Friedrich-Schiller-Universität Jena

The relation between long-term seating comfort and driver movement

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Zusammenhang von Langzeitsitzkomfort und Fahrerbewegungen

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ABSTRACT

The objective determination of seating comfort plays an important role for the development of seating systems. Currently the evaluation is based on subjective impressions and mainly focussed on static conditions. Objective methods are primarily based on evaluating the influence of vibrations on the driver or assessing the seat pressure distribution. Additional evaluations are done by using virtual human models which allow illustrating loads in various scenarios. Basically it is tried to correlate subjective ratings to objectively measurable parameters and to predict the level of seating comfort based on such a relation. No generally accepted approach exists, however. Models which take the time-dependent variation of parameter values into account are rare. A description of the typical driver in long-duration travel is not available. The aim of this thesis is to identify whether typical movement patterns exist and if they can be used to predict subjective seating comfort ratings.

Driver posture of various test persons using different seat models is assessed under field conditions with test durations of up to three hours. Additionally, the data is verified in driving simulator tests. Parameters for the description of postural variations are calculated from the kinematic data. Furthermore, a system for the continuous monitoring of the driver's posture is developed that can be integrated into the seat. The prediction of long-term seating comfort is based on the assumptions of a newly developed model.

It could be shown that driver posture changes over time. On the one hand, an initial posture changed is identified, indicating that is takes up to 15 minutes for the driver to adopt his final position. On the other hand it is found, that the driver continuously uses postural adaptations to temporarily limit the total load. Posture variations can be classified into either posture changes, posture adaptations or activity. The frequency and amplitude of such variations increases with time due to increasing loads. A prediction of subjective ratings from the described parameters is possible and is mainly based on the maximum time between posture changes and the time constant of posture adaptations.

Postural modifications of the driver can be divided into task-oriented and comfort-related movements. A new model is developed illustrating the genesis of long-term seating comfort and methods for its objective analysis. Long-term seating comfort is defined as the subjective reaction on the total individual load and is directly related to system stress. System stress is seen as the objective reaction on the total load. The total individual load is the result of the cumulative power of various soft and hard stressors. The detection of system stress through the evaluation of stress-induced postural modifications can therefore be used to objectively evaluate long-term seating comfort. Consequently, a rating, classification and comparison of different seat models is possible enabling the optimisation of existing and the development of new seating systems.

ZUSAMMENFASSUNG

Die objektive Bewertung von Sitzkomfort spielt eine bedeutende Rolle bei der Entwicklung neuer Sitzsysteme. Momentan erfolgt die Evaluierung vor allem durch subjektive Urteile und ist auf statische Versuchsbedingungen konzentriert. Objektive Verfahren zur Ermittlung der Belastung des Fahrers stützen sich primär auf die Bewertung von Schwingungen und Vibrationen sowie auf die Messung von Druckverteilungen zwischen Mensch und Sitz. Unterstützt wird die Sitzkomfortbewertung durch virtuelle Menschmodelle, die die Abbildung verschiedener Szenarien ermöglichen. Allgemein wird versucht, subjektive Aussagen mit objektiv messbaren Größen in Verbindung zu bringen und daraus eine Vorhersage des Sitzkomforts abzuleiten. Es existiert jedoch kein allgemeingültiger Ansatz. Auch gibt es wenig Modelle, die die zeitbezogene Variation verschiedener Parameter berücksichtigen. Eine allgemeingültige Beschreibung von typischen Fahrerbewegungen bei Langzeitfahrten existiert nicht. Ziel dieser Arbeit ist es, typische Bewegungsmuster zu identifizieren und zu prüfen, ob solche Muster die Vorhersage subjektiver Bewertungen ermöglichen.

Die Fahrerhaltung von mehreren Personen in verschiedenen Sitzmodellen wurde in realen Langzeitfahrten mit einer Dauer von bis zu drei Stunden erfasst. Zusätzlich dazu erfolgte eine Überprüfung verschiedener Ergebnisse in Simulatorversuchen. Aus den Daten wurden Parameter zur Beschreibung der Haltungsvariationen berechnet. Des Weiteren wurde ein System entwickelt, das in den Sitz integriert werden kann und die kontinuierliche Erfassung von Fahrerbewegungen ermöglicht. Die Vorhersage von Langzeitsitzkomfort erfolgte auf Basis eines neu definierten Komfortmodells.

Es konnte gezeigt werden, dass sich die Fahrerhaltung im Zeitverlauf ändert. Zum einen existiert eine initiale Haltungsänderung – der Fahrer benötigt bis zu 15 Minuten, um seine endgültige Position zu finden. Zum anderen können belastungsbedingte Haltungsänderungen beobachtet werden, die der Fahrer nutzt, um die Gesamtbelastung vorübergehend zu reduzieren. Diese lassen sich einer der folgenden Klassen zuordnen: Haltungsänderungen, Haltungsadaptationen und Aktivität. Die Bewegungshäufigkeit und –amplitude nimmt im Verlauf der Zeit belastungsbedingt zu. Eine Vorhersage

subjektiver Komfortbeurteilungen auf Basis der beobachteten Haltungsänderungen ist möglich. Sie stützt sich vor allem auf die maximale Zeit zwischen den Haltungsänderungen und die Zeitkonstante der Haltungsadaptationen.

Das Bewegungsverhalten des Fahrers lässt sich in aufgabenorientierte und komfortorientierte Bewegungen unterteilen. Auf Basis der Ergebnisse wurde ein neues Modell definiert, das die Entstehung von Langzeitsitzkomfort erklärt und Möglichkeiten zu dessen objektiver Erfassung beschreibt. Langzeitsitzkomfort wird als subjektive Reaktion des Fahrers auf die Gesamtbelastung definiert und ist direkt mit der Systembelastung verknüpft. Als Systembelastung wird die objektive Reaktion des Fahrers auf die Gesamtbelastung verstanden. Die Gesamtbelastung wird durch die kumulierte Wirkung verschiedener Einflussfaktoren erzeugt. Die Ermittlung der Systembelastung durch die Erfassung belastungsinduzierter Haltungsänderungen ermöglicht somit eine objektive Erfassung von Langzeitsitzkomfort. Dies erlaubt die Bewertung, die Klassifizierung und den Vergleich verschiedener Fahrzeugsitze und ist daher für die Verbesserung bestehender und die Entwicklung neuer Sitzsysteme von Bedeutung.

CONTENT

1 INTRODUCTION

1.1 BACKGROUND

There are many research projects that focus on „sitting“. The predominant point of interest of most authors is the field of office chairs, but vehicle seats have also been widely studied. The primary goal is to develop better chairs or seats. Basic topics for research are human anatomy and physiology, optimal sitting posture and seating comfort.

The anatomy of sitting human beings in cars has been recently investigated by Serre et al. [148]. As the result of their in-vitro study, the authors present a geometrical database of a driver in a typical sitting posture. The biomechanics of sitting were – besides many others – described by Harrison et al.. In the first part of their work the authors present an extensive literary review of yet existing studies and an extract of the basic knowledge in that field [75]. They summarized the following:

> “Sitting causes the pelvis to rotate backward and causes a reduction in lumbar lordosis, thigh-trunk-angle, and knee angle and an increase in muscle effort and disc pressure. Seated posture is affected by seat-back-angle, seat-bottom angle and foam density, height above floor, and presence of armrests.
>
> The configuration of the spine, postural position, and weight transfer is different in the three types of sitting: anterior, middle, and posterior. Lumbar lordosis is affected by the thigh-trunk-angle and the knee angle. Subjects in seats with backrest inclination of 110 to 130 degrees, with concomitant lumbar support, have the lowest disc pressures and lowest electromyographic recordings from spinal muscles. […] ”

In the second part, the authors describe an optimal driving posture and define basic criteria for the optimal driver seat [76]. They conclude that:

> “The optimal driver seat would have an adjustable seat back incline of 100 degrees from horizontal, a changeable seat-depth of the seat back to front edge of the seat bottom, adjustable height, an adjustable seat bottom incline, firm (dense) foam in the seat bottom cushion, horizontally and vertically adjustable lumbar support, […] seat shock absorbers to dampen frequencies in the 1 to 20 Hz range, and a linear front-back travel of the seat to enabling drivers of all sizes to reach

the pedals. The lumbar support should be pulsating in depth to reduce static load […]".

Furthermore, they present a biomechanical spine model that can be used to describe human sitting (for details see chapter 1.3.2).

Automotive sitting can be regarded as a separate research topic compared to the widely studied field of office sitting because of the special driving conditions [49]. It is widely accepted that typical disorders caused by prolonged sitting result from the static posture of the driver and also the lack of movement. To limit the load produced by these factors it is suggested to sit dynamically which means periodically changing the sitting posture [164]. In an automotive environment this is not easy to achieve, because possibilities to move are very limited. On the one hand, driver motion is limited by safety features such as the seat belt. On the other hand, posture variation is restricted by the typical sitting posture necessary to accomplish the driving task. Additionally, the backward tilted position and the contact forces between the back and the backrest prevent the upper body from moving freely. Modern front seats are usually built to fix the driver in a predefined posture rather than to allow dynamic sitting. This is mainly due to safety and ergonomic reasons. The current knowledge about prolonged sitting has been mainly derived from the results of office chair sitting research and is, as a consequence, not to be applied directly to automotive environments.

As a result of the past research, front seats of modern cars may be adjusted to the individual body of the respective driver. Many alternatives exist to adjust the seat according to the driver's preferred sitting posture. This fact is an important achievement, but also increases the possibilities of misuse. It must be noticed for example, that most drivers seldom use seat adjustments while driving or are even unfamiliar with certain features and their optimal configuration. Besides that, many injuries from car accidents could be avoided if a correct driving posture was ensured. One factor that increases the likelihood of injuries in rear-impact crashes is a high backrest angle which results in a great backrest-shoulder- and headrest-head-distance. Continuous posture monitoring, which could help to prevent such injuries, is very seldom used in today's cars, but some related techniques can be found. There are systems, for example, that allow the identification of driver positions that are “out of position”, i.e. in a position that has a higher injury risk. This is necessary according to some existing laws and regulations, for example the National Highway Traffic Safety Administration’s (NHTSA) regulation FMVSS 208, which requires that vehicle manufacturers provide automatic suppression of the passenger airbag when the person is in a hazardous position and therefore could be hurt by airbag deployment. Another example is the dynamic adjustment of a seat’s side bolsters when driving through a curve, a feature which can be found in luxury cars [131]. A further posture control may be achieved by currently available techniques, but it is not yet implemented. Besides the adjustment mechanisms, many comfort-based features such as so-called “massage” systems exist, aiming as well at altering the driver’s posture. Since little is known about driver posture in prolonged sitting, the optimal configuration of such systems is hard to achieve. In addition, the available systems have to be usually controlled manually by the driver, which does not lead to optimal results. Continuous posture monitoring could help to maximise the output for each individual.

1.2 DESCRIPTION OF A NEW SEATING COMFORT MODEL

Seating comfort is not just an ergonomic issue, but also something increasingly demanded by customers. The growing demand forces car manufacturers to stronger focus on occupant comfort since it has become an important sales argument [102]. The description and evaluation of seating comfort has been widely studied, but a clear definition could not yet be established. The current believe is that ‘comfort’ describes a subjective impression of the sitting situation. Independently of the definition used, researchers agree that seating comfort can only be optimised if the basic parameters that influence it are known and measurement techniques exist to access their influence. All modern seating comfort models are based on the findings of Zhang and Helander, who identified multidimensional properties of comfort and discomfort [81, 183]. They concluded from a variety of subjective ratings that discomfort and comfort are separate dimensions. DISCOMFORT is associated with subjective feelings relating to objective parameters such as poor biomechanics and fatigue, COMFORT with subjective impressions caused by subjective parameters like well-being and plushness (Figure 1).

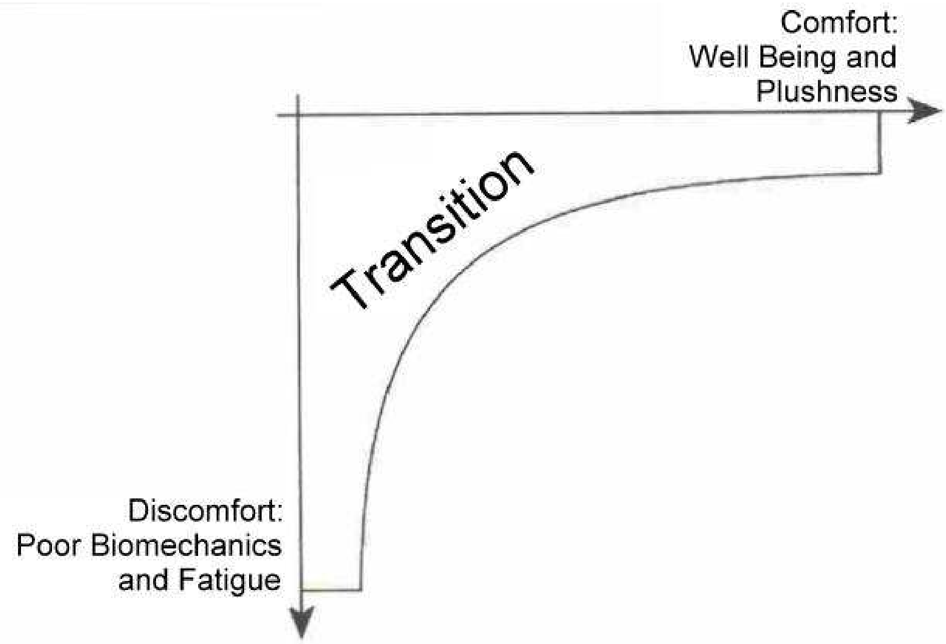

Figure 1: A conceptional model of the interaction of comfort and discomfort (adapted from Helander and Zhang [81])

Before the study of Helander and Zhang, comfort and discomfort were considered to be opposite feelings on a singular axis. Comfort was consequently defined as the absence of discomfort. Based on the new findings this definition was proven to be inexact. When looking at both factors independently, it could be shown that a reduction of one does not necessarily lead to an increase of the other. It can be said however, that both factors show a parabolic dependency (Figure 1). For example, when physical stress rises this is leading to an increase of subjective discomfort ratings, but they also negatively affect comfort. The consequence of this finding is that both comfort and discomfort need to be evaluated for the evaluation of the quality of a seat, i.e. seating comfort.

