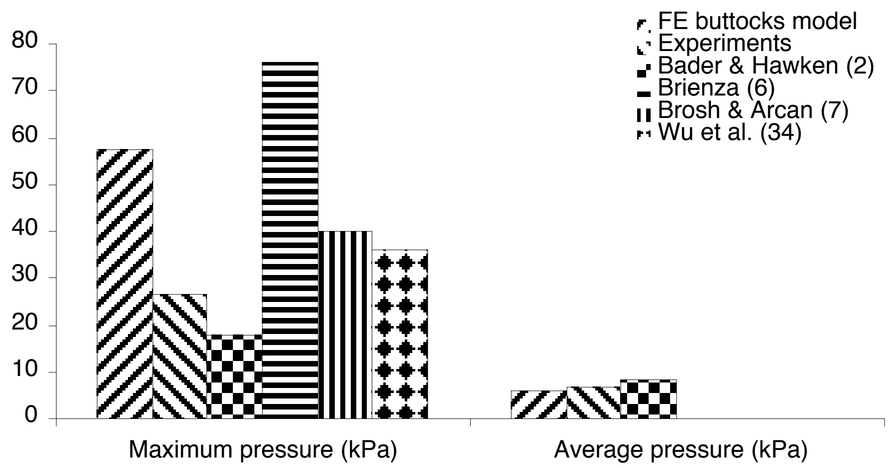


Figure 5.11: *Comparison of the values of maximum and average pressure predicted by the FE buttocks model on a rigid surface with values of volunteer experiments reported in literature.*

values were averages over 20 subjects and that individual differences were large. The experiments were limited by the maximum value the pressure mapping system could measure, i.e. 40 kPa. For some of the subjects this limit was exceeded.

In the validation on a soft cushion, the FE buttocks model shows similar pressure distributions to those measured in the volunteer experiments. In general the values of the maximum pressure and the average pressure predicted by the FE buttocks model are smaller than those measured in the experiments. This may be explained because the measured pressure distributions are not fully symmetrical, causing some higher pressure on one side (Figure 5.6). Also the limitations of the foam material model can cause the lower stresses at the contact interface in the simulation. The values of the contact area predicted by the FE buttocks model agree well with experimental data.

The parameter study shows the large influence of the stiffness of the human soft tissues and seat cushion on the seat pressure distribution at the contact interface (Figure 5.7 & 5.8). Maximum stresses and average stresses are very sensitive to changes in the properties of the human buttocks soft tissues and seat cushion. The simulation of the reference model on a soft cushion shows an expected pattern with respect to the simulation of the reference model on the rigid surface: an increase in contact area in combination with a decrease in average and maximum pressure.

The human buttocks model allows the investigation of the influence of posture on pressure distributions. Figure 5.12 shows the pressure distribution of the validated model on a rigid surface with a pelvis inclination of 0 and 5 degrees backwards. The area with high stresses around the ischial tuberosties increases due to the pelvis rotation and shifts a little forward with respect to the simulation without a pelvis rotation. However, the area with the maximum pressures decreases, i.e. stresses larger then 26.7 kPa. Figure 5.9c depicts the shear stresses in

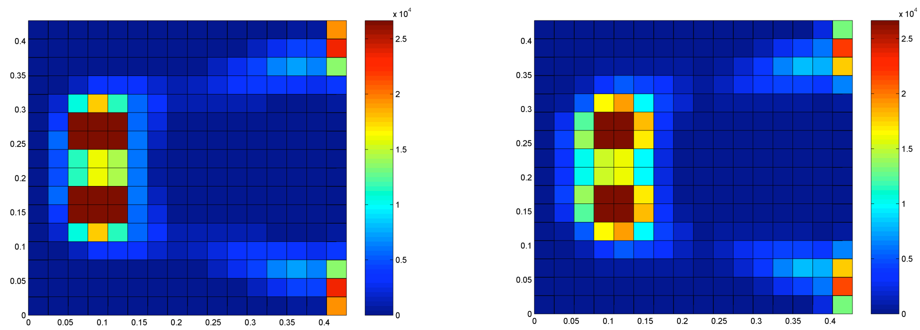


Figure 5.12: *The pressure distribution (Pa) of the FE buttocks model on a rigid surface. Left: pelvis angle 0 degree. Right: pelvis angle of 5 degrees.*

a simulation with the FE buttocks model on a rigid surface but with a change in pelvis angle of 5 degrees. Due to this rotation, the maximum shear stress decreases to 15.6 kPa. The total shear force (product of the sum of the shear stresses and the contact area) acting on the contact interface increases due to an increase in contact area.

The buttocks model predicts maximum stresses of 40-50 kPa in the soft tissues under the ischial tuberosities, a value comparable with the maximum stress acting on the surface (Figure 5.10). Maximum stresses of 105 kPa act in the soft tissues around the coccyx. Oomens *et al.* (2003) reported values of the same order of magnitude: their reported values of 250 kPa are a bit larger than the values of FE buttocks model of present study, which may be contributed to the fact that their model did not include a contribution of a thigh loading. In addition, Oomens *et al.* (2003) reported two areas yielding high stresses for simulations on a rigid seat: one in the muscle layer close to the bone and one in the fat layer close to the skin. Detailed comparison between both models is complicated by the many inherent differences between the two models with respect to geometric description of the bony structures and the level of detail of the soft tissues.

5.8 Conclusions

A finite element model of the human buttocks has been developed for prediction of seat pressure distributions at the contact interface between human and seat. The model has been based on an average seating male. The model comprises a detailed and realistic representation of the bony structures. The soft tissues have been lumped together, whereas only the skin has been modelled separately. The following can be concluded:

- A validation study based on volunteer experiments on a rigid surface shows that the FE buttocks model is able to predict realistic seat pressure distributions. The seat pressure distribution and the values for the maximum pressure, average pressure and contact area agree reasonably well with the volunteer data.
- A validation study based on volunteer experiments on a soft cushion has been performed. The response of the FE buttocks model shows a reasonable correlation with the volunteer data.
- A parameter study has been performed. This study shows that seat pressure distributions are sensitive for variations in seat properties, human soft tissue properties and posture.
- A main advantage of the use of computer models for investigation of the human-seat contact interaction over experimental data is that it is not limited by the measuring system and extends the analysis to other parameters. Shear stresses at the contact interface and stresses and

deformations of the soft tissues underneath the ischial tuberosities are two of such examples.

Chapter 6

Sensitivity study

This chapter describes a sensitivity study with the multi-body human model (Chapter 4) and the FE buttocks model (Chapter 5). The objective is to evaluate the applicability of the models as design tools for car and seat developers in an early stage of the design process. First, a number of seat and car manufacturers all over the world have been contacted and, by means of questionnaires they have responded to the key parameters in the design process of a new comfortable car seat (Section 6.1). A parameter study was then performed to examine whether the models are sensitive to variations in seat parameters that are important for seat developers in the design process of new seats.

Section 6.2 focuses on the sensitivity study on vertical vibrations performed with the multi-body human model and Section 6.3 describes the sensitivity study on seat pressure distributions performed using the FE buttocks model.

6.1 Questionnaire

Car and seat manufacturers have been contacted and asked by a questionnaire for their key parameters in the design of a new car seat. Thirty-seven questionnaires have been sent out all over the world (Europe, USA, Japan). In the questionnaire, the car and seat manufacturers were asked for the following questions:

- If you have to develop a new seat that has to fulfil the current safety and comfort requirements, which parameters/factors would you change in this process in relation to *vibrations* to get a new, more comfortable seat?
- If you have to develop a new seat that has to fulfil the current safety and comfort requirements, which parameters/factors would you change in this process in relation to *seat pressure distributions* to get a new, more comfortable seat?

The questionnaire mentions some possibly relevant parameters, but also offers the respondent to add its own parameters and opinion. The questionnaire is presented in Appendix A.

Thirty percent of the contacted people responded and filled in the form: five responses were received from Japan, four from Europe and two from the USA. Tables A.1 and A.2 provide an overview of the results of the questionnaire on vertical vibrations (Table A.1) and seat pressure distributions (Table A.2). No statistical analyses has been performed with the questionnaire responses: the results should be regarded as an indication. In the question focussing on vertical vibrations, the foam properties, support and seat suspension properties are marked most often (Table A.1). Almost all respondents would vary one of these properties in order to improve a new seat design on its properties in vertical vibrations. Geometry and frame properties seem to be less important for vertical vibrations. Table A.2 shows that the foam properties are very important key parameters for manufacturers in order to improve a seat design on its (dis)comfort level related to seat pressure distributions. Nine out of eleven respondents mentioned this factor. Variations in geometry are also relevant parameters in the design process. Variations in shape and size were most often mentioned. For both the response on vertical vibrations and seat pressure distributions it applies that the kind of response was evenly spread between Europe, Japan and the USA.

6.2 Sensitivity study on vertical vibrations

This section describes a sensitivity study on vertical vibrations using the multi-body human model. The questionnaire showed that variations in cushion properties (thickness, stiffness and damping) and variations in the seat suspension are the most important parameters for seat developers with respect to vibrations. By usage of multi-body techniques in MADYMO, the stiffness and the thickness are related to each other in the definition of the seat properties. Therefore, no variations in cushion thickness have been applied in this study. Section 6.2.1 describes the simulation set-up. Hypotheses are defined in Section 6.2.2.The data analysis and the results are described in the Section 6.2.3 and 6.2.4, respectively. In Section 6.2.5 the sensitivity study on vertical vibrations is discussed. Section 6.2.6 presents the conclusions.

6.2.1 Simulation set-up

The geometry and material properties of the seat model, validated in Chapter 2, and the multi-body human model, validated for vertical vibrations in Chapter 4, have been used for the reference simulation. Also the input signal, used in this sensitivity study, is equivalent to that of the input signal used in Chapter 4. A suspension system has been added, represented by a spring and a dashpot. The arrangement of the reference simulation in the sensitivity study on vertical vibrations is depicted in Figure 6.1.

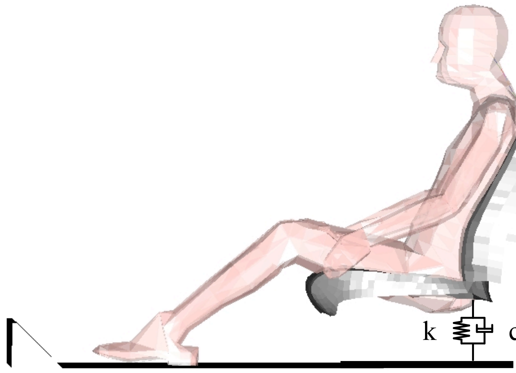


Figure 6.1: *The simulation set-up for the sensitivity study on vertical vibrations*

The sensitivity study contains the following variations:

- Increase and decrease in seat cushion and seat back stiffness by a factor of 2 with respect to the reference seat
- Addition of velocity dependent behaviour to the cushion properties by a damping coefficient: the damping coefficient is varied by a factor of 2 around the critical damping of c_{kr} = 1500 N·s/m
- Decrease in suspension stiffness from rigid to $k = 1 \cdot 10^4$ N/m and $k = 1 \cdot 10^3$ N/m
- Addition of suspension damping: the suspension damping is varied by a factor of 2 around the critical damping of c_{kr} = 2750 N·s/m

In all conditions, the simulation starts at an equilibrium state between human and seat. The linear acceleration of the pelvis in vertical direction has been generated as output.

6.2.2 Hypotheses

For the sensitivity study on vertical vibrations, the following hypotheses have been made:

- Cushion stiffness and damping affect the transfer of accelerations from seat to human
- Addition of a seat suspension system influences the extent to which a seat is able to isolate the transfer of accelerations from seat to the human

6.2.3 Data analysis

Human behaviour in vertical vibrations is determined by the transfer of accelerations from seat to human. Seat properties belong to the factors influencing this transfer. In this sensitivity study, International Standard ISO 2631-1 (1997) has been used to evaluate the human behaviour in vertical vibrations. This document describes values that give an approximate indication of likely reactions to various magnitudes of vibration.

The document states that the weighted root mean square (r.m.s.) of the accelerations shall be determined for each axis of translational vibrations at the surface that supports the person. Since only multi-body techniques, that do not allow deformations, have been used for the seat model and only vertical vibrations and reactions are investigated in this study, the vertical pelvis acceleration has been used. The weighted r.m.s. acceleration is defined by:

$$a_{w,rms} = \left[\frac{1}{T} \cdot \int_0^T a_w^2(t) \cdot dt \right]^{\frac{1}{2}}$$

with $a_w(t)$ the weighted acceleration as a function of time and T the duration of the measurement. The weighted acceleration, $a_w(t)$, is the multiplication of the contact interface acceleration with a prescribed frequency weighting function. This prescribed frequency weighting of the acceleration does not affect the signal at the frequencies between 5 and 8 Hz, but reduces the signal for all other frequencies. Table 6.1 lists the values of $a_{w,rms}$ related to discomfort sensation. It is noted that acceptable values of vibration magnitude for discomfort depend on many factors which vary with each application.

Less than 0.315 m/s^2	Not uncomfortable
0.315 m/s^2 to 0.63 m/s^2	A little uncomfortable
0.5 m/s^2 to 1.0 m/s^2	Fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2.0 m/s^2	Extremely uncomfortable

Table 6.1: *Approximate classification of weighted acceleration in terms of discomfort (based on ISO 2631-1 (1997))*

ISO 2631-1 (1997) also presents the Vibration Dose Value (VDV), which is a fourth power vibration dose method. This method is more sensitive to peaks than the basic evaluation method by using the fourth power instead of the second power of the acceleration time history as a basis for averaging as defined by:

$$VDV = \left[\int_0^T a_w^4(t) \cdot dt \right]^{\frac{1}{4}}$$

with $a_w(t)$ the frequency-weighted acceleration as a function of time and T the duration of the measurement. This VDV method may be important for the judgement of the effects of vibration on human beings when the following ratio is exceeded for evaluating comfort:

$$\frac{VDV}{a_{w,rms} \cdot T^{\frac{1}{4}}} \geq 1.75$$

Griffin (1990) presented the Seat Effective Amplitude Transmissibility (*SEAT%*). It represents an objective measure for comparing one seat to another, which is defined as:

$$SEAT\% = \left[\frac{\int G_{seat}(f) \cdot W_i^2(f) df}{\int G_{floor}(f) \cdot W_i^2(f) df} \right]^{\frac{1}{2}} \cdot 100\%$$

with G_{seat} the autopower spectrum at the human-seat contact interface and G_{floor} the autopower spectrum of the floor. The frequency weighting factor $W_i(f)$ has been based on research of human discomfort (Griffin, 1990): the frequencies between 5-15 Hz in a signal are passed and other frequencies in the signal are reduced. The *SEAT%* has to be interpreted as follows: a value of 100% means that a seat is providing no isolation and is no more comfortable than sitting on the floor of the vehicle, whereas lower percentage values indicate increased seat comfort.

In this study, both the basic evaluation method $a_{w,rms}$, the *VDV* and the *SEAT%* have been calculated and used for evaluation in the sensitivity study on vertical vibrations.

6.2.4 Results

Table 6.2 shows the $a_{w,rms}$, *VDV* and *SEAT%* values for the various conditions of the sensitivity study. Also the ratio between the *VDV* and the $a_{w,rms}$ is listed. Figure 6.2 presents the values of $a_{w,rms}$, *VDV* and *SEAT%* for various parameter variations as ratio of the reference situation.

For most test conditions, the ratio for the $a_{w,rms}$ and *VDV* exceeds or approximates the threshold value of 1.75 (Table 6.2). The exceptions correspond to the case with a twofold increase in cushion stiffness and the simulations with a twofold increase of cushion and suspension damping with values of 1.62, 1.68 and 1.64, respectively. The reference condition is similar to the threshold with a value of 1.78. It is evident that in addition to the basic evaluation method, investigation of the *VDV* and *SEAT%* values is advisable for all simulations.

A decrease in cushion and suspension stiffness highly affects the values for $a_{w,rms}$, *VDV* and *SEAT%*. A decrease in cushion stiffness results in $a_{w,rms}$, *VDV* and *SEAT%* values down to 60% of the reference simulation. A decrease in suspension stiffness even decreases the $a_{w,rms}$, *VDV* and *SEAT%* values down to 40% of the reference condition. The influence of an increase in cushion stiffness on $a_{w,rms}$, *VDV* and *SEAT%* values is limited: the *SEAT%* value increase to 140%, the $a_{w,rms}$ and *VDV* values are similar to the reference condition.

	A_{rms}	*VDV*	*SEAT%*	*Ratio ISO/VDV*
Reference	2.5	11.3	104	1.78
Stiffness2x-	1.8	8.8	64	1.99
Stiffness2x+	2.6	10.8	137	1.62
Damping1500	2.5	10.8	108	1.71
Damping3000	2.5	11.1	107	1.75
Damping6000	2.3	9.8	100	1.68
Suspensionk10-	1.2	7.1	45	2.34
Suspensionk100-	1.0	6.6	71	2.67
Suspensiond1375	2.1	9.4	96	1.77
Suspensiond2750	2.0	8.6	104	1.70
Suspensiond5500	2.0	8.3	107	1.64

Table 6.2: *Results of the sensitivity study on vertical vibrations*

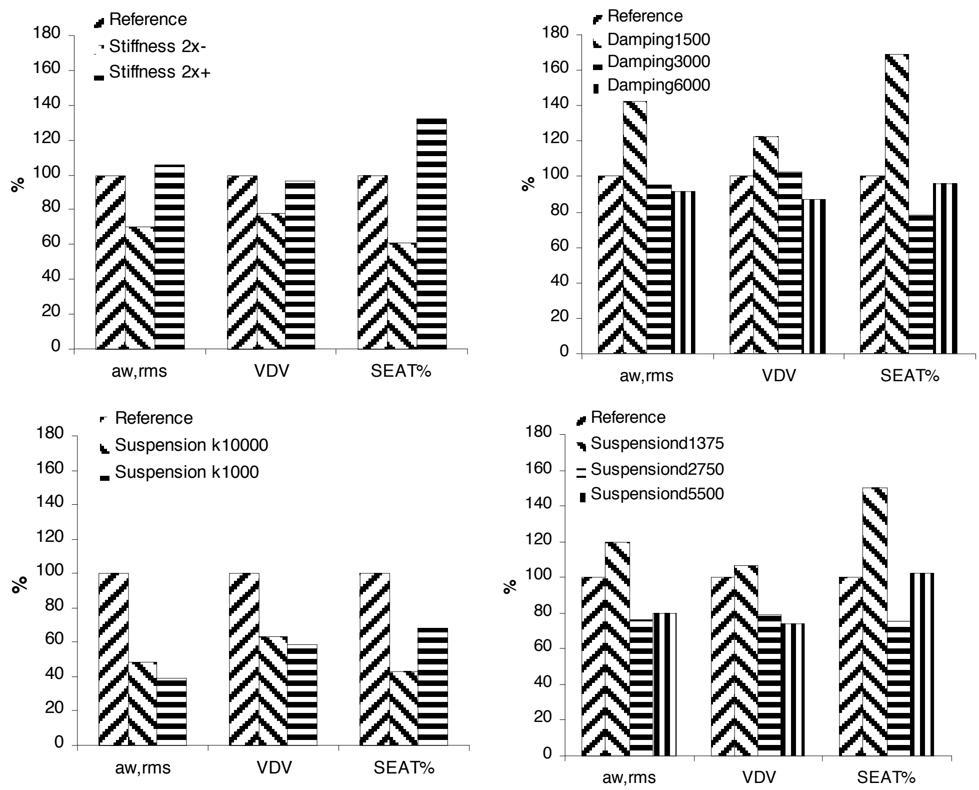


Figure 6.2: *The results of the sensitivity study on vertical vibrations: the values for* a_{rms}*, VDV and SEAT% have been expressed as a ratio of the results for the reference condition*

The addition of velocity dependent behaviour to the seat cushion properties does not seem to affect the values of $a_{w,rms}$, *VDV* and *SEAT%* positively. For a damping coefficient smaller than the critical damping, all parameters increase, even up to 160% of the reference condition. For a damping coefficient larger than the critical damping, the influence is negligible.

Addition of damping to the suspension system affects $a_{w,rms}$, *VDV* and *SEAT%*. For suspension damping values smaller than the critical damping, the values of $a_{w,rms}$, *VDV* and *SEAT%* increase. For suspension damping values larger than the critical damping, the values of $a_{w,rms}$ and *VDV* decrease to lower than 80% of the reference condition.