The findings mentioned above led to the development of a variety of methods for the evaluation of comfort and discomfort. The main focus was set on discomfort because of the parameters relating to it, i.e. contact pressure or fatigue, which are objectively measurable. Subjective comfort ratings were used in addition because they revealed different information. It has been found however, that they are time-consuming and do not necessarily produce reliable output [9]. Since no agreement on the best model could be established, manifold techniques were presented claiming to produce reproducible and comparable ratings of seating comfort [39]. In most studies, the relation of one ore more objectively measurable parameter, i.e. pressure, fatigue, ergonomics, vibration, temperature, air quality, noise and light, to subjective ratings was described [38]. Mainly because of the concentration on single factors, all existing models have certain shortcomings. The consequence is that, when aiming at evaluating seating comfort, a great variety of objective and subjective techniques need to be applied to achieve a general result. Since this is practically impossible, single parameter models are still used, leading to non-standardized and non-comparable results. Presently, it is possible to evaluate the influence of single parameters on subjective impressions, but this does not result in a general seating comfort rating in all cases. Estimating subjective impressions – as main driving interest of all recent studies – by assessing single physical factors is consequently not the optimal solution.

Since many parameters influence the driver and therefore the overall seating comfort, it appears reasonable to just assess the driver's reaction on the influencing factors without paying attention to single factors. A driver's behaviour modifications might indicate the total power of all underlying factors. The assumption that several parameters acting individually have the potential to produce the same subjective impression highlights the advantage of this approach. It is not possible to identify the exact cause for changes in subjective ratings with this model, but a reliable seating comfort rating could be achieved. Besides, a global view could help to understand complex parameter interactions and would improve the possibility to compare results attained under various conditions. The main influencing factors could then be evaluated additionally using the available methods.

In the following section, a global approach for the evaluation of seating comfort in prolonged driving based on the driver's behaviour modifications is described. The model is presented at the very start because assumptions and definition are made and used in the further content of this work that are different to the accepted opinion. Parts of it cannot be proven at this point, but will be supported by the findings of the following chapters. It is still a theoretical approach which has not been validated.

The aim of the model is to describe the influence of underlying stressors on the overall individual load in prolonged driving and to provide a reliable method for the assessment of seating comfort.

Assuming that various stressors influence the total load that acts on the driver, it can be said that the load level changes with changing stressor power and the reaction of the driver is determined by individual properties (Figure 2). An increasing load level results in subjective as well as objective reactions, if its level approaches or exceeds individual physiological and/or psychological thresholds. Because these reactions are based on the same cause, i.e. the total load level, there should be a relation between subjective and objective reaction.

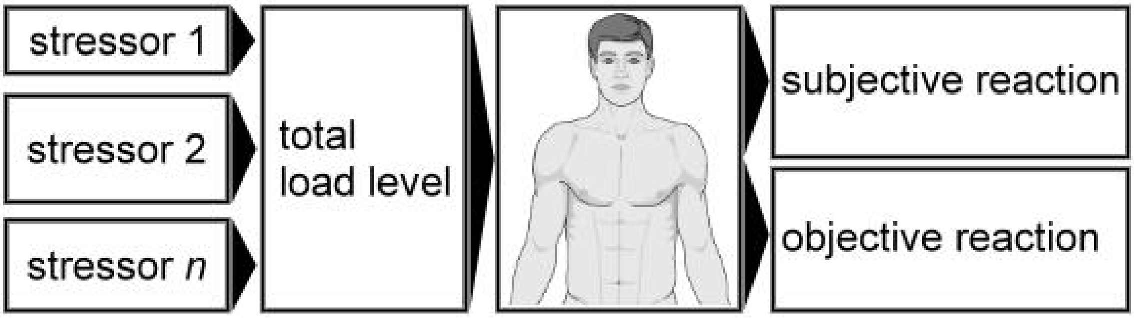

Figure 2: Illustration of the relation of stressors and the individual reaction. The power of stressors accumulates to the total load level. Objective and subjective reactions are caused dependent on individual properties. A relation is considered between objective and subjective reactions.

Stressors may be divided into two groups: SOFT STRESSORS that dominantly interfere with personal attitudes, e.g. aesthetics; and HARD STRESSORS that mainly apply physical load on the body, e.g. pressure. Contrary to the model of Helander and Zhang, soft and hard stressors do not only lead to a SUBJECTIVE REACTION, i.e. the change of the seating comfort impression, but also cause an OBJECTIVE REACTION, i.e. physiological changes and behaviour modifications. The TOTAL INDIVIDUAL LOAD is the sum of loads caused by hard and soft stressors. The subjective reaction on the total individual load is referred to as STRESS-INDUCED IMPRESSION CHANGE. The term used to describe the objective reaction on the absolute individual load is STRESS-INDUCED BEHAVIOUR MODIFICATION. The level of SEATING COMFORT can be derived from stress-induced impression changes. The total SYSTEM STRESS correlates with stress-induced behaviour modifications. Since the effective influence of stressors on subjective and objective reactions is likely to vary for each individual, a similar reaction may be produced by different stressors and/or different stressor levels. The total system stress, however, is believed to correspond to the level of seating comfort. The system stress may therefore be used as an estimate for seating comfort (Figure 2).

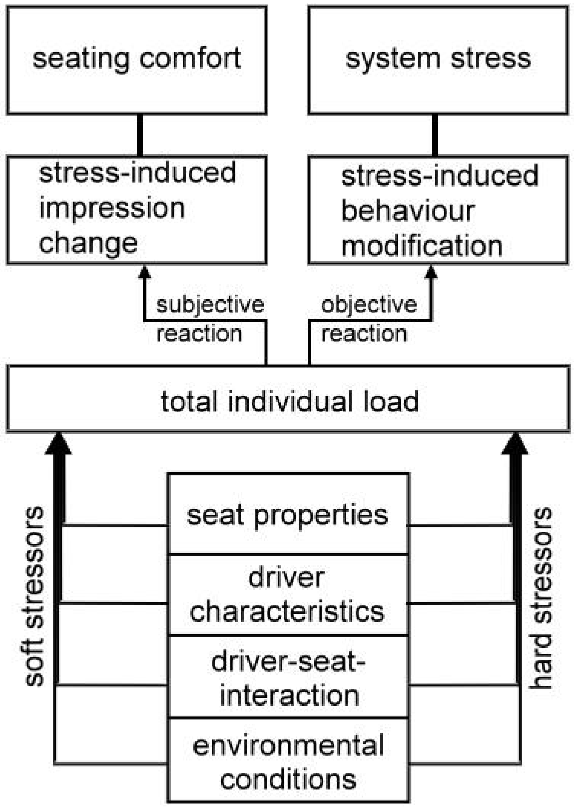

Figure 3: Illustration of a basic model for the evaluation of seating comfort. The power of hard and soft stressors accumulates to the total individual load. The subjective reaction on the total individual load are stress-induced impression changes which accumulate to a seating comfort impression. The objective reaction, a stress-induced behaviour modification, correlates to the system stress. System stress, estimated by stress-induced behaviour modifications, may therefore be used to evaluate seating comfort.

In summary, **seating comfort can be defined as the result of the subjective reaction on the total individual load caused by soft and hard stressors**. Assuming the fact that the total individual load also causes an objectively measurable reaction, **system stress derived from load-induced behaviour modifications may be used to estimate seating comfort**.

All hard and soft stressors which have an impact on the total individual load can be assigned to one of four basic groups: seat properties, driver characteristics, driver-seat-interaction, and environmental conditions (Figure 3, Table 1, a detailed description will be given in the chapters 1.3 and 1.4). If the classification of a stressor to one group is not clear, the stressor will be assigned according to its major impact in the driving situation.

Table 1: Selected soft and hard stressors assigned to four groups which influence the total individual load. Soft stressors interfere with personal attitudes and consequently lead to stress-induced impression changes. Hard stressors apply physical load on the body and cause load-induced behaviour modifications.

Groups	**Soft stressors**	**Hard stressors**
seat properties	look-and-feel, aesthetics	available seat features, adjustment possibilities, cushion properties
driver characteristics	individual comfort perception	posture, fatigue level, personal history
driver-seat-interaction	anthropometric preferences	contact pressure, shear force
environmental conditions	mental stress, noise, weather conditions	vibration, climate

To estimate the system load and thus seating comfort, stress-induced behaviour modifications must be evaluated. Postural adaptations may be used to reflect the objective reaction of the driver caused by an increasing total individual load (Figure 4). Since stressor power and consequently the total individual load inevitably increases over prolonged sitting periods [123], posture is varied to decrease physical stress and to maintain an acceptable load level. A basic model describing the relation between posture changes and physical load was established by Fujimaki and Noro [57]. Their original description is provided here as quotation because the terms used, which differ from the above introduces terms, are needed to understand their model (Figure 4). The authors found the following:

> “During the stable condition the feeling of discomfort increases by a certain degree. When the discomfort reaches a certain level, the sitting condition will shift to the unstable condition and discomfort will increase rapidly. When the discomfort further increases to reach a certain level, macro movement occurs and

the feeling of discomfort will be reduced. At this conjuncture, discomfort will not be reduced completely, and a certain level of discomfort will be stored. The pattern repeats and the cycle shortens. The reduction of discomfort by a macro movement becomes less effective as the stored discomfort increases, and to reduce the stored discomfort, continuous macro movements will occur. And this pattern also repeats."

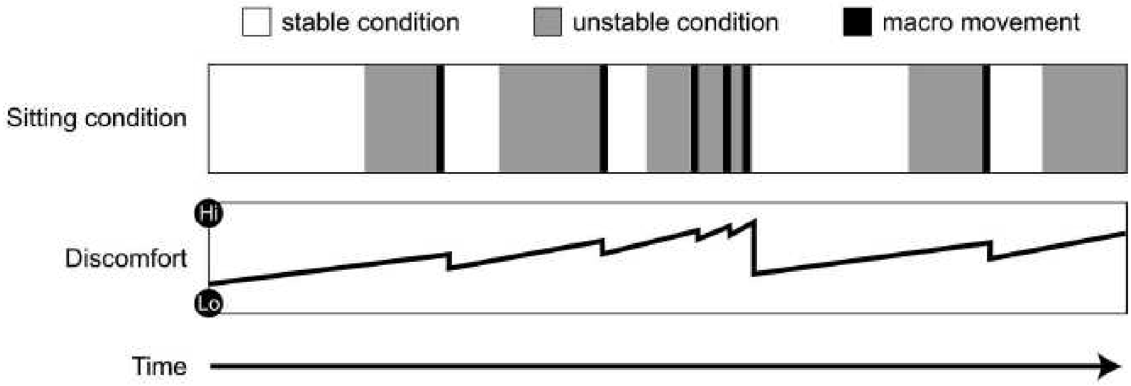

Figure 4: Theoretical model of sitting condition and discomfort in prolonged sitting [57].

The model introduces two basic new ideas. First, it is assumed that the total individual load continuously increases with time. That appears reasonable for prolonged driving and was proven to be true for certain stressors, e.g. pressure (Figure 10, compare chapter 1.3.3). Second, it is supposed that posture changes reduce the total individual load. If this is the case, the frequency of posture changes would increase with time as a result of the increasing total individual load. An increasing frequency of posture changes with time was found by Fujimaki and Noro and also in other studies [17, 24, 26, 52, 82]. It therefore seems reasonable to use posture variations as an estimate for system stress derived from stress-induced behaviour modifications. As a consequence, the level of seating comfort may be objectively assessed by monitoring postural adaptations of the driver.