6.2.5 Discussion

The sensitivity study on vertical vibrations showed that the output of the human model is sensitive for variations in the key parameters of car and seat manufacturers in the design process of a new car seat. The seat cushion and suspension stiffnesses have a large influence on $a_{w,rms}$, *VDV* and *SEAT%*. For example, a decrease in cushion and suspension stiffness causes smaller values for $a_{w,rms}$ and *SEAT%* down till 40 % and 43% of the reference condition, respectively. The influence of the variations, performed in the present sensitivity study, on *VDV* values shows a similar trend but these variations had a smaller effect than on either $a_{w,rms}$ or *SEAT%*.

The influence of the addition of velocity dependent behaviour to the cushion properties on (dis)comfort related parameters is limited. The values, and so the discomfort, increase for damping coefficients smaller than the critical damping. Damping coefficients larger than the critical damping do not have large influence on (dis)comfort related parameters. Its seems that the damping stresses caused by the velocity dependent behaviour are negligible with respect to the elastic stresses.

With respect to the hypotheses, it may be concluded that:

- Cushion stiffness affects the transfer of accelerations from seat to human. The influence of cushion damping is limited.
- The addition of a seat suspension system affects the transfer of accelerations from floor via seat to human. Especially a reduction in the stiffness of the connection between floor and seat has a large influence.

For the majority of the conditions applies that the ratio between $a_{w,rms}$ and *VDV* exceeds the limit of 1.75. Therefore, the investigation of other evaluation methods (*VDV* and *SEAT%)* besides the basic method ($a_{w,rms}$) is very useful. The main advantage of the basic method compared with the other methods is that the former defines a subjective sensation of discomfort (ISO 2631-1, 1997). All conditions simulated in this sensitivity study would be experienced as uncomfortable. It should be noted that the swept sine input signal used in this study is not a realistic input signal, although it comprises a realistic maximum acceleration. Normally the seat is part of a car that provides isolation to vibrations by its tyres and wheel suspension at the lower frequencies. In reality, these seats would never cause such a bad comfort judgement. However, this does not mean that ISO 2631-1 can not be applied in this study. For investigation of various situations with a reference condition, such as in this sensitivity study, ISO 2631-1 still enables the investigation of influence of variations in seat parameters on (dis)comfort sensation. The sensitivity study clearly shows that the variations in seat properties applied in this study result in a different sensation of (dis)comfort. While the reference situation results in a judgement of ‘extremely uncomfortable’, the decrease in seat and suspension stiffness changes this judgement to ‘uncomfortable’ and ‘very uncomfortable’ respectively.

As noted before, ISO 2631-1 (1997) prescribes the usage of the seat acceleration of the contact interface between human and seat. In the present study, the acceleration at the top of the seat cushion has been replaced by the pelvis acceleration, since only multi-body techniques have been used for the seat model. The use of the pelvis acceleration, as opposed to the seat acceleration, could cause some differences in the absolute values of $a_{w,rms}$, *VDV* and *SEAT%* due to the damping effect of the soft tissues under the pelvic bony structures. However, for comparison of various situations, as in this sensitivity study, this effect is not regarded as a problem.

Investigation of the *SEAT%* values shows that in some situations, the values exceed 100%, indicating that the input vibration has been amplified by the seat. Values smaller than 100% indicate isolation of the input acceleration by the seat. The reference simulation and the simulations with the increased seat cushion stiffness and damping coefficient would in effect provide seats that amplify the input vibration (Figure 6.2). However, as remarked before, in reality these seats will never directly be subjected to a vibration input, since a car already provides isolation to the vibration by its tires and wheel suspension. The simulations, in which some suspension is simulated, already show that the *SEAT%* values largely improve when the suspension stiffness is decreased or damping has been added.

6.3 Sensitivity study on seat pressure distributions

The questionnaire showed that variations in thickness, stiffness and density of the seat foam and geometric variations of the seat cushions were considered the key parameters for car and seat developers in the design phase of a new, more comfortable seat with respect to seat pressure distributions.

The set-up for the sensitivity study and the data analysis are described in the Sections 6.3.1 and 6.3.2. The hypotheses defined for the sensitivity study are listed in Section 6.3.3. The results are presented in Section 6.3.4.

6.3.1 Set-up

The standard car seat as described in Chapter 2 was used for the reference seat. The material properties of the foam cushion used in the validation of the FE buttocks model in Chapter 5 (Figure 5.2) have been added to this reference seat (i.e. ρ = 56.1 kg/m^3). A friction coefficient of 0.3 has been defined in the contact interaction between human and seat. This value is of the same order of magnitude as the values reported in Chapter 2. The seat model was discretized, using 8 node hexahedron elements. The reference seat comprises 6 layers of these elements with an element size of 10 mm. The dimensions of the reference seat are shown in Figure 6.3.

The sensitivity study considers the following variations with respect to the reference seat:

- increase and decrease of the width (w) of the seat cushion with 50 mm
- increase and decrease of the depth (d) of the seat cushion with 50 mm
- increase and decrease of the thickness (t) of the seat cushion with 20 mm
- increase and decrease of the foam stiffness with a factor of 2
- increase and decrease of the friction coefficient at the contact interface between human and seat with a factor of 2

Figure 6.4 provides a graphical overview of the geometric variations applied in the sensitivity study. Under all conditions the FE buttocks model has been positioned just above the seat. The FE buttocks model was allowed to settle into the cushion due to an applied gravitational field and reach equilibrium with the seat cushion.

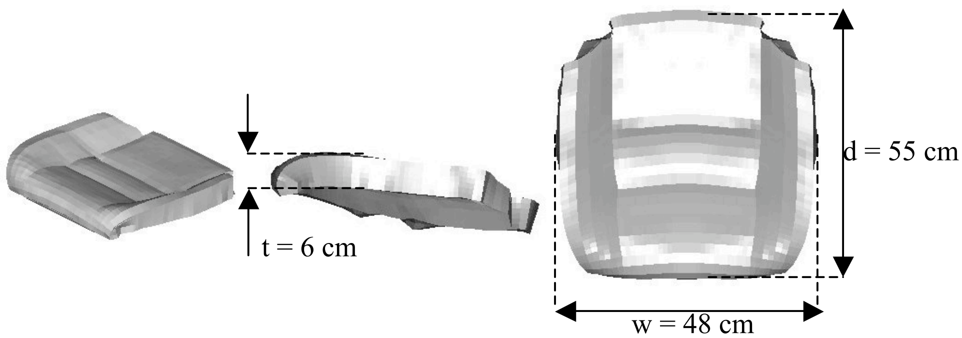


Figure 6.3: *The reference seat model used in the sensitivity study on seat pressure distributions with the FE buttocks model: width (w) = 48 cm, depth (d) = 55 cm, thickness (t) = 6 cm*

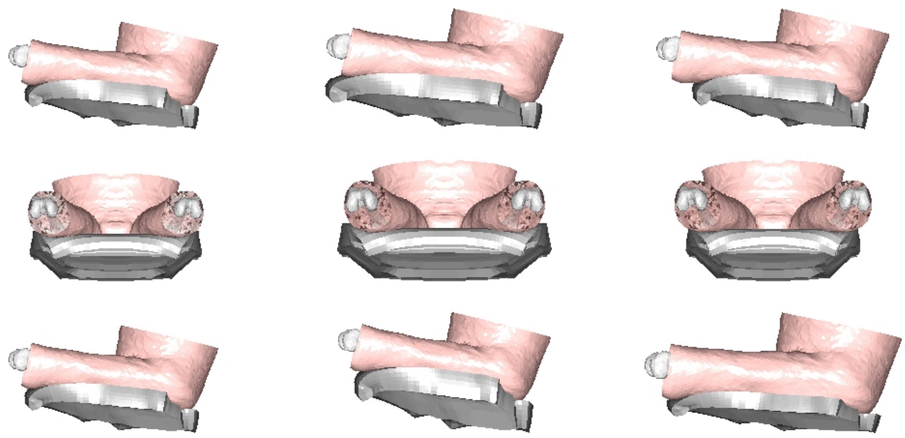


Figure 6.4: *Overview of the geometric variations applied in the sensitivity study. First row: variation in cushion depth (reference seat, increase in depth, decrease in depth. Second row: variation in cushion width (reference model, increase in width, decrease in width). Third row: variation in thickness (reference model, increase in thickness, decrease in thickness)*

In order to be able to investigate seat pressure distributions, the stresses in z-direction, with respect to the global co-ordinate system, at the top layer of the seat cushion have been generated as output parameters. The stresses in the sagittal plane in the elements on the top layer of the cushion model have been generated as output for investigation of the interface shear stresses. Von Mises stresses have been generated as output parameters for investigation of the stress distribution within the soft tissues of the FE buttocks model.

6.3.2 Hypotheses

With respect to the sensitivity study on seat pressure distribution, the following hypotheses have been formulated:

- Variations in cushion geometry and stiffness affect the seat pressure distributions at the contact interface between human and seat
- Variations in cushion geometry and stiffness affect the von Mises stresses in the soft tissues
- The friction coefficient at the contact interface relates to changes in shear stresses at the contact interface

6.3.2 Data analysis

Literature showed that the average pressure, the maximum pressure and the size of the contact area are parameters commonly used to study the relation between seat pressure distributions and (dis)comfort (Ebe & Griffin, 2001; Inagaki *et al.*, 2000; Kamijio *et al.*, 1982; Lee *et al.*, 1995; Milvojevich *et al.*, 2000; Park *et al.*, 1997, 1998; Reed *et al.*, 1991; Tewari *et al.*, 2000; Thakurta *et al.*, 1995; Uenishi *et al.*, 2000; Yun *et al.*, 1992; Zhao *et al.*, 1994). Therefore, these parameters were used in the sensitivity study.

Ahmadian *et al.* (2002) introduced the Seat Pressure Distribution (SPD%) describing the ability of a seat cushion to uniformly distribute pressure. The authors assume that a more uniform distribution is beneficial in terms of (dis)comfort and fatigue, since a uniform pressure minimises the presence of high pressure gradients. The *SPD%* is defined by:

$$SPD\% = \frac{\sum_{i=1}^{n}(p_i - p_m)^2}{4 \cdot n \cdot p_m^2} \cdot 100\%$$

with n the total number of nonzero cell elements, p_i the pressure at the i^{th} non-zero cell and p_m the mean pressure of the n elements. For a perfectly uniform distributed seat cushion each pressure p_i would be equal to the mean pressure p_m resulting in a zero value of *SPD%*.