1.3 HARD STRESSORS INFLUENCING THE TOTAL INDIVIDUAL LOAD

In the following section, the influence of hard and soft stressors on the total individual load is presented. Basically, it can be said that the total individual load is the sum of the power of hard and soft stressors (Figure 3). According to the model presented above, the description is provided for hard and soft stressors separately and for the following groups: seat properties, driver characteristics, driver-seat-interaction, and environmental conditions (Table 1). In some cases stressors cannot be assigned to one of the groups clearly. In this case, the assignment will be made according to the stressors dominant impact in the driving situation. The groups are only defined by reason of clarity and do not influence the model output, because the sum of all stressors, i.e. the total individual load, is regarded to cause subjective and objective reactions.

1.3.1 SEAT PARAMETERS

Seat parameters such as available *seat features*, *adjustment possibilities* and *cushion properties* can be regarded as hard stressors, because they apply physical load and thus have an effect on the total individual load.

Because of the different anthropometries [130], *a seat must be adjustable* [50] in order to accommodate a wide range of drivers. Today's car seats have all basic devices for adjusting the backrest’s inclination, the seat’s height, the distance to the steering wheel and the headrest (Figure 5). Safe and comfortable sitting could not be accomplished without these items [64, 75]. Several additional features, e.g. lumbar support, seat pan inclination and seat pan length, are sometimes implemented to decrease loads. An optimal setup would additionally include adjustments to the seat's depth, the seat’s bottom incline, a lumbar support and bilateral arm rests [76]. Besides some luxury cars, such a variety of features is usually not implemented in modern cars though, due to cost and weight issues.

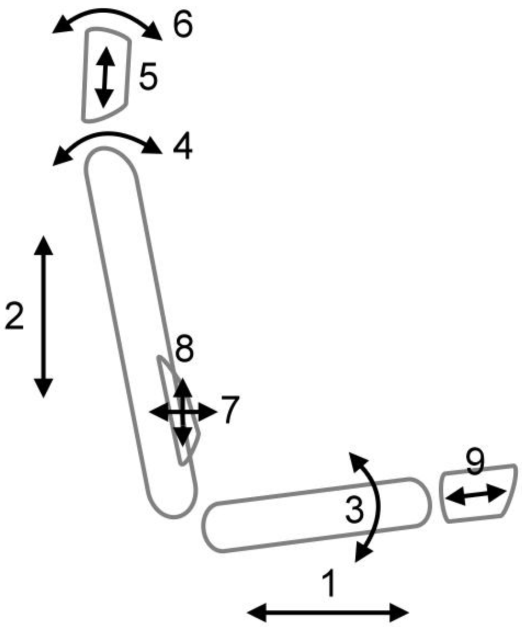

Figure 5: Basic seat adjustments: distance to the steering wheel (1), seat height (2), seat pan inclination (3), seatback inclination (4), headrest height (5), headrest inclination (6), horizontal lumbar support adjustment (7), vertical lumbar support adjustment (8), and seat pan length (9). Further adjustments are available.

Appropriate seat angels, i.e. the angle between seat pan and backrest, and seat pan angles proved to decrease loads [68, 107]. The optimal seatback inclination ranges between 110 and 130 degrees to horizontal (for a literary overview see Harrison et al. [75]). Basically one can say that good adjustment is achieved with a backrest inclination of 120 and a backward seat bottom inclination of at least five degrees [76]. Body angles that allow an optimal performance can be defined for the typical driving posture Figure 6. A trunk inclination of 112 degrees to horizontal in combination with a 105 degrees elbow, 115 degrees knee, and 115 degrees foot angle is widely accepted as concept of the “comfort angles” for the 50th percentile male [10].

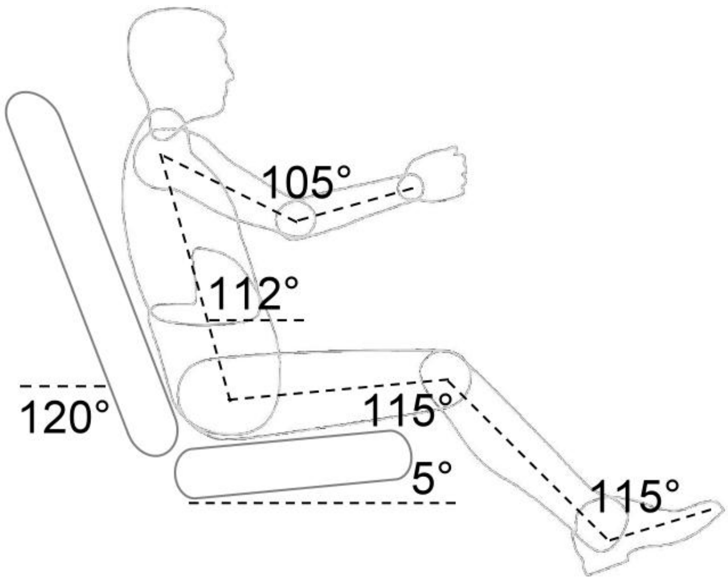

Figure 6: Optimal seatback and seat pan inclination according to recent studies [76] and "comfort angles", i.e. angles that are chosen by the majority of drivers [10]

Seat properties such as the position of the backrest and headrest also strongly influence driver safety (e.g. Svensson et al., 1996). The safety topic has been discussed extensively in the up-to-date literature and is still being discussed very actively. Specifications will not be addressed in details at this point, but it needs to be said that safety regulations have a great impact on the seat development and thus the seating comfort topic. In most cases, safety specifications, e.g. side impact protection, have a higher priority than comfort features. Moreover, some seat properties that would decrease the total load can not be implemented because of safety issues, e.g. freely moving backrests that can be found in office chairs.

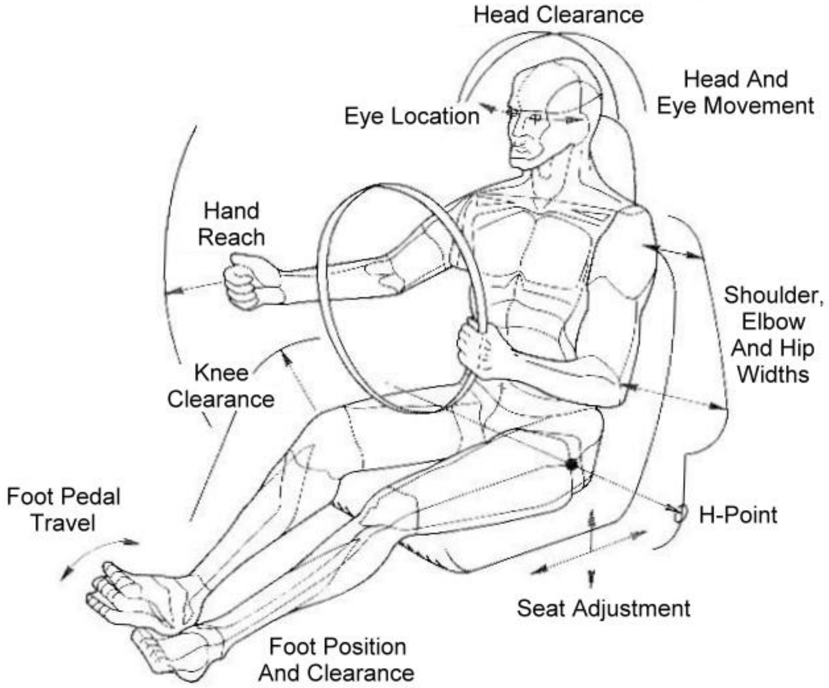

Figure 7: Basic considerations for seating package development [144]

The *position of the driver* in the car is important for the driving performance [51]. It is essential for being able to fulfil the driving task that all necessary items such as pedals, steering wheel and gear shift are within easy reach (Figure 7). The driver also must be able to look outside the window without having problems. This is why all items of the car's interior are arranged relative to several specific points (Figure 8), e.g. the H-Point (Hip Point) or SgR-Point (Seating Reference Point). Such reference points are needed during the development of a car to ensure that the driver sits in the desired position. The H-Point is the theoretical intersection point between trunk and thigh line and the sagittal plane of the body (Figure 7). The SgRP is defined as the H-Point of the 95% male in the rearmost seating position with a seatback angle of 25 degree to vertical and a 87 degree foot angle [144]. The H-Point can be directly measured [89] or calculated from anatomical landmarks [27]. Due to the fact that the H-Point is a virtual reference point, it does not necessarily coincide with the hip centre of the human body [77]. It is predominantly influenced by seat parameters, adjustments, anthropometrics and driver motion. Instead, H-Point ellipses, which describe a possible range of H-Point locations, are rather used for seat design than single H-Point locations (Figure 8). Because of the problems associated with measuring the H-Point directly, it is today often virtually assessed with human models [115]. This leads to a higher accuracy. The influence of driver motion which results in a change of the H-Point location over time is not being taken into account by up-to-date methods however.

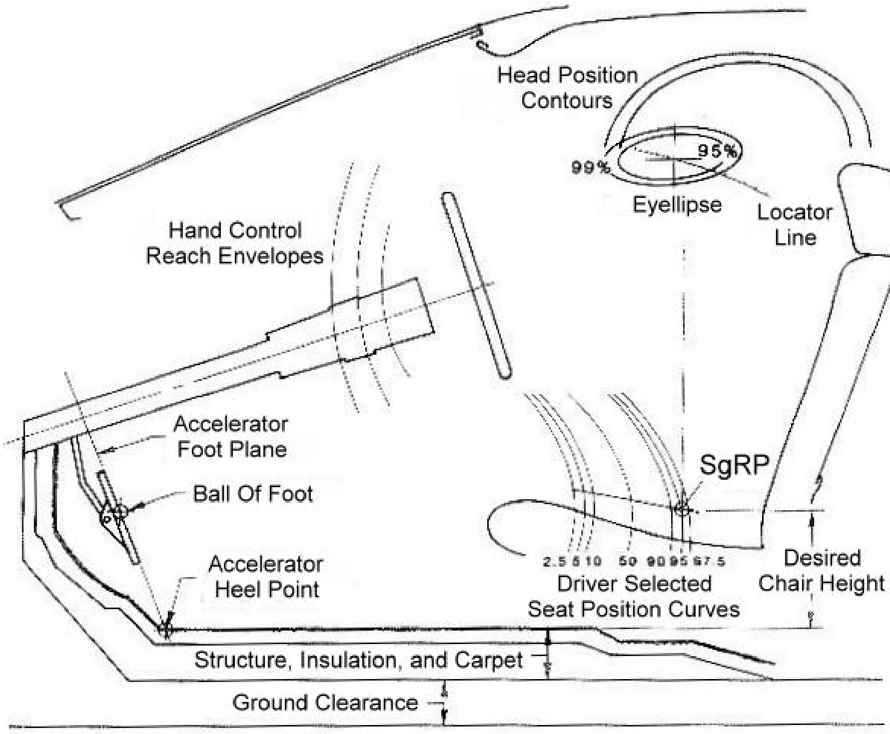

Figure 8: Seating package development based on specific landmarks [144]

Another load influencing factor is the field of *seat cushion properties*, e.g. stiffness and contour. Cushion stiffness effects the total individual load [46, 47, 75, 107] since it influences the contact parameters between the driver and the seat dominantly (see chapter 1.3.3). It may also influence the driver's posture, especially when soft cushions are used. The contour is essential for supporting the driver properly: On the one hand, the energy needed for postural control depends on the extent to which the body is supported. If sitting without being properly supported the variation of the centre of mass is significantly higher than when the trunk is being supported adequately [31]. If drivers are seated in a stable way, it is easier for them to perform their task and fatigue is developed less quickly. On the other hand, if pelvis and trunk are stabilized well, also the condition of the lumbar lordosis is influenced positively; therefore problems associated with slumped sitting, e.g. low-back pain [21] decrease. An optimal contour can only be defined for a small fraction of the population, because back shape contours strongly differ between subjects [25]. Seat manufacturers therefore implement several seat adjustment mechanisms to accommodate a wider range of drivers (Figure 5).

1.3.2 DRIVER CHARACTERISTICS

The total individual load can only be assessed reliably if driver characteristics such as *posture*, *fatigue* and *personal history* are taken into consideration.

The adoption of an individual driver *posture* on the one hand depends on the available adjustment possibilities of the seat and driver anthropometrics (compare chapter 1.3.1). Interindividual differences including gender-based differences are predominantly explained by stature variation [140]. The fact, that women sit closer to the steering wheel than men, for example, is accounted for mainly by the body height [120]. It still must be noticed, that men and women show different responses to seated exposures, i.e. men flex lumbar and trunk angles more and usually show a more posterior rotated pelvis [44]. Other influencing factors are the age and spinal curvature [97]. On the other hand, personal characteristics strongly influence the driving posture (see 1.4.2). The result is a great variety of postures that can be found among drivers. Zhang et al. [184] for example found 29 different front-passenger postures. A reliable prediction of driving postures based on eye and hip locations [141] is therefore only possible for a mean population and not for the individual [12]. Nevertheless, assessing the driving posture is important for evaluating the total individual load [82, 95, 181]. Postural adaptations are generally used to estimate the level of system stress and thus seating comfort [17, 24, 26, 52, 82]. The typical exposure to prolonged pressure (see the following chapter 1.3.3) and the increased intradiscal pressure when sitting compared to standing [126, 178] increase the total individual load and therefore cause subjective and objective reactions. Through postural changes the driver can decrease the total load [57] and increase the level of arousal [145]. A high number of repositioning is believed to indicate high system stress and low seating comfort [56, 166] and is also associated with decreased performance capabilities [20, 110].

When sitting for prolonged periods, the total individual load is also influenced by the level of *fatigue*, because the ability of certain mechanisms to decrease the load is reduced. Especially the muscles that have to stabilize pelvis, trunk and head show increased activity as time passes by [15]. If the seat supports the upper body better, the energy it needs to stable itself actively is reduced, meaning the activity of the muscles is reduced compared to sitting with little or no support [129]. Effects occur after approximately one hour and are compensated with an adaptation of the sitting posture. Parallel to increasing fatigue, a decrease of driving performance, i.e. the ability to keep an appropriate trajectory, is observed the longer the ride lasts [133]. The main causes associated with this effect are the amount of time of being behind the wheel and the driver's age. As a consequence, increasing driver fatigue can be regarded as stressor because it adds additional load on the driver. Besides that, it can become a safety issue. Because muscular activity is an fatigue indicator, EMG measurements, i.e. measurements of muscular activity, have been used to evaluate system stress [6, 39, 106]. Parameters, i.e. the root mean squared activity of the EMG signal [100] and the time-varying Amplitude Probability Density Function (Lamotte et al., 1996) were found to correlate with subjective seating comfort ratings. This relation could not be confirmed in all studies however [48].

One has to mention in addition to this that the *personal history*, e.g. the constant work-related exposure to prolonged sitting or previous back pain, can influence the individual reaction on similar loads. It is widely accepted that occupational drivers face a higher risk for developing back problems [11, 112, 113, 116]. Seating comfort ratings among this population were found to be worse compared to the ones of frequent drivers. It was shown that the frequency of reported complaints regarding seating comfort was higher if the annual mileage was higher [135].

1.3.3 DRIVER-SEAT-INTERACTION

When evaluating the total individual load, it is essential to take a look at the interaction of the driver and the seat. Dominant stressors in that field are *pressure* and *shear*.

When sitting in a car seat, pressure and shear are acting on the human body in all contact areas. Pressure is defined as the perpendicular force (F_P) per unit area. Shear is a force (F_S) that acts parallel or tangential to the surface (Figure 9).

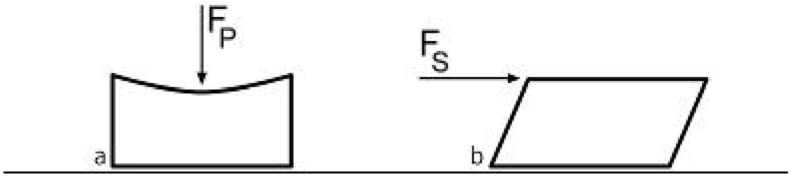

Figure 9: Pressure (a) and shear force (b)

The average shear stress (τ) equals the shear force divided by the area (a*b) over which it acts (Goossens, 2004; Equation I).

$$\tau = \frac{F_s}{a*b} \qquad \text{I}$$

Both, pressure and shear, lead to blood flow occlusion and ischemia of skin tissue [18, 67], causing local discomfort in short-term up to severe skin damage. Pressure ulcers, i.e. areas of localized damage to the skin and underlying tissue caused by pressure, shear, friction and/or a combination of these, mainly develop near bony prominences. This is due to the fact that the skin and underlying tissue at these spots is relatively thin and additionally the load distribution is restricted to a small area. Pressure ulcers are than caused by the high load concentrations and large deformations which lead to tissue damage because of blood flow occlusion [62].

People that are exposed to prolonged pressure and shear, e.g. patients or paraplegics, show blood flow occlusion at lower levels compared to the standard population. For healthy persons, a pressure of 120 mmHg is needed to cause the described effect. Values found for patients start at about 20 mmHg. Additionally, shear forces were found to be about 3 times higher in patients compared to a healthy control group [19]. Other factors such as gender, body weight and sitting position also influence the effect on the individual [154]. The basic conclusion is, however, that shear and pressure lead to local discomfort through ischemia of tissue. The aim therefore is to minimize these forces by optimizing contact parameters, e.g. altering seat and backrest angles [63] or seat cushion material [61]. Another strategy to minimize negative effects would be to frequently change posture, which shifts high stresses to different body locations. This strategy is used to minimize the development of pressure ulcers in paraplegic patients, for example [37]. It was found that the amount of pressure that can be applied on the skin without tissue damage caused by blood-flow occlusion exponentially decreases with time (Figure 10, Goossens [62]). As a consequence, damages dominantly appear after extended exposure to pressure and shear. However, postural changes can only limit but not prevent discomfort and tissue damage because the time needed for complete pressure relief and tissue recovery is at least two minutes if no pressure is applied [33].

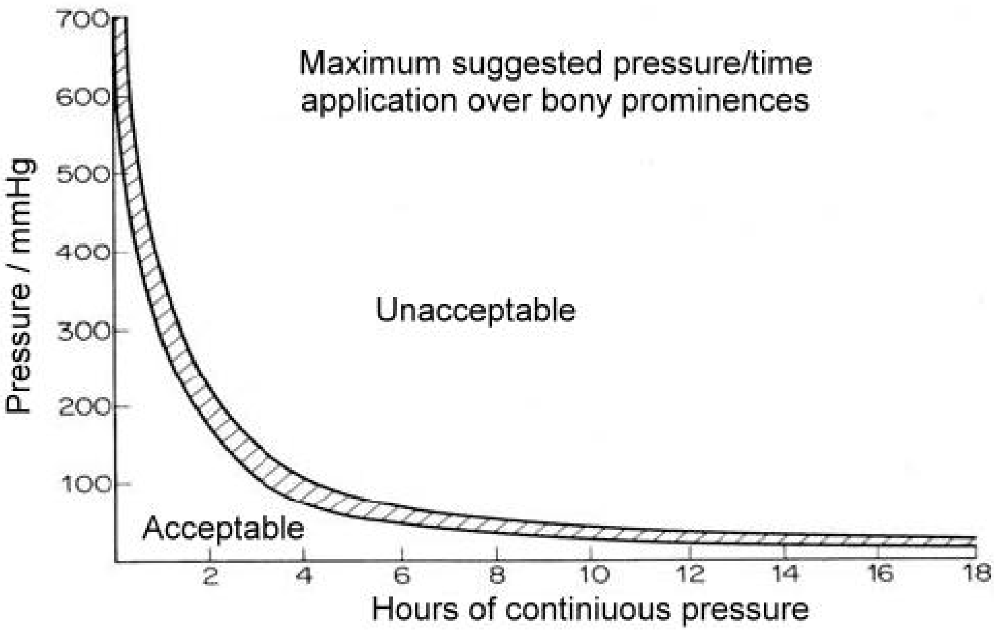

Figure 10: Pressure-Time Tolerance Curve (PTTC) - maximum acceptable pressure over bony prominences (Goossens [62] adapted from Reswick and Rogers [143]).

Comparing major studies, pressure measurement appeared to be the objective method with the clearest association to seating comfort ratings [39]. This method has therefore become a standard tool for industrial seat analyses and is widely used to analyse seating comfort [22, 40, 70, 138, 158, 159]. It is also used to optimize cushions, e.g. the contour or the firmness [34]. A clear relation to subjective ratings, however, could not always be established [71, 136]. One possible shortcoming could be that the influence of other stressors overruled the power of pressure (compare Figure 2). Another reason is that most analyses are carried out as short-term measurements under static conditions. This is assumed because it was found that the total individual load changes with time and that effects of seat properties on the total load seem to occur only after an extended time of sitting [59]. This is underlined by the results of recent long-term studies which proved that subjective seating comfort ratings can be predicted using continuous contact pressure measurements [122]. Seat pressure measurements may be used to analyse seating comfort therefore, but the quality of these measurements depends on the system used and the experimental conditions [72]. Because of the high importance of pressure measurement for the development of vehicle seats, details are provided in the following section describing the interpretation of measurement results and some parameters that are currently used to estimate subjective comfort ratings.

Pressure profiles may be evaluated in certain ways, but usually a large contact area with even pressure distribution is regarded optimal. An optimized distribution of pressure can be achieved basically by adapting a seat's shape, the foam parameters and its suspension [114]. To perform an analysis, a pressure profile between a seated person and the seat is generated with systems that are commercially available (compare Figure 19). From the data, certain parameters are calculated. The most common are the "Static and Dynamic Seat Pressure Distribution" (SPD%), the "Pressure change rate root-mean-square" (Pcrms), and the "area Pressure change root-mean-square" (aPcrms). SPD% and Pcrms correlate well with seating comfort ratings while aPcrms does not [5, 111]. The calculation of all three parameters is described regardless of this finding, because they are widely used in the up-to-date literature. The following section (indented section) is taken from Linden [111], because it is regarded as an optimal description.

> "The ability of a seat cushion to uniformly distribute pressure can be evaluated with SPD% (Equation II).
>
> $$SPD\% = \frac{\sum_{i-1}^{n}\left(p_i - p_m\right)^2}{4np_m^2} \times 100 \qquad \text{II}$$
>
> This method is used in conjunction with a body pressure mapping system where n is the total number of nonzero cell elements, p_i is the pressure at the i:th cell, and p_m is the mean pressure of the n elements. A lower percentage value describes a more uniform pressure distribution at the seat cushion. A value of zero is equivalent to each pressure p_i equal to the mean pressure p_m.

A method based on analyzing dynamic variations is to calculate the body pressure change rate over time. Using the time history of the dynamic pressure P(t) [*annotation:* the overall pressure of one time frame], Pcrms may be calculated as (Equation III):

$$Pcrms = \left(\frac{1}{T} \int_{o}^{T} \left(\frac{dP(t)}{dt} \right)^{2} dt \right)^{1/2} \times 100 \qquad \text{III}$$

T is the total time period. A lower Pcrms indicates a more comfortable seat cushion because it indicates a lower time-dependent pressure variation, but there is no threshold value that separates a comfortable seat from an uncomfortable one. Pcrms can be used to objectively compare and evaluate different seat cushions made from similar materials.

A development of Pcrms, considering the pressure level by weighting high level pressure area, is aPcrms (Equation IV).

$$aPcrms = \sum_{i-1}^{4} A(r_i) Pcrms(r_i) W(r_i) \qquad \text{IV}$$

Table 2: Pressure ranges and weighting factors used in calculating aPcrms

Pressure range r_i	**Weighting factor $W(r_i)$**
r_1: $40 \leq p_a(n) < 60$ mmHg	$W(r_1) = 1$
r_2: $60 \leq p_a(n) < 80$ mmHg	$W(r_2) = 2$
r_3: $80 \leq p_a(n) < 100$ mmHg	$W(r_3) = 3$
r_4: $p_a(n) > 100$ mmHg	$W(r_4) = 4$

For each of the n individual pressure cells an average pressure, $p_a(n)$ is calculated over the test run. Each area $A(r_i)$ is determined by calculating the total area of the cells with average pressure within the specific pressure ranges, r_i. There are four pressure ranges. The weighted pressure change rate is the average Pcrms (aPcrms) of cells within each pressure range times the weighting factor for that range. Cells with average pressure below 40 mmHg do not contribute to the value of aPcrms, and a lower aPcrms will result in a more comfortable seat cushion."

The described pressure parameters are also used to virtually assess the power of pressure as a hard stressor [115]. Models based on multiple linear regression [102] or artificial networks [99] allow the forecasting of seating comfort ratings. Human-seat interaction is also modelled using finite element techniques [137, 168, 169].

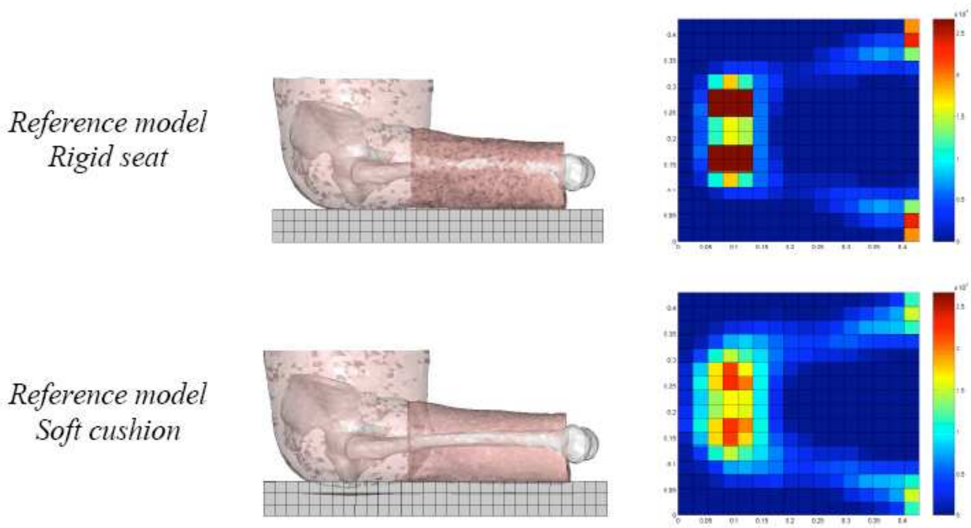

Figure 11: Modelling of the human-seat-interaction using finite element techniques [167]

The evaluation of pressure profiles by means of electronic data processing (Figure 11) is still restricted to static and short-term test conditions. The development of dynamic models that can be used to estimate long-term effect is an important research focus in the near future.