Furthermore, the shear stresses at the contact interface in the sagittal plane between human and seat have been investigated. These shear stresses are very difficult to measure, but several studies indicate that they have a significant influence on the contact interaction between human and seat (Bader & Hawken, 1990; Krouskop *et al.*, 1990). Both positive (forward sliding) and negative (backward sliding) values have been investigated. Moreover, the internal von Mises stress distributions in the soft tissues were studied in planes crossing the coccyx and the ischial tuberosities.

Unfortunately, no direct relationship between values of the above described parameters and the sensation of (dis)comfort is available in literature, like ISO 2631-1 (1997) does for human exposure in whole-body vibrations. So, in this study no direct link can be made between the variations in seat properties and (dis)comfort.

6.3.4 Results

Table 6.3 and Figure 6.5 show the values of the average pressure, the maximum pressure, the contact area, the maximum and minimum shear stresses and the *SPD%* for all conditions. All parameters have been normalised to the values of the reference seat simulation.

It is clear that geometric variations do influence the human-seat interaction. In particular, the influence of the cushion thickness on the human-seat interaction is large. For example, a reduced cushion thickness can lead to a 40%-60% increase in values of the maximum pressure, shear stresses and *SPD%* compared to the

	Width+	*Width-*	*Depth+*	*Depth-*	*Thick+*	*Thick-*	*Stiff+*	*Stiff-*	*Fric+*	*Fric-*
Average pressure	94	112	98	104	99	98	116	86	101	98
Max. pressure	109	96	106	94	81	160	143	129	101	100
Contact area	107	87	101	96	107	92	86	108	100	101
Max. shear stress	107	94	92	119	111	134	138	99	98	103
Min. shear stress	117	105	103	105	109	139	151	61	105	100
SPD%	61	78	114	88	100	142	148	124	98	106

Table 6.3: *The results of the sensitivity study on seat pressure distributions: the values for the average pressure, the maximum pressure, the contact area and the maximum and minimum shear stresses have been expressed as a ratio of the results of the reference seat simulation*

reference condition. The average pressure and the contact area are less sensitive to variations in cushion thickness. The increase of the cushion thickness has a softening effect on the seat cushion: all nodes on the bottom of the cushion have been supported to the rigid inertial space. This situation can be compared to a situation in which a foam cushion is positioned on top of large rigid surface. In this situation it applies that the thicker the cushion, the larger the cushion deformation is. The more a cushion is able to deform, the less influence the buttocks have of the rigid supporting surface. This results in a decrease of the maximum pressure. On the other hand, in case of a decrease in cushion thickness, the cushion is less able to deform. The influence of the rigid support of the cushion increases and the maximum pressure increases.

The influence of cushion width and depth was more limited than variations in cushion thickness. The variations in the former two parameters influence the average pressure, maximum pressure, contact area, shear stresses and *SPD%* by less than 20% with respect to the reference condition. An increase of the cushion width by 50 mm decreases the average pressure and the *SPD%* by 6% and 39%, respectively, whereas the maximum pressure and shear stresses increase with 9% and 17%, respectively. A decrease in cushion width of 50 mm increases the average pressure and decreases the maximum pressure and the *SPD%*. An increase in cushion depth increases the contact area and the *SPD%* and decreases the shear stresses. A decrease in cushion depth results in smaller values for the maximum pressure and the *SPD%*; the shear stresses increase up to 19%.

The foam stiffness has a major influence on the human-seat interaction. An increase or decrease in cushion stiffness results in a 16% increase and a 14% decrease in the average pressure. The maximum pressure increases up to 43% and 29% due to the increase and decrease in cushion stiffness respectively. The contact area varies up to 14% with respect to the reference simulation due to variations in

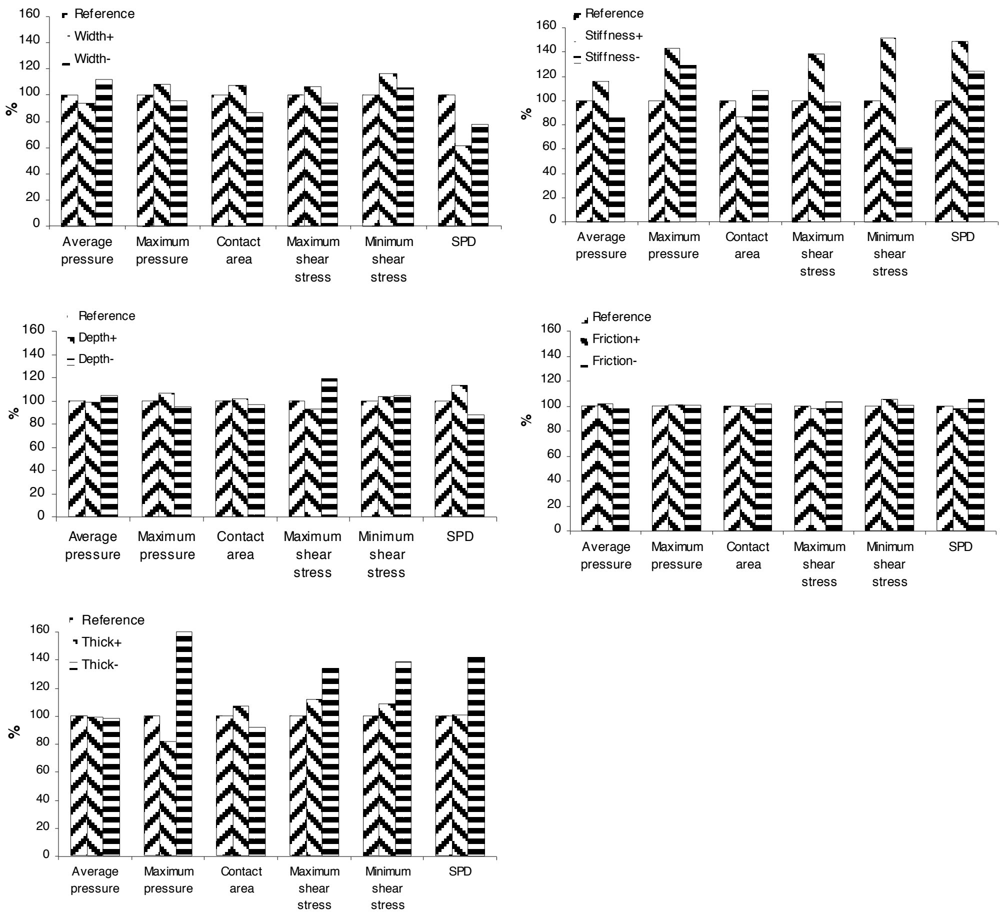


Figure 6.5: *The results of the sensitivity study on seat pressure distributions: the values for the average pressure, the maximum pressure, the contact area and the maximum and minimum shear stresses have been expressed as a ratio of the results of the reference seat simulation*

cushion stiffness. The shear stresses increase 51% due to an increase in cushion stiffness, while a decrease in cushion stiffness leads to a reduction of the shear stresses to 61% of the reference simulation. The *SPD%* increases due to both an increase and a decrease in cushion stiffness, to 48% and 24% respectively. In case of a decrease of the cushion stiffness, the support of the buttocks by the cushion wings decreases (due to the softening effect) and the pelvis region is subjected to larger loads. In case of an increase in cushion stiffness, the support of the buttocks by the cushion wings increases. In both cases, the pressures at the contact interface are more distributed than in the reference simulation.

The influence of the friction on the shear stress distribution at the contact interface between human and seat is limited. In all situations, they do not vary more than 5% with respect to the reference condition. It seems that the range of friction coefficients defined in this sensitivity study is too small to notify any significant differences between the various situations in the static application of this sensitivity.

Figure 6.6 shows the von Mises stresses in the human soft tissues for those simulations in which differences were discernible with respect to the reference simulation, i.e. the simulation with a decrease in cushion width and the simulations with the variations in thickness and stiffness. The von Mises stresses have been depicted in the sagittal plane, along the mid-sagittal plane through the coccyx and along a plane through the ischial tuberosities. Furthermore, the von Mises stresses have been depicted along the frontal plane through the ischial tuberosities. Figure 6.6 shows that in case of a decrease in cushion width, the von Mises stresses in the human soft tissues increase, especially in those areas supported by the cushion wings. The width of the cushion has become too small for the buttocks and the buttocks are stuck between the cushion wings. The increase of cushion thickness results in a softer cushion: the contact area increases (Table 6.3, Figure 6.5), the area with stresses up to 5 kPa under the ischial tuberosities decreases and the buttocks are not only supported by the area around the ischial tuberosities, but also by the thighs (the stresses increase in this region). A decrease in cushion thickness causes higher stressses around the ischial tuberosities and the coccyx, whereas the thigh pressure decreases. The buttocks are mainly supported by the pelvis region. In case of an increase of the cushion stiffness with a factor of two, the stresses in the human tissues under the ischial tuberosities and the coccyx increase. Also the stresses in the thighs increase. In case of a decrease of the cushion stiffness with the stresses around the coccyx and the ischial tuberosities increase. On the other hand, the stresses in the thighs decrease in case of a decrease in cushion stiffness.

6.3.5 Discussion

The sensitivity study on seat pressure distributions showed that the output of the FE buttocks model is sensitive to variations in seat design parameters relevant for seat designers in the development process of new car seats. Especially variations in cushion thickness and stiffness highly influence those factors relating to the (dis)comfort sensation of drivers: maximum pressure, average pressure, contact area, shear stresses and *SPD%*. The influence of variations in cushion width and depth and the friction on the contact interface between human and seat is more limited.