1.3.4 ENVIRONMENTAL CONDITIONS

In addition to the aforementioned factors, increased total loads may also be caused by environmental conditions such as *vibration* and *climate*.

Vibration, i.e. mechanical oscillations about an equilibrium point (Wikipedia), in vehicles is mainly caused by road conditions and vehicle engines. It is transferred into the body through the seat. Certain frequencies in the range of the resonance frequency of the human body and especially the spine have been proven to cause low back pain

[134]. The resonance frequency of the spine is at about 5 Hz [177], later studies found frequency ranges of 4 – 6 [134], 4.75 – 6.25 [119] and 3.5 – 8 Hz [78].

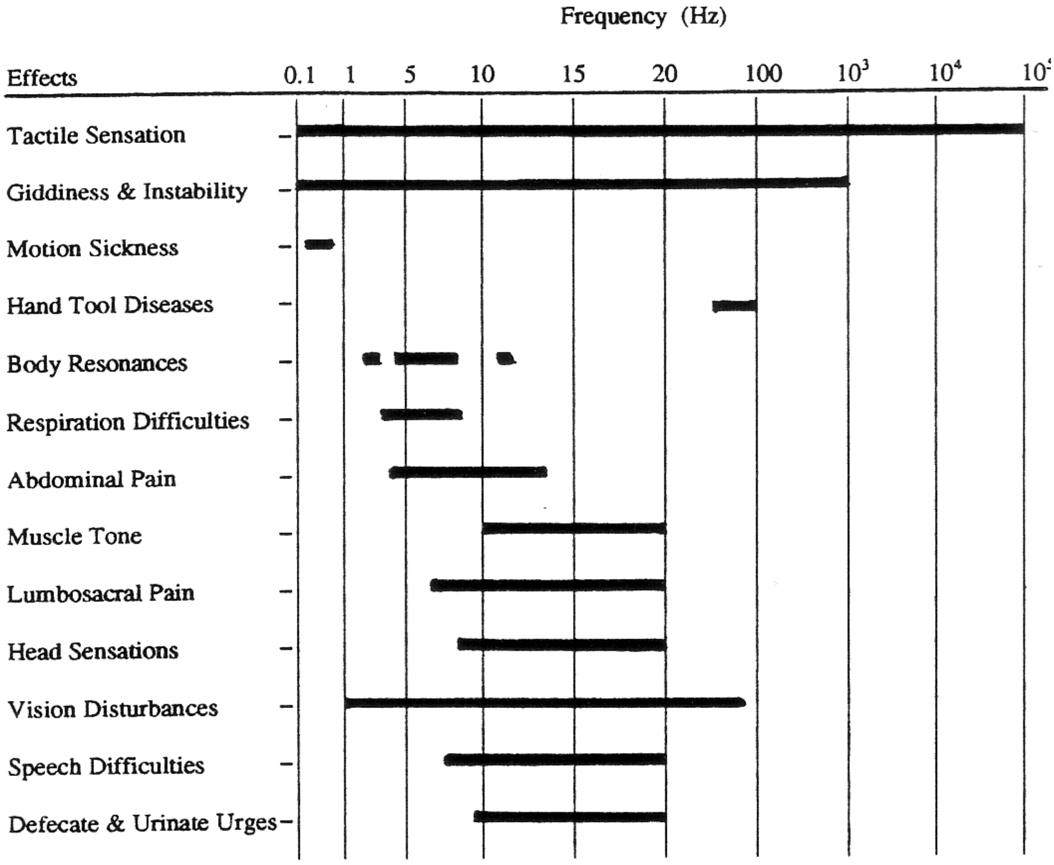

Figure 12: Physiological effects at different frequencies. Besides the vibrational resonance found in humans in the 0 to 20 Hz range, there are a multitude of other vibrational side effects [76].

Since vibration is regarded a mechanical stressor leading to low back pain [176], discomfort [118] and several side effects (Figure 12), the intensity reaching the driver should be limited. A common approach to achieve this is to dampen the mentioned frequencies by using mechanical or gas springs for the seat suspension or by using assorted material when building the seat. The transmission of vibration can be limited in addition to this by allowing the whole seat [174] or the backrest [92] to slide. There are several regulations that describe measurement procedures by means of which vibration values and strategies may be obtained to avoid negative effect for the driver, e.g. VDI 2057 from 1963 or ISO 2631 from 1974 [16]. Usually, the transmission of vibration into the seat is assessed using the Seat Effective Amplitude Transmissibility (SEAT%). By means of this objective measuring method, seats can be compared directly. A basic way of calculating this parameter is described here, because it is widely used in the up-to-date literature. A detailed description will not be given, however, because different methodological enhancements are available (compare for example [111]) and further research is still being conducted. The following section (indented section) is adapted from Ahmadian [5].

> "The SEAT% method (Equation V) measures the transmission of acceleration from the floor to the seat cushion, $G_{ss}(f)$ and $G_{ff}(f)$ being the seat and floor power spectra respectively. The weighting factor $W_i(f)$ which depends on frequency, as defined in Table 3, is based on research of human discomfort [69]. "

$$SEAT\% = \left[\frac{\int G_{ss}(f) W_i^2(f) df}{\int G_{ff}(f) W_i^2(f) df} \right]^{1/2} \times 100 \qquad \text{V}$$

Table 3: Frequency dependent weighting factors for calculating SEAT% [69]

Frequency range f	**Weighting factor $W_i(f)$**
0.5 < f < 2.0	$W_i(f) = 0.4$
2.0 < f < 5.0	$W_i(f) = f / 5.0$
5.0 < f < 16.0	$W_i(f) = 1.0$
16.0 < f < 80.0	$W_i(f) = 16 / f$

> The frequency weighting is done to take into account the human response to vibration. The most commonly used standards for frequency weighting are ISO 2631-1 [88]; BS 6841 [30]; and the straight-line approximations given in the Handbook of Human Vibration [69].

In addition to measuring vibration directly, methods for modelling vibration responses are available [117], which allow to virtually optimise its parameters before building a new seat. The final evaluation, however, is still being performed using test subjects, because humans are quite sensitive to transients in vehicle motion [155].

It has also been shown that the *climate*, i.e. temperature and humidity, influences seating comfort [90]. If the temperature lies outside a certain range which is specific for various body parts (Figure 13), discomfort increases [28, 83]. The Equivalent Homogenous Temperature (EHT), proposed by Wyon et al. [180], can be used to estimate the comfort range for various body parts in non-uniform environments [23]. The EHT is usually calculated from physiological models [74].

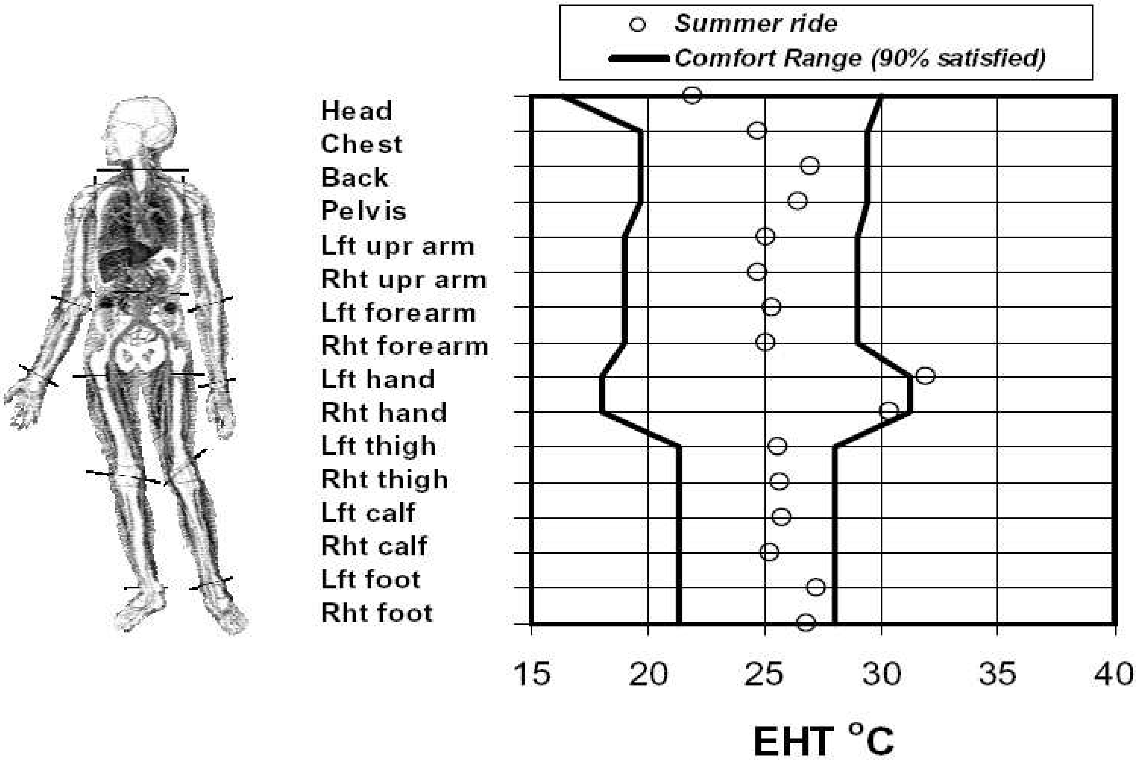

Figure 13: EHT index for 16 body segment for a summer ride [74]. The temperature comfort range depends on the body segment.

Additionally, higher temperatures and the corresponding higher humidity between seat and body are key factors for the development of pressure sores [41]. As for all other described stressors, models exist that allow the prediction of thermal comfort based on human tests [182].

1.4 SOFT STRESSORS INFLUENCING THE TOTAL INDIVIDUAL LOAD

The feeling of comfort is a personal sensation, which can be derived from subjective statements. The most common subjective techniques are the *general comfort rating*, the *body area discomfort rating*, the *chair feature checklist*, the *method of adjustment*, and *personal comments* [32].

The *general comfort rating* aims at eliciting a subject's overall comfort by rating techniques such as rating on a verbal scale, absolute rating (0-100), direct rating, pair comparison, and semantic differentials. For rating on a verbal scale, the test person has to choose one item from a list of predefined phrases to express his actual feeling of comfort. Typical phrases are "I feel completely relaxed", "I feel restless and fidgety", and "I feel unbearable pain" with several gradations in between to attain a very good to extremely bad comfort rating [149]. When using an absolute rating scale, the test person judges his feeling for several questions, e.g. "Do you feel pain?", on a scale between 0 (worst rating) and 100 (best rating). Direct ranking demands the test person to rank the tested seats into a single rank order. When comparing a large number of seats, this can be done in several steps. For a pair comparison, the test person is asked to select the better one of two seats. If more than two seats are to be tested, each seat is tested against all others. At the end, a ranking of all seats is obtained. The semantic differentials technique is widely used and proved to be very efficient for comfort assessment. Each tested seat variable is judged on a bipolar scale such as "narrow - wide" or "hard - soft". Gradations can be given graphically by marking a spot on a line between both descriptors or verbally by using predefined numerical values, e.g. 1 - 10.

The *body area comfort rating* is used to compress different sensations from various body parts (local comfort) into a general rating. Typically, the following parts are used: neck, shoulders, back, lumbar region, buttocks, rear thigh, calves, and feet [85]. The test person marks the corresponding feeling of comfort for each body part on a bipolar scale of semantic differentials (see above) with the adjectives "comfortable" and "uncomfortable". The results are then used to create an overall comfort rating or to identify areas in which comfort is best or worst.

In contrast to the indirect methods described above, the *chair feature checklist* can be used to directly evaluate certain features of the seat, e.g. its height, depth, width, shape, slope, and back curvature [149]. Three decisions, e.g. “too high”, “correct”, “too low”, can be made with regard to comfort-relevant seat features. A rating is given after each feature has been thoroughly described. Finally, all seats tested are compared based on these ratings.

To attain an optimal range of seat adjustments, another direct method can be used: the *method of adjustment*. A group of test persons is asked to adjust the seat in order to conform it to a given criterion, e.g. “most comfortable”, “too low”. It is also common to have the seat adjusted by a different person. In this case, the test person evaluates several settings which are incrementally increasing or decreasing according to the criterion. The result of this approach is an adjustment range, which conforms to the tested criterion, e.g. “most comfortable”, “too high”. Based on the ratings of a group of persons, reasonable and optimal adjustment ranges can be defined.

Besides all rating methods, the test subject must be asked for *personal comments*. This will reveal additional information that might not have been covered by planned questions and assessment techniques. It also increases the compliance of test persons. However, since such comments are hard to evaluate, comfort ratings cannot exclusively be based on this method.

Subjective ratings are widely used in almost every area of ergonomics research for the assessment of workload, fatigue, usability, annoyance and comfort, but the scientific quality of such methods is nevertheless under debate [9]. Researchers therefore seek for better evaluation tools. Two methods which have been developed recently, the Evaluation of Automotive Discomfort Questionnaire [150] and the consumer-driven wheelchair discomfort assessment tool [36], prove that further optimization is still possible and that the methodological development will continue in the near future.

Many soft stressors influence subjective comfort ratings. The next section will provide an overview of selected influencing factors. As in chapter 1.3 the classification from Table 1 is applied.

1.4.1 SEAT PARAMETERS

Besides ergonomic seat features, parameters such as *aesthetics* and the *look-and-feel* of a product influence seating comfort ratings. The sentence “forget about ergonomics, focus on seat design” [79] is deliberately provocative, but points out the influence of aesthetics on subjective statements. Chair users have difficulties in recognizing the difference between ergonomic features and design elements, since small differences, e.g. in joint angles or cushion shape, cannot be perceived due to relatively insensitive feedback from joints, ligaments, and the spine (see chapter 1.4.2). Aesthetic features, on the other hand, are easier to distinguish, but only reflect the person’s taste. Some tools exist that aim at measuring the “pleasure of use” [94], but these have to be enhanced still. Test setups need to be chosen carefully in order to minimize or numeralise aesthetic influences. The opposite approach, the so-called Kansei engineering [127], is to implement customer demands and feeling into product design in order to raise the users subjective feeling of comfort. Unless measurement and prediction of the emotional value in design is made possible, the influence of aesthetics on the seating comfort impression can neither be avoided completely nor reliably be used to increase the seating comfort perception.

1.4.2 DRIVER CHARACTERISTICS

Self reports of driver behaviour are useful and reliable [173]. It was also shown that drivers are capable of differentiating various chair features [43]. Individual driver characteristics such as the fact that people perceive seating comfort in different ways, or that subjective ratings depend on the actual psychophysical condition of the test person, influence the absolute level of the perceived load.

It has been shown, that the *sensitivity* of test persons to various parameters is individually different. When evaluating data, individual perception levels need to be taken into account. It has been shown, that the human perception is limited and measures have been identified to describe thresholds in perception levels, the average person can identify. It could be proven, for example, that humans are quite sensitive to transients in dynamic behaviour, i.e. car motion [155]. Perceptible pressure differences in the area of the ischial tuberosities depend on the pressure level and contact area, but usually range between 1.9 and 3.5 kPA [60]. Concerning the backrest's inclination, adaptations above three degrees can be perceived [80] by the driver. Smaller alterations are not distinguishable by most persons. It is also widely accepted, that the thermal sensation differs between humans. It could also be shown, for example, that people accept much lower cabin temperatures when the seat is heated separately compared to situations with no seat heating [28].

In addition to this, subjective ratings are influenced by psychophysical conditions. Back pain, for example, influences comfort ratings [73] as well as people's sensitivity, e.g. to a change in lumbar position [157]. Another important factor is the overall riding time. Ratings change over time, but predominantly within the first three hours [53].

1.4.3 Driver-seat-interaction and environmental conditions

Anthropometric preferences, e.g. "comfort angles" (compare chapter 1.3.1), are different between humans and do not always match with widely accepted values [98]. Differences regarding the preferred seating posture or the feeling of what is considered a "good fit" are easily noticed when several test persons are asked to evaluate the same seat. Different sitting preferences seem to exist (chapter 4.3), but no reliable classification is available. An individual adjustment of the seat is, however, important for comfortable sitting [50]. It must therefore be said that creating an optimal seat for the entire population is impossible. The aim should rather be to focus one's design efforts on the target group of a special seat / car. In many cases, a certain range of users cannot be accommodated optimally. Further research is necessary to classify certain preference types to be able to take subjective preferences into consideration when rating seating comfort.

In addition to this, there are environmental conditions such as *stress*, *noise* and *weather* and also *traffic conditions* that influence subjective ratings. It has also been shown, that ratings change with the *time of the day* [32]. Distractive factors therefore need to be minimized as much as possible. This is why tests are often carried out in controllable surroundings or simulated environments. Driving simulators produce reliable output [139], but conditions are different to real-life situations. Conditions in field studies, on the other hand, are hard to standardize. Both approaches should therefore be used simultaneously whenever possible.

1.5 OBJECTIVES

Although topics related to „sitting“ and „seating comfort“ are frequently discussed in recent literature, very little is known about the effects of soft and hard stressors for extended duration driving. Fundamental knowledge is gained predominantly from short-term studies and in simulated environments. Measurements usually do not exceed 15 minutes, seated posture is monitored only rarely more than one hour and mainly addresses office chair users [166]. Long-term measurements of postural adaptations in the automotive field are seldom.

Mobility is a fundamental criterion in modern society. The quality of the seat, being the direct interface between the driver and his car, plays a major role with regard to safe and relaxed driving and also dominantly influences seating comfort. When aiming at evaluating the overall comfort, many factors have to be taken into account (compare chapter 1.2). A detailed analysis of all influencing parameters would be very time-consuming and expensive. A more practical way to assess seating comfort is to evaluate driver behaviour, which is influenced by various hard and soft stressors. As shown above, postural adaptations might be used as criterion to describe driver behaviour and thus estimate system load. Unfortunately, little is known about sitting posture in prolonged driving. Seat development is based on knowledge that was gained primarily through static experiments. Information exists, however, that driver posture is not static but changes over time. Additionally, no method is available to easily and reliably monitor the driver’s posture. The primary focus of the present work therefore is to study the driver’s behaviour modifications when seated for a long period of time under realistic conditions and to use the results in order to optimize car seats. This is achieved by

1. developing a method for analysing driver posture in everyday situations and
2. describing basic possibilities for the driver to minimize the total individual load in prolonged driving.

The general goal of this dissertation is to develop a new method by means of which driver behaviour can be analysed objectively under realistic conditions. The method will allow insights in the postural changes of the driver which depend on the amount of time he or she spends in the car and will also generate basic knowledge about stressor induced changes of the total individual load when driving a car for a prolonged period. On the one hand, it is essential to apply scientific methods in order to derive reliable results. On the other hand, however, real-life conditions must be kept in mind to establish a method as basic tool for seat design. Therefore, the final concept must be easy-to-use and may not interfere with driver perception and behaviour. One possible solution to achieve this goal is a system with few sensors that are integrated in the seat and automatically controlled by a predefined routine.

Furthermore, the driver's basic strategies to minimize the absolute load for prolonged driving will be investigated. It will have to be evaluated if movements or certain patterns in the behaviour exist that lead to or promote the limitation of the total individual load over time. It is believed that such patterns occur. Thus, the elementary question is, whether they can be identified and described by adequate parameters. If so, techniques must be developed to minimize negative effects. New means for further car seat improvement and for the maximisation of seating comfort could be derived from this knowledge.

1.6 THESIS OUTLINE

Starting with a basic description of stressors which influence seating comfort in this chapter, three main steps that focus on achieving the aim of this work will be described:

1. measuring stress-induced posture modifications in prolonged driving
2. underlining the relation between system stress and seating comfort, and
3. developing new methods to analyse and reduce the total individual load.

In order to measure postural changes in prolonged driving, a measurement method must first be chosen. Chapter 2.3 provides an overview of the available methods and comments on their advantages and disadvantages. From the pool of available instruments, the sonoSens® Monitor appears to be the best choice. The validity of this device is therefore evaluated (chapter 2.4). The main concern addressed is the influence of the contact of the sensors with the backrest on the results. Since is it found that the impact is negligible, the sonoSens® Monitor is hence used to evaluate postural changes in prolonged driving under realistic conditions (chapter 2.5). Based on the data, parameters are defined that describe the driver's behaviour modifications. A routine for the calculation of the chosen parameters is outlined in addition to this.

The results of chapter 1 indicate that driver posture changes over time. The relation between driver behaviour and seating comfort is therefore evaluated as the next step in chapter 3. In the first part, postural changes for prolonged driving periods are used in order to evaluate whether patterns exist that could limit the total individual load of the driver or not. It could again be shown that driver posture is not static. Parameters describing the driver's postural changes are therefore used in the second part of chapter 3 to identify the relation between the driver's behaviour modifications and seating comfort. A model is presented as a result that allows an accurate prediction of seating comfort based on the assessment of postural changes.

New methods to analyse and influence driver behaviour are evaluated in chapter 1 due to the fact that posture changes in prolonged sitting periods have been found to decrease the total individual load. In the first part, a system for posture measurement based on the continuous assessment of local pressure changes is developed and evaluated. The initial posture change of the driver found in chapter 3 is evaluated in the second part using this system and the sonoSens® Monitor. Finally, the effect slight changes of the seatback inclination have on the driver's posture is assessed. The results show that driver posture as well as contact pressure can be altered by small variations of the seatback angle.

The results of the previous chapters are summarized and their practical relevance is discussed in chapter 5. In addition to this, the main assumptions of the proposed seating comfort model are compared to the findings. Based on the results, a conclusion is presented and recommendations for further seating comfort evaluation are provided.

2 MEASURING POSTURAL CHANGES IN PROLONGED DRIVING

2.1 ABSTRACT

The evaluation of the driver's behaviour modifications is one possibility to objectively analyse seating comfort (chapter 1.3.2). The aim of this chapter is to analyse the driver's behaviour modifications over prolonged periods in order to verify if they can adequately be described by macro- and micromovements as stated in recent studies [166]. Micromovements are movements with small amplitude around the mean posture and are seen as the main reason for the change of the perceived load. Macromovements are major posture changes that occur if loads approach the individual limit. Out of a choice of available methods with which postural adaptations in prolonged driving could be measured, the sonoSens Monitor appears to be the optimal device for the task. Verification proved that sonometry, i.e. ultrasonic distance measurement, provides accurate measurement results. It could be shown from the analysis of driver posture in field conditions that the driver's behaviour modifications can be described by posture changes (macromovements) and activity (micromovements) as reported in recent studies. Nevertheless, results indicate that an additional parameter – posture adaptations – is needed for an accurate description. Based on these findings, a model to analyse posture data is developed and presented.

2.2 INTRODUCTION

One major parameter that can be linked to seating comfort is the driver's posture (chapter 1.3.2). Besides the description of an ergonomically optimal driver posture, little is known about the connection between posture and comfort. DeLooze [39] only found five studies – all dealing with office chairs – which evaluated that connection. A clear correlation between posture variation and subjective comfort ratings could not be found, however. Since then, some studies were carried out that revealed a clear relation between posture parameters and subjective ratings. Vergara and Page [166] used continuous pressure measurement to assess posture variation in prolonged driving. They present two basic results that describe the connection between seating comfort and posture: the mean posture and micromovements, i.e. movements with small amplitude around the mean posture, are seen as the main reason for the change of the perceived load. Macromovements, i.e. major posture changes, occur if loads approach the individual limit. Based on these findings it can be concluded, that load-induced posture variations of the driver can be described adequately by two basic parameters:

1. movements with small amplitude (micromovements) that influence the total individual load and consequently seating comfort, and
2. postural changes (macromovements) that can be interpreted as a reaction on increased loads.

This assumption was confirmed by Solaz et al. [152]. When analysing posture in prolonged driving in a simulated environment, they found that the test persons with low pelvis mobility and high numbers of repositionings reported the highest discomfort. Besides appearing when the total load approaches the individual threshold, macromovements were found to decrease the total individual load [57]. The analysis of the driver behaviour modifications might consequently be a suitable way to evaluate seating comfort.

2.3 METHODS TO DETERMINE DRIVER POSTURE

Driver behaviour can be assessed using a variety of direct or indirect methods. When aiming at monitoring driver posture in real-life conditions, choices are narrow due to several constraints, i.e. limited space, electricity supply, body parts which are not freely visible (e.g. low back) or safety reasons. Furthermore, measurements must not interfere with the driver's perception and behaviour. In the following section, some feasible techniques are described together with their dominant advantages and disadvantages (Table 4).

2.3.1 DIRECT MEASUREMENT OF DRIVER POSTURE

Body posture can be directly inferred from observation, body angle measurements, and sonometry.

Posture observation can be performed by external observers directly, with the help of video files, and by self-reports. Self reports do not seem to provide reliable results [125] and are therefore not further described here. Observation by external observers is often done with the help of video files and supported by computer analysis. Usually, markers are applied to certain body joints or specific landmarks, which are then traced in the recorded sequence. From the results, parameters describing the movement, i.e. displacement, velocity and acceleration, can be calculated. This technique is widely used for motion analyses in biomechanics. Its use to analyse driver movements is limited, however. On the one hand, certain body parts are hidden by the car seat and are therefore not accessible. On the other hand, space and electricity requirements necessary to perform such measurements can only be provided with great effort. Additionally, video observation produces large amounts of data. Observation is therefore usually used to monitor basic driver or occupant postures, e.g. to determine the percentage of out-of-position postures in real-life scenarios [42, 132]. Furthermore, it can be used to accurately study driver reactions to certain manœuvres [55], but measurements require test track conditions in this case (Figure 14).

Figure 14: Observation of driver movements using video [55].