Normally, variations in density would affect the seat pressure distribution in a similar way as variations in stiffness do. However, in the definition of the foam material in MADYMO (TNO Automotive, 2001) an experimental stress-strain

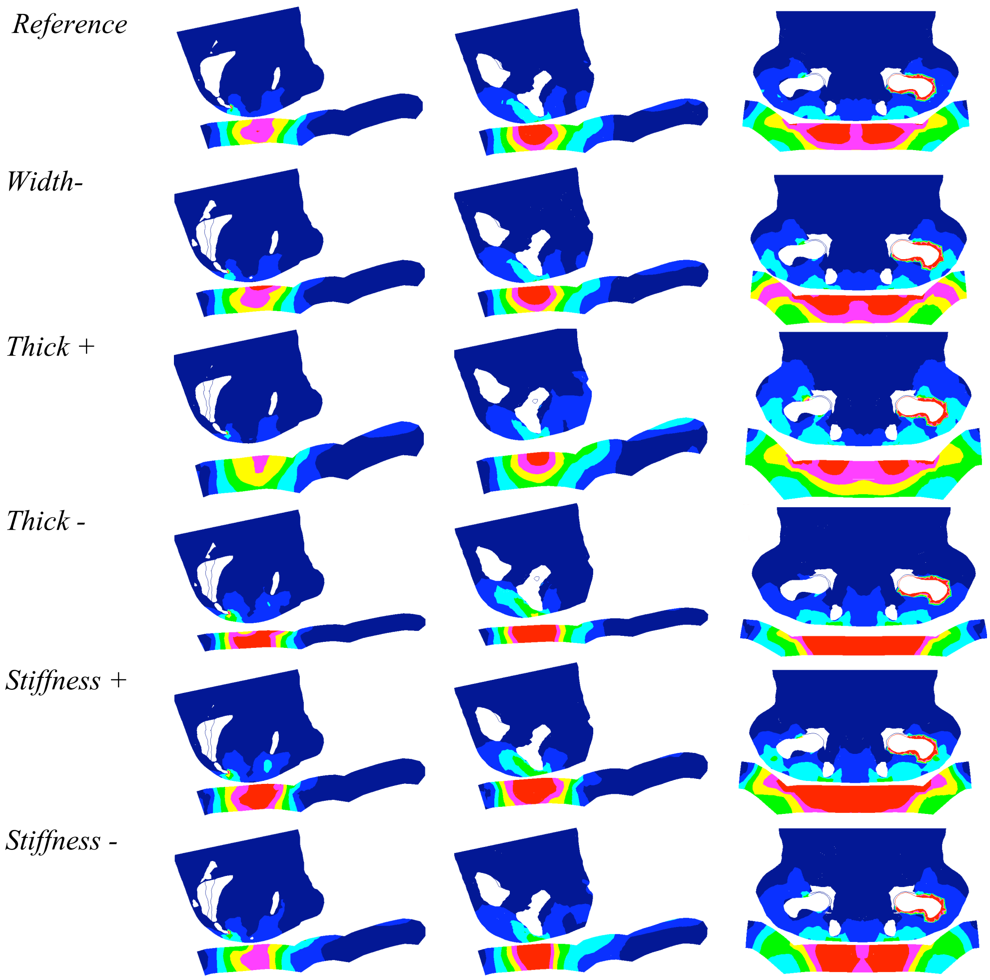


Figure 6.6: *The von Mises stresses (Pa) in the human soft tissues. First column: stresses along mid sagittal plane through coccyx. Second column: stresses along sagittal plane through ischial tuberosities. Third column: stresses along frontal plane through ischial tuberosities.*

relationship of the cushion is required for input to the model. The density is only taken into account in inertial/dynamic effects and in calculation of the time step. Since the current sensitivity study only focuses on quasi-static conditions, the influence of the density on the seat pressure distribution in current sensitivity study is negligible. For that reason, variations in density have not been taken into account in this sensitivity study.

Regarding the hypotheses defined in Section 6.2.2 it may be concluded that:

- Variations in geometry and cushion stiffness affect the seat pressure distribution at the contact interface between human and seat. Especially, the seat cushion thickness and stiffness have a large influence. Variations in cushion width and depth have a limited influence.
- Variations in cushion stiffness affect the von Mises stresses in the soft tissues. Variations in cushion geometry have a limited influence on the von Mises stresses in the soft tissues. Only a decrease in cushion width seems to affect the stresses in the soft tissues.
- The variations in friction coefficient, applied in this sensitivity study, do not affect the shear stresses at the contact interface between human and seat.

The sensitivity study with the FE buttocks model on seat pressure distributions demonstrates that the output of the simulations with the seat model and the FE buttocks model is sensitive to variations in key seat design parameters, although the seat has been represented in a simplistic manner, since no frame and spring bed have been modelled. The exact influence of these variations on comfort is hard to describe. No ISO standards exist for the relation between pressure measures and (dis)comfort, like ISO 2631 (1997) does for human comfort sensation in vibrations. The values for the *SPD%* are probably most easily to relate to comfort: the better the stresses are distributed over the contact interface, the higher the comfort score. However, this is only partly true: when the stresses are distributed very well (the *SPD%* value approaches zero), the support a seat supplies will decrease as well. In case the support is too low, the comfort sensation will decrease. More research will be required to report the exact relations between comfort and the objective parameters that can be distilled from a seat pressure distribution.

Moreover, the FE buttocks model might provide more insight in the (dis)comfort sensation of people: the model can predict the internal stresses in the soft tissues and the shear stresses at the contact interface. Since both parameters are hard to measure experimentally, the influence of these parameters on the (dis)comfort sensation is unclear. The FE buttocks model can be a valuable tool to map the factors related to the human seat contact interaction, in order to increase the knowledge of experienced (dis)comfort. The usage of simulations with the FE buttocks model in combination with the current way of investigations on (dis)comfort would have a significant additional value and results in a more detailed analysis on human (dis)comfort.

6.4 Conclusions

A sensitivity study on seat pressure distributions and vertical vibrations has been performed using the FE buttocks model and the multi-body human model. In the sensitivity study, seat parameters have been varied of which seat developers indicated that they are key factors in the design process of a new, more comfortable car seat. The following can be concluded:

- The sensitivity study on vertical vibrations has shown that the multi-body human model is able to predict the influence of variations in cushion and suspension properties on human (dis)comfort sensation in vertical vibrations.
- The sensitivity study on seat pressure distributions showed that the FE buttocks model is able to predict the influence of variations in seat geometry and seat properties on the seat pressure distribution at the contact interface between human and seat.

The above findings indicate that both models are rather promising tools for seat developers in early stages of the design process of a new, more comfortable seat.

Chapter 7

Discussion, conclusions and recommendations

This research aims to contribute to the development and application of numerical tools for comfort analyses of automotive seating. Computer models of human and seat enable analyses of (dis)comfort in early stages of the design process for both static and dynamic conditions. Thereby, the development time and costs of new car seats could be reduced and mechanics inside the human due to the contact interaction between human and seat can be investigated. The objectives of this research were formulated in Chapter 1 as:

- The development and validation of a human body model that is suitable for realistic prediction of seat-to-human transmissibilities in vertical vibrations.
- The development and validation of a human buttocks model that is able to predict realistic seat pressure distributions at the contact interface between human and seat. It should be possible to include this model in the model validated for vertical vibrations
- Performance of a sensitivity study to show the suitability of the numerical human body and seat models in comfort analyses for seat designers in the development process of new car seats.

In this Chapter, the main findings of this research are discussed. In section 7.1, the development and application of the human model for vertical vibrations is discussed. Section 7.2 deals with the FE buttocks model developed for the prediction of seat pressure distributions. Section 7.3 deals with an objective qualification of the validation results of the numerical models. Section 7.4 discusses the interaction between the numerical tools and (dis)comfort. In Section 7.5 conclusions are drawn. Finally, in Section 7.6 recommendations are given for future research.

7.1 Human behaviour in vertical vibrations: experiments and simulation

In Chapter 3, volunteer experiments on a rigid seat and a standard car seat were described. The volunteer experiments were meant to investigate the human behaviour in vertical vibrations by transmissibility and non-linear behaviour. Previous studies reported in literature only investigated the transfer of signals from seat to human. New in the present study was that human responses have been separated from influences of seat parameters by distinguishing seat-to-human transmissibility from the behaviour inside the human body, i.e. pelvis-to-T1/head transmissibility. The main findings from the volunteer experiments were:

- Clear resonance frequencies appeared in all seat-to-human transmissibilities and transmissibilities inside the human from pelvis to seat.
- A large inter-subject variability was found which can mainly be contributed to differences in initial posture and anthropometry between the volunteers.
- There is a large influence of a seat on the human behaviour when subjected to vertical excitations.

These experiments have been used in Chapter 4 for the validation of the multi-body occupant model for vertical vibrations. Additionally, the spinal local forces were investigated with the human model. The validation study showed that:

- The seat-to-human transmissibilities of the 50th percentile human occupant model agree reasonably well with the volunteer responses
- Investigation of spinal local forces showed that both compressive and shear forces act in the spine when subjected to vertical vibrations

Although a first step in the validation process of the multi-body occupant for vertical vibrations is performed, extension of the validation of the multi-body human model for vertical vibrations is required, both on whole-body level in terms of seat-to-human transmissibility as on segment level in terms of spinal forces. This extended validation has to focus on the frequency domain between 0-25 Hz, which is common for analyses of human behaviour in vertical vibrations. Further, experiments with a rigid seat without a backrest would be very useful for the validation of the spinal behaviour of the multi-body human model in vertical vibrations without any environmental disturbances.

The validation study showed a decreasing correlation in seat-to-human transmissibilities with the volunteer experiments from pelvis to head. The spine and neck model require modifications to improve these correlations. A more detailed representation of the muscles in the spine and the neck and its functioning, as in the detailed neck model by van der Horst (2002), may lead to better results. In Chapter 4, the effect of muscles has been modelled relatively simple by means of rotational stiffnesses. Literature reports on the influence of muscle co-contraction on the human-to-seat transmissibility. In the detailed neck model (van der Horst, 2002) all soft tissues have been modelled separately and muscle activation can be defined. The model can easily be included in the multi-body occupant model. Limitation of the current detailed neck model is that the head does not adopt a stable upright position when subjected to gravity only. A separate study is required to determine the muscle activation in static conditions. The usage of optimisation techniques enables to find the activity of each muscle related to different postures.

7.2 FE buttocks model and seat pressure distributions

Chapter 5 describes the development and validation of a finite element model of the human buttocks for prediction of seat pressure distributions. The model contains a realistic geometric description of the bony structures. The soft tissues have been lumped together with only the skin properties modelled separately. The validation study showed that the seat pressure distributions predicted by the FE pelvis model agree well with the volunteer results and the stresses of the model are of the same order of magnitude as the measured data.

Currently, the FE buttocks model is a separate model, but in the set-up it is taken into account that the FE buttocks model can be included in the multi-body occupant model. A main advantage compared to models published in literature, is its detailed and realistic geometric representation of the soft tissues and bony structures. It enables analyses of posture in relation to seat pressure distributions by the inclusion of the hip joints and analyses of contact interface shear forces and stresses inside the human soft tissues.

The current validation can be regarded as a valuable first step. Extension is required to improve the reliability and accuracy of the model. This requires reproducible volunteer experiments with a significant number of subjects involving both rigid seat and soft seat conditions. Special attention should be paid to the postural control of the volunteers.