Driver posture can also be assessed by monitoring the angles of certain body parts. Angles between body segments can be measured with goniometry. A sensor consists of two bodies that are connected by a flexible axle. The bodies are attached to opposite sides of a joint (Figure 15). Changes in the joint angle lead to a deformation of the sensor, from which absolute joint angles can be calculated. Often, potentiometers are used, which change resistance according to deformation. Another possibility is to use strain gauges to measure deformation.

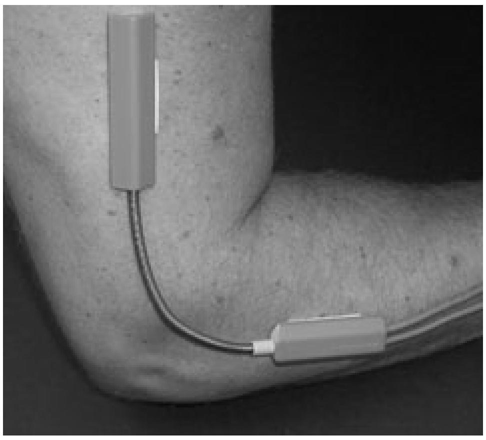

Figure 15: The application of a goniometer to measure the elbow joint angle (Source: Mindware Technologies Ltd.)

The inclination of body parts can be measured with inclinometers. Acceleration sensors are used to measure inclination. They consist of a small seismic mass surrounded by a viscous fluid and included in a closed system. The mass is connected to the system by a resistance strain gauge. When a force acts on the mass causing acceleration (a), a resistance change of the strain gauge can be measured. Inclination can be assessed by measuring the influence of the gravitational force (g) on the seismic mass (Figure 16). When the sensor is not tilted relatively to the direction of g-force, the acceleration in the other direction(s) is zero. If the inclination is increased, the g-force accelerates the mass in more than one direction. The inclination angle can consequently be calculated from the acceleration ratio.

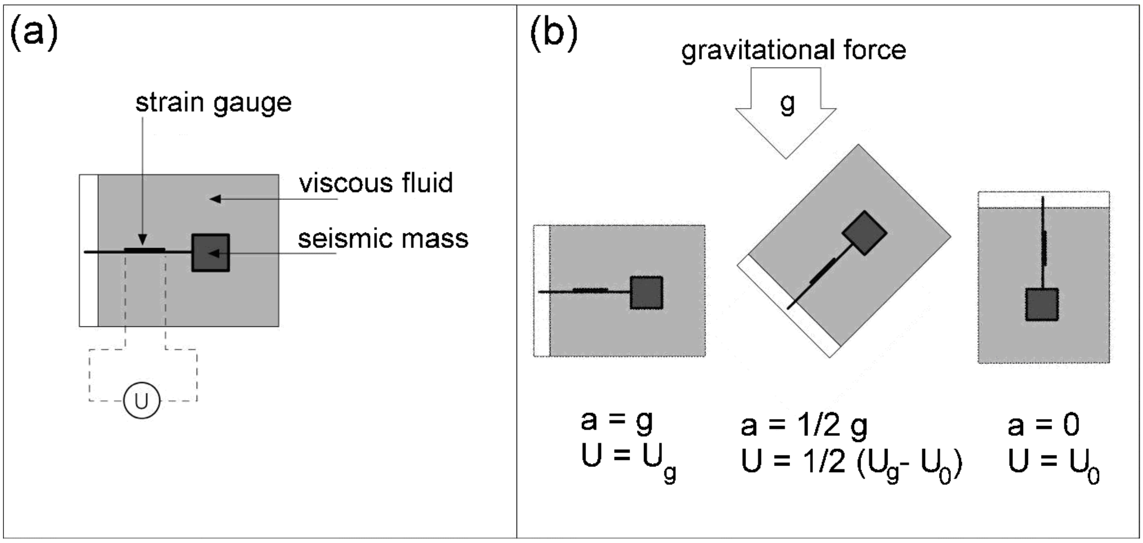

Figure 16: Basic parts of an acceleration sensor (a) and its use for the measurement of inclination (b). A detailed description can be found in chapter 4.2.

Both methods, goniometry and inclination measurement, have dominantly been used to separately monitor pelvic, lumbar, and trunk posture [91, 153, 179]. For the assessment of greater parts of the body, several tools have been developed combining the aforementioned techniques, e.g. the so-called rachimeter (Figure 17).

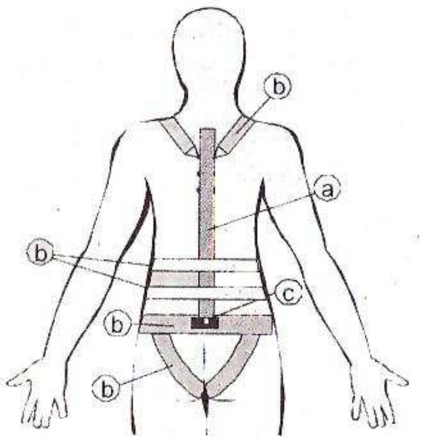

Figure 17: Outline of the rachimeter and its attachment system: (a) rachimeter, i.e. a thin flexible goniometer; (b) straps and belts; (c) rachimeter base including an inclinometer [166]

The main disadvantages of the available devices are their size and the need of additional equipment, e.g. amplifier, data processor, and storage unit. Especially the sensors on the back and pelvis have contact with the seat, which because of their height above the skin leads to interference. Additionally, attachment straps and belt may restrict subject motion. Recent studies show, however, that posture can be measured using these tools, e.g. when the subject is standing or sitting without using the backrest.

Upper body movements can be monitored using sonometry [14];. Movements are measured as distance changes between characteristic points on the back (Figure 18). The extension of the skin during body movements causes a change of the distance between the sensors, which is recorded by the sonoSens® Monitor. Through continuous transmission of the ultrasonic signal between the transmitter and the receiver, changes in body posture can be calculated from sensor distance changes (chapter 2.4).

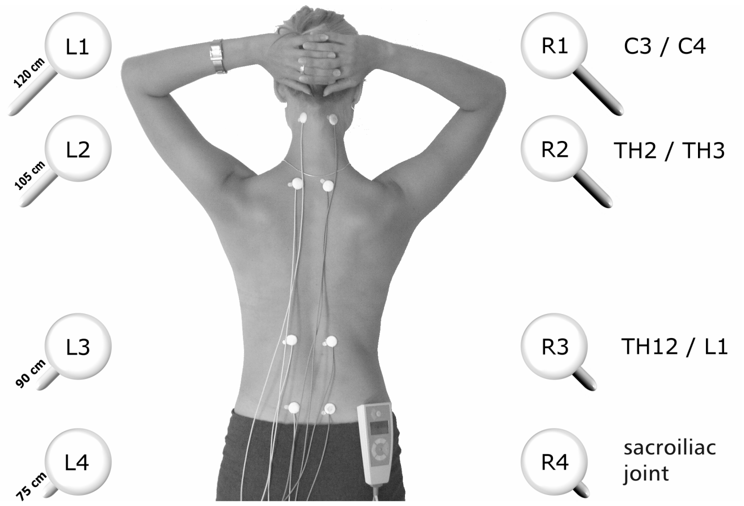

Figure 18: Application of the sonoSens® Monitor (Friendly Sensors AG, Jena, Germany) to measure lumbar, thoracic and neck movements. Sensors are attached 5cm left and right of the spinal processes at the given landmarks.

Sonometry is an easy method for long-term posture monitoring. The measurement of head and neck movements does not seem to be accurate, however, because anatomic alignment of cervical vertebrae cannot be inferred from variation in surface measurements of head and neck posture, [93].

2.3.2 INDIRECT MEASUREMENT OF DRIVER POSTURE

The most common methods for the indirect assessment of posture changes are contact pressure, electromyography, and seat contour measurements.

Pressure profiles and changes of the centre of pressure can be used to estimate driver posture. Pressure sensors change resistance when a force in normal direction is applied. Usually, a mat containing an array of pressure sensors is positioned between body and seat. From the resulting pressure profile (Figure 19), several parameters describing the interaction between body and seat can be calculated (see Chapter 1.3.3). From the change of the centre of pressure, for example, basic posture and movement parameters can be concluded.

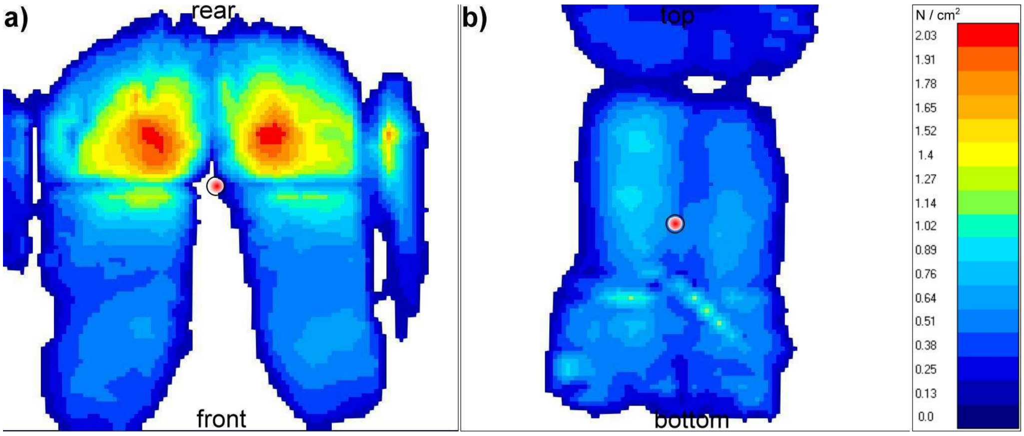

Figure 19: Typical contact pressure profile between seat pan (a) and backrest (b) and the driver's body. Absolute values in N / cm^2 are indicated by colours (blue: low pressure; red: high pressure). The centre of pressure is marked with a circular symbol.

Dynamic pressure measurement, i.e. the continuous recording of pressure changes, has been successfully used for long-term analysis of driver posture [8, 13, 22]. It must, however, be said that sensor mats may shift, wrinkle, or influence cushion properties and therefore may alter results. Additionally, the need of additional equipment for data storage and power supply increases complexity.

Surface electromyography (SEMG) is used to assess muscular activity in certain postures and to estimate muscle loads. SEMG is generally performed using surface electrodes to detect the electrical potential generated to initialise muscle cell contraction (Figure 20). Basic information is gained from the ratio of overall and maximum activity and from the recruitment pattern of certain muscles or muscle groups. High back muscle activity resulting from high loads has been proven to increase discomfort [86, 100, 108].

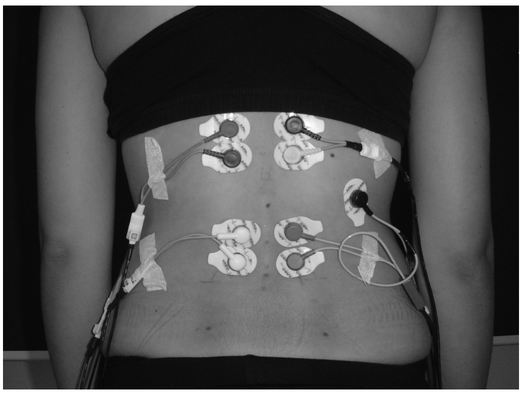

Figure 20: Application of surface electrodes to assess muscular activity

SEMG has become a standard tool for the analysis of muscle loads in seated postures. The large amount of time needed for skin preparation and application of the electrodes hinders the everyday use of the method, however. Besides that, complex post-processing methods, which are still under debate, are needed for data evaluation.

Seated postures and postural adaptation may also be derived from seat contour measurement. A matrix of thin strain gauges or goniometers can be used to measure contact shapes between body and seat (Figure 21). Changes in posture result in a changed deformation of the seat surface. Parameters describing postural adaptations can be calculated as a consequence of that.

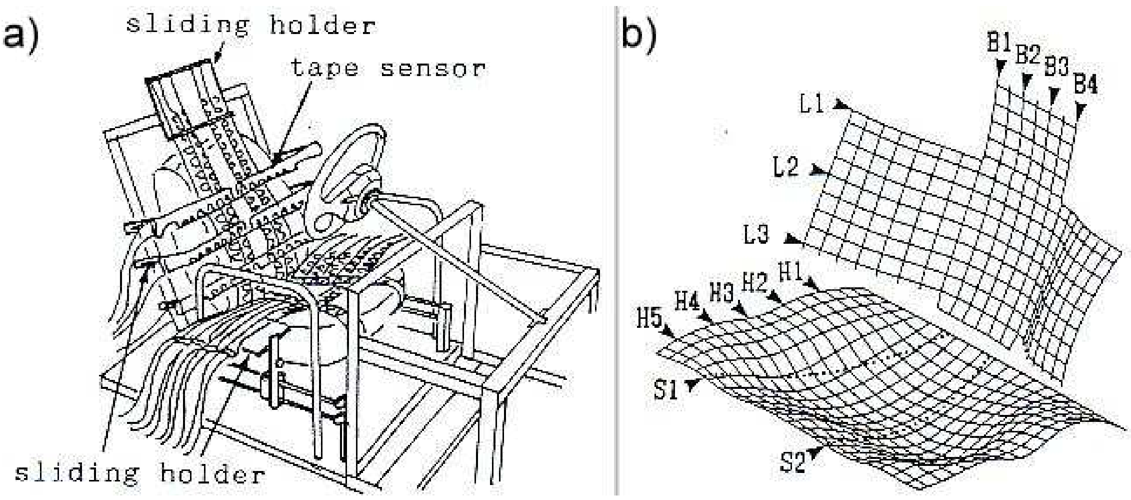

Figure 21: Illustration of seat contour measurement: (a) position of strain gauges on the seat; (b) example of measured contact shape [181]

Subjective comfort ratings relate to contact shapes in short-term, static experiments [181]. Besides, pressure measurement is used more often than contour measurement because of certain advances in pressure measurement techniques.