The current mesh has been based on the geometry of an old man seated on an automotive seat, which is a limitation. A healthy man would have more muscles and fat in his legs and underneath the ischial tuberosities, resulting in a different stress distribution at the contact interface between human and seat. Moreover, the geometry was digitised while the subject was seated in a car seat. Consequently, the buttocks and the back of the legs were indented. This initial indentation in the mesh was removed manually as part of this project. However, a small indentation in the buttocks and thighs is still visible in the mesh, resulting in a separation between the stress distribution of the buttocks part and the thigh part (Chapter 5).

The FE buttocks model has been developed in MADYMO. MADYMO uses the explicit time integration method to solve the equations of motion. For the short duration and the complex dynamic contact interactions in crash analyses, this explicit time integration method is very suitable. However, for the quasi-static applications of the FE buttocks model described in this thesis this results in high a computational time by the required small time step. For these quasi-static applications an implicit time integration method is more effective. The decision to use MADYMO has been based on the objective that it should be possible to include the FE buttocks model into the multi-body occupant model. This will enable combined analyses of human behaviour in vertical vibrations by seat-to-human transmissibilities and seat pressure distributions. This dynamic application, requiring a detailed description of contact interaction between human and seat and the prediction of the human non-linear behaviour, favours the use of an explicit code. For that reason, also for the development of the FE buttocks model MADYMO has been used.

7.3 Objective qualification of numerical results

The numerical models, developed in the Chapter 2-5, have been validated based on engineering judgement. A more objective procedure for validation of the output signal of the numerical models with respect to volunteer responses is required. This will also enable the comparison between various models published in literature. However, currently no guidelines exist for comparison of numerical with experimental results for ergonomic applications. ADVISER (van Hoof *et al.*, 2003) is an evaluation and rating tool enabling the user to compare various graphs based on objective criteria. ADVISER has been developed within a European project aiming to contribute to an increase of the status of virtual testing to a comparable level as attained in current regulated crash-test procedures. An important step in this process is the development of procedures and guidelines to standardise numerical models and simulations. The software tool ADVISER has been developed to facilitate the implementation of this step in passive safety design and regulations. In Section 7.3.1 and 7.3.2 an approach for objective evaluation of numerical with experimental results is described based on ADVISER. All criteria used in Section 7.3.1 and 7.3.2 are currently available in ADVISER. It should be regarded as a first step towards an objective evaluation method, which will have to be further developed in future.

7.3.1 Human behaviour in vertical vibrations

In case of analyses of human behaviour in vertical vibrations (Chapter 4), criteria could be defined for the location of the resonance frequency in the seat-to-human transmissibilities, the amplitude of the signal at the resonance frequency and the ratio between the part of the numerical curve inside the experimental corridor and outside the corridor. The quality score on the location of the resonance frequency in the seat-to-human transmissibilities could be defined by:

$$Frequency\_score_{Overall\_Extremum} = \left(1 - \frac{\left|Freq_{Overall\_Test\_Extremum} - Freq_{Overall\_Model\_Extremum}\right|}{Evaluation\_domain}\right) x100\%$$

with $Freq_{Overall\_Test\_Extremum}$ the resonance frequency of the experiments, $Freq_{Overall\_Model\_Extremum}$ the resonance frequency of the numerical simulation and $Evaluation\_domain$ the frequency domain analysed. The score on the amplitude of the seat-to-human transmissibilities at the resonance frequency could be defined by:

$$Amplitude\_score_{Overall\_Extremum} = \left(1 - \frac{\left|Amplitude_{Overall\_Test\_Extremum} - Amplitude_{Overall\_Model\_Extremum}\right|}{\left|Amplitude_{Overall\_Test\_Extremum}\right|}\right) x100\%$$

with $Amplitude_{Overall\_Test\_Extremum}$ the amplitude of the experimental signal at the resonance frequency and $Amplitude_{Overall\_Model\_Extremum}$ the amplitude of the simulation signal at the resonance frequency. In both formulas, the experimental value could be based on the mean value of all volunteer tests. The evaluation with respect to the corridors could be defined by:

$$Corridor\_score = \left(1 - \frac{Number\_of\_points\_simulation\_inside\_corridor}{Number\_of\_points\_simulation\_outside\_corridor}\right) x100\%$$

Table 7.1 lists the results of the objective quantification of the validation results of the human model for vertical vibrations based on the above assumed criteria for both the rigid seat condition and the standard car seat condition.

7.3.2 Seat pressure distributions

In case of analyses of seat pressure distributions, criteria could be defined for comparison of the values of the maximum pressure, the average pressure and the contact area predicted by the FE buttocks model with the experimental results. The score could be defined by:

	Rigid seat conditions				*Standard car seat conditions*			
	Total	*Ampl.*	*Freq.*	*Cor.*	*Total*	*Ampl.*	*Freq.*	*Cor.*
Seat-to-pelvis	92 %	87 %	98 %	89 %	42 %	0 %	99 %	25 %
Seat-to-T1	67 %	55 %	94 %	54 %	42 %	26 %	95 %	6 %
Seat-to-head	15 %	0 %	13 %	32 %	51 %	27 %	99 %	26 %
Total score	58 %				45 %			
Overall score	52 %							

Table 7.1: *Results of the objective quantification of the validation of the human model for vertical vibrations*

$$Value\_score = \left(1 - \frac{Value_{Test} - Value_{Model}}{Value_{Test}}\right) x100\%$$

with $Value_{Test}$ the value of the maximum pressure, average pressure or contact area of the volunteer experiments and $Value_{Model}$ the corresponding values of the numerical simulation. Table 7.2 lists the results of the objective quantification of the validation results of the FE buttocks model on a rigid and a soft cushion.

7.3.3 Discussion

In general, the results of objective quantification of the validation results of the numerical models (Table 7.1 & 7.2) agree with the qualitative judgements described in the Chapter 2-5. Table 7.1 represents the decreasing correlation from pelvis to head in the seat-to-human transmissibilities for the rigid seat vibration experiments. The results on the standard car seat experiments reflect that the resonance frequency is predicted well, but the amplitude is overestimated. Table 7.2 represents the reasonable correlation between the FE buttocks model and the experiments well. The score on the maximum pressure in the rigid seat experiments has been set to 'Not applicable' since the experiment was limited by the properties of the measuring system (Chapter 5).

As noted before, the above described approach for the objective evaluation method for comparison of results from a numerical simulation with experimental results should be regarded as a first step in the definition of guidelines for validation of numerical models for comfort analyses. More research is required on the definition of more sophisticated criteria and guidelines for validation of numerical models developed for ergonomic applications. In case of analyses of human behaviour in vertical vibration its is recommended to include also the prediction of a second or third resonance frequency. In case of prediction of seat pressure distributions, it is recommended to include a criterion evaluating the shape of the distribution.

Further, the described approach is mainly based on 'a distance only error score', which means that the difference in magnitude between the numerical and

	Maximum pressure	*Average pressure*	*Contact area*
Rigid seat	Not applicable	89 %	79 %
Soft seat	80 %	60 %	85 %
Total	80 %		

Table 7.2: *Results of the objective quantification of the FE buttocks model for seat pressure distributions*

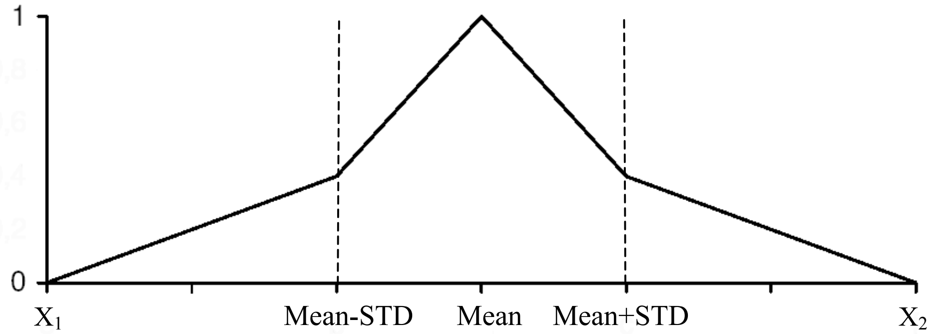


Figure 7.1: *Example of a correlation function suitable for objective evaluation of numerical versus experimental results*

experimental results are evaluated. For both the prediction of seat pressure distributions and the human behaviour in vertical vibrations, it is recommended to extend this method to one which uses a statistical function. This enables the user to define a correlation function prescribing the correlation score as a function of the distance between the numerical result and the mean value of the experiments (Figure 7.1). In this case, the user can make a distinction in judgement between values close to the mean value, values within the standard deviation, values outside the standard deviation but within certain boundaries (X_1, X_2) or values outside these boundaries.

7.4 Numerical tools and comfort

The human models, that were developed and validated in Chapters 2-5, were used in a sensitivity study (Chapter 6). It has been investigated whether the output of the models is sensitive to variations in seat parameters that are relevant for seat developers in the design process of a new, more comfortable car seat. The sensitivity study was based on parameters that are reported in literature to correlate to (dis)comfort. The sensitivity study showed that the human occupant model and the FE buttocks model are suitable to predict the influence of variations in seat parameters on human behaviour in vertical vibrations and seat pressure distributions, respectively.

The seat cushion stiffness is a factor that has been varied in both the sensitivity study on vertical vibrations and the sensitivity study on seat pressure distributions. In both studies the stiffness has been varied with a factor of two. The study on vertical vibrations showed that an increase in cushion stiffness resulted in an increase in the (dis)comfort related parameters, while a decrease resulted in a decrease in the (dis)comfort related parameters. According to ISO 2631-1 (1997), the discomfort level would be reduced by a decrease in cushion stiffness. The study on seat pressure distributions showed that due to an increase in cushion stiffness the normal and shear stresses increase. Although no direct relationship has been reported between (dis)comfort and seat pressure distributions, it can be assumed that an increase of all stresses at the contact interface between human and seat will cause an increased discomfort feeling. A reduction in cushion stiffness decreases the shear stresses and average pressure and increases the contact area and the maximum pressure. As explained in Chapter 5, the increase in maximum pressure can be contributed to the rigid connection of the bottom node layer with the surroundings. The decrease in average pressure, which is generally assumed to decrease the discomfort, seems to be contradictory with the increase in maximum pressure, which would suggest an increase in discomfort. Summarising, an increase in cushion stiffness will result in an increase in discomfort for both vertical vibrations and seat pressure distributions. For a decrease in cushion stiffness, the results of the present sensitivity study are not so evident. This also indicates that the (dis)comfort parameters have to be selected carefully. The discomfort score is very sensitive for the choice of objective parameters: the various parameters may result in contradictory judgements.

The influence of the variation in cushion stiffness in the vibration study seems to be larger than in the study on seat pressure distributions. However, this does not mean that vibrations affect the discomfort sensation more than seat pressure distributions: such pronouncements require due caution, since in the present thesis vibrations and seat pressure distributions apply for different situations. The vibration study refers to dynamic conditions, while the sensitivity study on seat pressure distributions has been performed for static conditions. Only when the influence of variations in cushion stiffness affects the seat-to-human transmissibility in vibrations more than it influences seat pressure distributions in vibration conditions, such a conclusion would be justified.

A limitation of the sensitivity study is that the parameters have been varied limitedly. It can be regarded as a first step towards a real design study. In the sensitivity study, each value has been varied independently. No cross references have been simulated. The use of Design of Experiments (DoE) techniques enables a more efficient choice of design variables. By a smart definition of the design variables, the influence of each variable can be tested in more detail and even more parameters can be included without increasing the amount of simulations.

In ergonomic applications, it is important to take the inter-subject variability into account. The experiments on human behaviour in vertical vibrations (Chapter 3) and seat pressure distributions (Chapter 4) showed the large variability between the subjects. The variation in anthropometry between subjects is one of the factors causing this inter-subject variability. A design is not developed just for the 50th percentile occupant male, but for a population of occupants. For that reason, the introduction of a scalable human model would be a major step forward in the introduction of numerical tools for comfort analyses of automotive seating. The user can then define a human model with any anthropometry he/she prefers and evaluate a new design for its (dis)comfort level with a group of human models representative for the target group of the new design. A scalable human model would allow investigation of the influence of anthropometry on the seat-to-human transmissibilities in vertical vibrations and on seat pressure distributions. Main limitation of the current scaling techniques for dynamic human models is that they are only suitable for scaling of simple geometries, like ellipsoids and planes. Accurate scaling of finite element systems (FE buttocks model) or the skin of the occupant model is not yet possible. Further research in this field is required.

Another aspect in the inter-subject variability is the posture. The influence of posture on seat-to-human transmissibility has been reported in literature (Griffin, 1990). In experiments always small differences in initial posture will exist between various volunteers. But also the mass distribution inside the human, muscle tension and the biomechanical properties, in e.g. the spine, muscles and soft tissues in the buttocks area, vary per person. The parameter study in Chapter 5 showed that seat pressure distributions are very sensitive for variations in the human soft tissue properties. Stochastic simulations can account for these variations in posture and soft tissue properties. The user can define for each stochastic parameter the boundary values and the distribution. In the stochastic simulation, the values of the parameters are randomly selected from the pre-defined distribution and for each situation a simulation is performed. These simulations enable the designer to analyse human behaviour in vertical vibrations and seat pressure distributions by numerical simulations more realistically, since the inter-subject variability present in the real world can be better accounted for.

For (dis)comfort prediction, the (exact) relation between the objective parameters, predicted by the numerical tools, and the subjective sensation of (dis)comfort is required (Figure 1.1). These relations can be determined by volunteer experiments in which the objective parameters are measured and the subjects are asked for their (dis)comfort sensation. Preferably, also the relations between the various objective parameters within the seat pressure distribution and the vertical vibration should be known. More specific, what is the contribution of e.g. the maximum pressure or the average pressure to the overall score on seat pressure distributions? But also the relation between seat pressure distributions, vertical vibrations and other factors not investigated in this study, like posture, to the overall (dis)comfort sensation of subjects should be determined to come to a complete (dis)comfort score. For vertical vibrations the relationship between discomfort and the r.m.s.-value of the frequency weighted acceleration between human and seat is described in ISO 2631-1 (1997). To the author's knowledge, for seat pressure distributions such a relationship does not exist. Also the contribution of the various objective parameters to overall (dis)comfort have not been described in literature. More research on these relationships is required.

Moreover, numerical tools can have a significant added value for research on the (dis)comfort sensation of drivers and related physical complaints. Numerical tools enable the researcher to investigate aspects of the contact interaction between human and seat in addition to the aspects that can be determined by the current established experimental approach. Numerical tools may provide information about spinal loading, shear stresses at the contact interface and soft tissue loading. In combination with results of subjective evaluation, relations can be investigated between these spinal and soft tissue loading and contact interface shear stresses and the (dis)comfort sensation. This way, the numerical models might contribute to a better insight in (dis)comfort sensation.

7.5 Conclusions

- A vibration model has been developed that is suitable for prediction of human behaviour in vertical vibrations. The vibration model contains a multi-body seat model and a multi-body occupant model. A method has been outlined for the development of seat models by usage of numerically efficient multi-body techniques. Volunteer experiments on a rigid and a standard car seat have been performed for the validation of the human model. The human model shows reasonable correlation with the volunteer responses for the rigid and standard car seat condition. Further validation of the model is required.
- The vibration input in vertical direction results in a spinal loading and movements of vertebrae in both horizontal and vertical direction. The spinal loading is very sensitive for the contact interaction between human and seat back.
- A FE buttocks model has been developed. This model is able to predict seat pressure distributions. A validation study has been performed based on volunteer experiments on a rigid and a soft cushion. The seat pressure distribution and the values for the maximum pressure, average pressure and contact area agree reasonably well with the volunteer data. Further validation is required.
- A parameter study with the FE buttocks model showed that seat pressure distributions are highly sensitive to variations in human soft tissue properties and cushion properties.
- The sensitivity study showed that the multi-body human model is able to predict the influence of variations in cushion and suspension properties on human (dis)comfort sensation in vertical vibrations. This human

(dis)comfort sensation in vertical vibrations is highly sensitive to variations in seat cushion and suspension stiffness.

- The FE buttocks model predicts the influence of variations in seat geometry, seat properties, human soft tissue properties and posture on the seat pressure distribution at the contact interface between human and seat. Seat pressure distributions are highly sensitive for variations in seat cushion stiffness and thickness.

7.6 Recommendations

To further improve the multi-body human model for analyses of vertical vibrations, a more extensive validation for vertical vibrations is recommended. Especially, experiments at higher frequencies (preferably 0-25 Hz) and experiments without a seat back are recommended. For validation on a rigid surface, studies reported in literature can be used (Panjabi *et al.*, 1986; Griffin, 1990; Pope *et al.*, 1990; Paddan & Griffin, 1993; Seidel *et al.*, 1997). For experiments on a soft surface, the description of the cushion properties is usually poor in literature, which limits their use for model validation.

As discussed in Section 7.1, the active muscle behaviour is currently modelled relatively simple by rotational stiffnesses in the spine and neck. Literature describes the influence of muscle co-contraction on the seat-to-human transmissibilities. It is therefore recommended to model the muscles in the spine and the neck in more detail.

In literature several studies have reported a relationship between vertical vibrations and low back pain. Although these low back pains have a large social impact on a subject's life, the cause of the low back pain is still not well understood. A diversity of views is expressed in literature regarding these low back pains. Studies with numerical models of the lower back are a useful way to evaluate these propositions. This will inevitably involve a more detailed representation (FE invertebral discs, muscles, realistic geometric description of the vertebrae) of the lower back.

The transmissibility of accelerations from seat to human strongly depends on the subject's posture. Studying this sensitivity to the posture of the human model on seat-to-human transmissibilities provides more information about the importance of the positioning of the human model for vibration simulations. Further, new application areas for the multi-body human model could be for-after vibration, lateral vibrations or multi-directional vibrations, military environments, aircrafts or sports.

A more extensive validation of the FE buttocks model in static and dynamic conditions on both rigid and soft surfaces, that are accurately characterised, is recommended. Both for validation on a rigid surface as for validation on soft surfaces, very few studies are available in literature. New reproducible experiments are required. These experiments should involve a significant number of subjects and an accurate postural control of the subjects.

The geometry of the FE buttocks model has been based on an average seating male. However, this was an old man (with a rounded stomach and thin upper legs) while seated on a car seat. The geometry of the model has been corrected for this as much as possible. It is recommended to update the description of the geometry to one of a 50^{th} percentile healthy male.

Currently, simulations with the FE buttocks model require long computation times. Investigation into the parameters to decrease this computation time and increase the robustness helps to increase the user-friendliness of the model. Coupling with an implicit code is recommended for analyses of quasi-static conditions.

Inclusion of the FE buttocks model in the multi-body occupant model would allow to increase the application field of the FE buttocks model, e.g. by combined analyses of pressure distributions on the seat cushion and seat back. For prediction of the pressure distributions at the seat back, the multi-body occupant model may be sufficient. In contrast with the buttocks area, the human back does not have much soft tissues and deformations are mainly caused by joint articulations. A study on the validity of the occupant model for the prediction of seat back pressure distributions is required. A new application area of the FE buttocks model might be clinical studies on e.g. the prevention of pressure ulcer. Moreover, inclusion of the FE buttocks model in the multi-body human model allows combined analyses of the transfer of accelerations from seat to human and the human-seat contact interaction by seat pressure distributions.

Currently, the results of the validation of numerical models are often analysed based on engineering judgement. For both the validation of the multi-body human model and the FE buttocks model, a first approach has been presented towards an objective evaluation method of numerical simulation results with experimental test data. More research is recommended in order to define more sophisticated criteria and guidelines, applicable for ergonomic applications, that can be used for an objective evaluation of numerical results with experimental data. This will enable a comparison of various models published in literature with each other.

A combination of the results of the numerical analyses with subjective evaluation of comfort will provide a more sophisticated tool for comfort analyses of automotive seating. In the sensitivity study performed in this thesis, a first step has been made by using ISO 2631-1 (1997) and other in literature reported factors relating to comfort, like SEAT% and SPD%. Experiments combining the measurement of objective parameters with evaluation of subjective sensation of comfort and numerical results are required for such a comfort tool. These experiments can also be used to establish relations between the subjective sensation of comfort and objective parameters like shear stresses at the contact interface between human and seat, stresses inside the human due to this contact interaction or spinal loading in vertical vibrations.

A next step in the validation of the numerical tools, developed in this study, could be a real design study. Starting from an existing design, a seat designer has to be asked to develop a new, more comfortable seat using his knowledge and experience. Simultaneously, a new seat design has to be developed by usage of virtual testing. In this numerical approach, techniques for scaling, stochastic simulations, design of experiments and optimisation can be combined with a tool relating the numerical output with (dis)comfort sensation to be able to design an optimal seat taking into account inter-subject and intra-subject variability that exists between people. The validation can be based on a comparison between the final design developed by usage of virtual testing and the final design developed by the seat designer. Thereafter, the numerical tools could be used for definition of guidelines for the design of new seats with respect to seating comfort.

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Appendix A

Questionnaire sensitivity study

This appendix describes the questionnaire sent out to car and seat manufacturers preceding the sensitivity study of Chapter 6. Section A.1 shows the questionnaire, Section A.2 presents the response of the car and seat manufactures.

A.1 Questionnaire

Car and seat manufacturers all over the world have been contacted and by a questionnaire asked for their key parameters in the design process of a new, more comfortable car seat. The questionnaire focussed on vertical vibrations and seat pressure distributions. Hereafter, the questionnaire is printed.

Delft, 28 January 2003

Dear Sir/Madam,

Higher demands by people on the performance of vehicles and the comfort-related physical complaints by professional drivers have led to an increasing demand for more comfortable cars. The use of computer models of human and seat could facilitate the time consuming and costly process of developing more-comfortable car seats or interiors.

As part of my PhD-study, I am developing numerical tools that can be used for comfort analyses during the design process of new car seats.

Literature showed that vertical vibrations and pressure distribution are objective factors relating to the personal subjective feeling of comfort. Comfortable levels of acceleration magnitudes and exposure times are defined in ISO standards. I have verified the vertical vibration response of the multi-body human model developed

in MADYMO with volunteer tests that were performed as part of my thesis project. The model correlated well with the volunteer responses and allowed analyses of spinal loading during vertical vibrations.
For prediction of seat pressure distributions, I have developed a finite element model of the pelvis and the thighs with a detailed geometric description of bony structures and skin. In the model, the soft tissues have been lumped together; the skin has been modelled separately. I am currently validating the model based on volunteer experiments.

As a next step in my PhD-project, I would like to show the applicability of both numerical models in the development process of new comfortable seats. Is my finite element model of the human buttocks able to predict variations in pressure distributions due to variation of *that* parameters that developers use in the development process of new car seats? And can the human model predict variations in seat-to-human transmissibilities due to variations in *that* seat parameters that are important for seat developers in de design of new seats?

For that reason, I kindly ask you whether you can help me in providing information on what are key-parameters for you in the design process of a new comfortable car seat. In addition, I am interested in what you consider to be the minimum requirements a numerical model has to meet to be applicable in the design process of new, comfortable car seats.

I would really appreciate it if you could fill in the questionnaire attached to this letter. Your response to this questionnaire will be kept confidential. If you have any questions, please feel free to contact me.

Thanking you in advance for your help.

Best regards,

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QUESTIONNAIRE

1. If you have to develop a new seat that has to fulfil the current safety and comfort requirements, which parameters/factors would you change in this process in relation to **seat pressure distributions** to get a new, more comfortable seat?

☐ Geometry
- ☐ Shape of the cushion
- ☐ Size of the cushion
  - ☐ Enlargement of cushion width
  - ☐ Reduction of cushion width
  - ☐ Enlargement of cushion depth
  - ☐ Reduction of cushion depth
  - ☐ Other:
- ☐ Angle of the seating plane
- ☐ Other:

☐ Foam
- ☐ Thickness
- ☐ Stiffness
- ☐ Damping properties
- ☐ Density
- ☐ Other:

☐ Frame
- ☐ Material
- ☐ Thickness
- ☐ Profile
- ☐ Other:

☐ Support foam/connection foam-frame
- ☐ Material
- ☐ Stiffness
- ☐ Profile
- ☐ Other:

☐ Material seat cover

☐ Other:

Remarks:

2. If you have to develop a new seat that has to fulfil the current safety and comfort requirements, which parameters/factors would you change in this process in relation to **vibrations** to get a more comfortable seat?

☐ Geometry
- ☐ Shape of the seat cushion
- ☐ Shape of the seat back
- ☐ Size of the seat cushion
  - ☐ Enlargement of the cushion width
  - ☐ Reduction of the cushion width
  - ☐ Enlargement of the cushion depth
  - ☐ Reduction of the cushion depth
- ☐ Size of the seat back
  - ☐ Enlargement of the cushion width
  - ☐ Reduction of the cushion width
  - ☐ Enlargement of the cushion height
  - ☐ Reduction of the cushion height
  - ☐ Other:
- ☐ Angle of the seating plane
- ☐ Other:

☐ Foam
- ☐ Thickness
- ☐ Stiffness
- ☐ Damping properties
- ☐ Density
- ☐ Other:

☐ Frame
- ☐ Material
- ☐ Thickness
- ☐ Profile
- ☐ Other:

☐ Support foam/connection foam-frame
- ☐ Material

- ☐ Stiffness
- ☐ Profile
- ☐ Other:

☐ Seat suspension

- ☐ Stiffness
- ☐ Damping properties
- ☐ Other:

☐ Material of the seat cover

☐ Other:

<u>Remarks:</u>

3. Would you like to receive a copy of my thesis (publication expected January 2004)

   ☐ Yes
   ☐ No

A.2 Response

Table A.1 provides an overview of the response on the question relating to human behaviour in vertical vibrations: 'If you have to develop a new seat that has to fulfil the current safety and comfort requirements, which parameters/factors would you change in this process in relation to vibrations to get a new, more comfortable seat?' Table A.2 presents the response on the question relating to seat pressure distributions: 'If you have to develop a new seat that has to fulfil the current safety and comfort requirements, which parameters/factors would you change in this process in relation to seat pressure distributions to get a new, more comfortable seat?'

			Total
Geometry			5
	Shape of the cushion		6
	Shape of the seat back		6
	Size of the cushion		3
		Enlargement of cushion width	3
		Reduction of cushion width	1
		Enlargement of cushion depth	2
		Reduction of cushion depth	1
	Size of the seat back		5
		Enlargement of cushion width	3
		Reduction of cushion width	2
		Enlargement of cushion depth	3
		Reduction of cushion depth	2
	Angle of seating plane		3
Foam			10
	Thickness		8
	Stiffness		10
	Damping properties		11
	Density		6
Frame			6
	Material		4
	Thickness		4
	Profile		3
Support			9
	Material		4
	Stiffness		6
	Profile		3
Seat suspension			10
	Stiffness		9
	Damping properties		9
Material cover			2

Table A.1: *Response of the car and seat manufacturers on the questionnaire relating the question on vertical vibrations*

			Total
Geometry			6
	Shape of the cushion		8
	Size of the cushion		7
		Enlargement of cushion width	6
		Reduction of cushion width	4
		Enlargement of cushion depth	6
		Reduction of cushion depth	4
	Angle of seating plane		5
Foam			10
	Thickness		9
	Stiffness		10
	Damping properties		5
	Density		6
Frame			7
	Material		3
	Thickness		4
	Profile		4
Support			4
	Material		2
	Stiffness		4
	Profile		3
Material cover			6

Table A.2: *Response of the car and seat manufacturers on the questionnaire relating the question on seat pressure distributions*

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Curriculum vitae

Muriëlle Verver was born on December 8th, 1975, in Enschede, The Netherlands. After she graduated at the Murmellius Gymnasium in Alkmaar in 1994, she started to study Mechanical Engineering at the University of Twente, The Netherlands. She received her master's degree in November 1999 for the work done at the topic "Improvement and Validation of a Detailed Neck Model in Impact Loading". This research was conducted at TNO Automotive in Delft, The Netherlands. For her master's thesis she received the KivI Spykerprijs in 2000. In this period she got interested in biomechanical research. For that reason, she decided to start with a PhD-study on the development of numerical tools for comfort analyses of automotive seating. This thesis is the result of this PhD-project, that was performed in a close co-operation between Eindhoven University of Technology and TNO Automotive. As of January 1st 2004, Muriëlle is employed at the Safety department in TNO Automotive.

Stellingen

Behorende bij het proefschrift

Numerical tools for comfort analyses of automotive seating

1. Het gebruik van numerieke methoden bij comfortanalyses kan de efficiëntie van het ontwerpproces van autostoelen verhogen.
   Dit proefschrift, Hoofdstuk 1

2. Bij analyses van belastingen op de wervelkolom ten gevolge van vertikale trillingen, kan men de belastingen in andere richtingen niet verwaarlozen.
   Dit proefschrift, Hoofdstuk 4

3. Niet alleen de stoeleigenschappen, maar ook de eigenschappen van het menselijk zitvlak zijn bepalend voor zitdrukverdelingen op het contactvlak tussen mens en stoel.
   Dit proefschrift, Hoofdstuk 5

4. Het gebruik van numerieke modellen voor comfort analyses opent nieuwe deuren: parameters die in de praktijk nog niet gemeten kunnen worden, kunnen wel voorspeld worden.
   Dit proefschrift, Hoofdstuk 4 & 5

5. Het gebruik van numerieke methoden naast de in de ergonomie gebruikelijke experimentele methoden komt het onderzoek dat inzicht moet verschaffen in de comfort ervaring van personen ten goede.
   Dit proefschrift, Hoofdstuk 7

6. De uitspraak 'Wie mooi wil zijn moet pijn lijden' gaat zeker op voor het dragen van hoge hakken. De verhoogde spierspanning ten gevolge van het dragen van hoge hakken resulteert dan wel in strakke kuiten, bovenbenen en billen. Echter, de belasting op de gewrichten van enkels, knieën en heupen wordt aanzienlijk verhoogd.
   Kerrigan et al., Knee osteoarthritis and high-heeled shoes, The Lancet, Vol. 351, pp 1399-1401, 1998

7. De al tien jaar durende kosten-baten-discussie tussen overheid en automobiel industrie rondom regelgeving op het gebied van voetgangersveiligheid in het verkeer heeft inmiddels in Europa al rond de 20.000 doden gekost.
   ETSC-report, Priorities for EU motor vehicle safety design, ISBN 90-76024-12-X, 1991

8. De mate van detail van een numeriek biomechanisch model is niet evenredig met de nauwkeurigheid van het model.

9. Numerieke comfort simulaties zorgen voor meer discomfort dan numerieke ongevalsimulaties.

10. Promoveren is papier produceren.

11. Je veter-strik-diploma gebruik je misschien wel vaker dan je ingenieurs-diploma.

12. De top is zelden het eind van de reis.

Muriëlle Verver
Delft, maart 2004.