Table 4: Characterisation of selected methods to directly and indirectly assess driver posture and identification of the main advantages and disadvantages for the measurement of driver posture under field conditions

Method	**Measured Parameters**	**Main Advantage(s)**	**Main Disadvantage(s)**
Direct methods			
observation (video)	marker locations, from which absolute displacements of joint angles can be calculated	accurate kinematic analysis of whole-body movements visual inspection after measurement	some body parts are not directly accessible space and electricity requirements
goniometry	absolute joint angles	easy setup and data processing portability	equipment's size and thickness need of additional equipment
acceleration measurement	acceleration and inclination of body parts	easy setup, portability	equipment's size and thickness need of additional equipment
sonometry	movement-induced sensor distance changes, from which relative posture changes can be calculated	easy setup and data processing portability, small sensors no additional equipment needed	inaccurate measurement of head and neck movements no data with respect to the global reference system
Indirect methods			
Contact pressure measurement	contact pressure profile between body and seat	easy setup and data processing portability	sensor mats may shift, wrinkle, or influence seat properties need of additional equipment
electromyography	electrical muscular potential	Direct assessment of muscular work and loads	large set-up time complex data evaluation

2.3.3 DISCUSSION

Because of the fact that the aim is to study the driver's behaviour modifications in real-life conditions, several constraints limit the use of available systems for the acquisition of data, such as:

- limited space and electricity supply
- partly hidden body parts that are partly hidden (e.g. low back)
- safety issues
- interference with driver perception and behaviour
- interference with seat parameters, e.g. cushion properties

The chosen method should be easy to set-up and provide fast results due to the fact that project time is usually narrow.

Based on the overview of available measurement techniques presented above and the described constraints (Table 4), the sonoSens® Monitor has been chosen to analyse driver behaviour for the following reasons:

First, the system can be used without any additional equipment, e.g. laptop computer, power supply, mountings; second, it allows direct measurement of driver posture for extended time periods; third, it is small and lightweight, and does not alter the seat's parameters; forth, the setup and calibration does not take more than 15 minutes; and finally fifth, measurement files, which are stored in an internal memory and transferred to a PC after the session, are rather small, allowing fast analysis.

The inaccurate measurement of head posture (compare description of sonoSens® Monitor) is not a reason to refrain from using the device, since relative postural changes are evaluated instead of the absolute posture.

2.4 EVALUATION OF THE SONOSENS® MONITOR FOR MEASUREMENT OF DRIVER POSTURE

Sonometry was formally used for the measurement of upper trunk postures and was proven to produce valid and reliable data [54, 172]. It could be shown, that that the ultrasonic measurements of sagittal movements, i.e. flexion and extension, are highly correlated to data obtained with the Schober technique, i.e. the measurement of the distance change between skin markers with a measuring tape, and data derived from an electronic inclinometer (Table 5). The reliability of the device was proven to be high. Interclass correlation coefficients were 0.991 for short-term, 0.977 for medium-term and 0.937 for long-term measurements [54].

Table 5: Validity of the Ultrasonic Device: correlation (r) between ultrasonic and Schober measurements for lumbar flexion and ultrasonic and electronic inclinometer measurements for extension plus flexion (n=16) as well as the level of significance (p). [54]

	Schober's Test (mm)	**Ultrasonic Device Flexion (mm)**	**Ultrasonic Device Extension & Flexion (mm)**	**Electr. Inclinometer Extension & Flexion (mm)**
Mean	59.7	39.4	60.1	68.9
SD	10.1	7.3	8.9	10.2
r	0.989		0.884	
p	<0.001		<0.001	

It could also be shown that the spinal alignment can be reliably derived from the position of markers applied to the skin [124]. In addition to this, results from previous studies indicate that measurements do not interfere with people's behaviour. Gait-related movements of the upper body could also be successfully assessed using the sonoSens® Monitor [1, 84]. Additional tests are necessary to ensure accurate measurements of driver posture though due to the fact that when sitting in a car seat, sensors unavoidably touch the backrest which might influence measurement results. The possible consequences on the measurement results were therefore investigated. Contact pressure and friction were identified being the main reasons for the interference. A first test was carried out to evaluate the maximum effect possible in order to estimate the maximum influence of pressure and friction on the measurement outcome. Further research was done to identify parameters with regard to pressure and friction and their influence under realistic conditions. Finally, the driver's movements derived from sonometry and video were compared.

In order to be able to detect the actual motion of single sensors and to maximize friction, the backrest cushion of the corresponding car seat was replaced by a polyurethane mesh. Maximum side flexion was simultaneously measured with sonometry and video, the backrest being inclined by 20 degrees (compare Figure 6). Due to the fact that the highest contact pressures (see next paragraph) and dominant sensor displacements appear at scapulae level, the data of a sensor pair attached at TH 8 level was used for the analysis. Results showed that when friction is high the skin's elasticity prevents the sensor almost completely from being displaced compared to unhindered motion (Figure 22). Sensors were displaced only 2.9 ± 2.1 percent of their unhindered displacement in maximum trunk flexion (to the right and to the left).

Figure 22: Sensor positions for the neutral position of the trunk (middle) compared to left and right flexed postures. High friction between sensors and backrest may possibly inhibit sensor motion due to skin elasticity.

Further research was done to evaluate realistic pressure and friction parameters for typical driver seats and postures. Based on the literature the coefficient of friction between back and backrest ranges between 0.18 and 0.24 dependent on the cloth material [95]. Contact pressure between back and backrest with a backrest inclination of 20 degrees was evaluated using pressure measurement (XSensor system, interfaceforce, Moenchengladbach, Germany). Maximum pressure of 12 persons (weight: 78.8 ± 17.7) sitting on four different seats was 1.1 ± 0.2 Newton per square centimetre. Maximum pressure was predominantly found at the lower scapulae level. With the sensors attached to the back, maximum contact pressure was not different compared to the situation without sensors (Figure 23 a / b). Some sensors could only be spotted with pressure measurement when lying on the back on solid ground with hip and knees 90 degrees flexed (Figure 23 c).

Based on the presented values, the friction force between sensor and backrest is approx. 0.25 N (a mean contact force of 1.1 N multiplied by the coefficient of friction of approx. 0.22). Shear forces between back and backrest are not documented in literature but are believed to be lower than shear forces under the buttock, which are reported to be around 40 N [65]. An influence of the contact of the sensors with the backrest on the measurement results is therefore only possible for shear forces below one Newton. Actual forces needed are believed to be even lower, because the highest contact pressures were seen at locations were no sensors are present. Moreover, pressure is likely to be reduced before posture changes, which again would reduce friction. An exact statement about the interaction between sensors and seat are only possible fit the relative motion of the sensors to the backrest could be measured. This was not possible in this study. The use of pressure mats does not produce the necessary results because the sensors cannot be spotted. Besides, the mats would alter the friction parameters. No other measurement system was available to assess the interaction. Consequently, the influence of the sensory contact on the measurement output cannot be qualified so far, but is believed to be low.

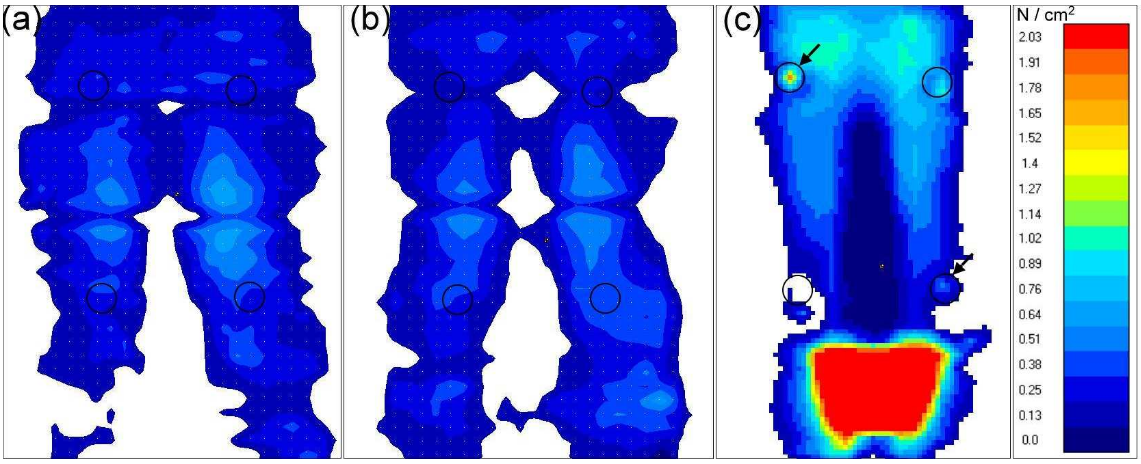

Figure 23: Back pressure profile of a test person. Approx. sensor locations are indicated by circles. Pressure values do not differ with (b) and without (a) sensors attached to the back. When lying on solid ground with hip and knees 90 degrees flexed, some sensors at level L4 and TH 2 can be spotted (arrows).

In order to estimate the quality of the measurement output when sitting in a car seat and to verify the above made statements, movements derived from sonometry and video were compared in two test cases. First, repeated movements were measured. A test person sitting in an up-to-date car seat with his hands on his thighs was advised to do maximum trunk movements in the frontal plane without loosing contact to the backrest. Movement were restricted by the side bolsters of the backrest (compare Figure 22). After each movement, he was asked to return to his initial sitting posture and hold this position for 30 – 60 seconds. Second, a long-term test was performed. The same person was advised sit still until a posture change was demanded. He was allowed to watch TV during the measurement. No specific movements were assigned. Nevertheless, the person showed postural variation, e.g. sudden gross and trend-like movements. During both tests, the movements of the upper body were measured with sonometry and video. Because back posture was not accessible with video because of the backrest, passive markers were applied to the front part of the body at both acromions and the sternum, and the camera was directed to the front of the person's body. After recording, marker positions were tracked in horizontal (x) and vertical (y) direction and compared to the distance changes measured with the sonoSens.

Even if movement data could not be directly compared because it was measured at different locations, sonoSens and video data were significantly correlated ($p<0.001$). The pair wise linear correlation coefficient between the horizontal movements of the sternum marker and trunk movements in frontal plane for the first test was -0.9 (Figure 24).

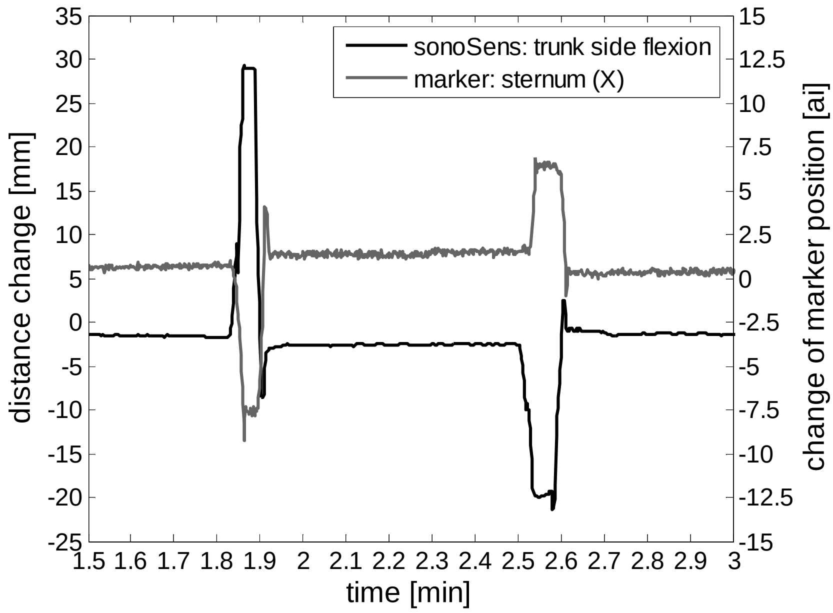

Figure 24: Comparison of sonoSens and video data for trunk movement in the frontal plane, i.e. flexion to the right and left. Data sample from the first test (repeated movement).

The primary aim of the second test was to assess small movement changes. No major influences of the contact of the sonoSens sensors with the backrest on the sensor's movements could be detected. The pair wise linear correlation coefficient between the vertical movements of the sternum marker and trunk movements in sagittal plane for the second test was 0.91. All sudden gross movements as well as trend-like posture changes could be detected by both methods (Figure 25). The latter underlines the assumption that the sensor contact with the backrest does not influence sensor motion. This indicates that shear forces are higher than friction as supposed earlier.

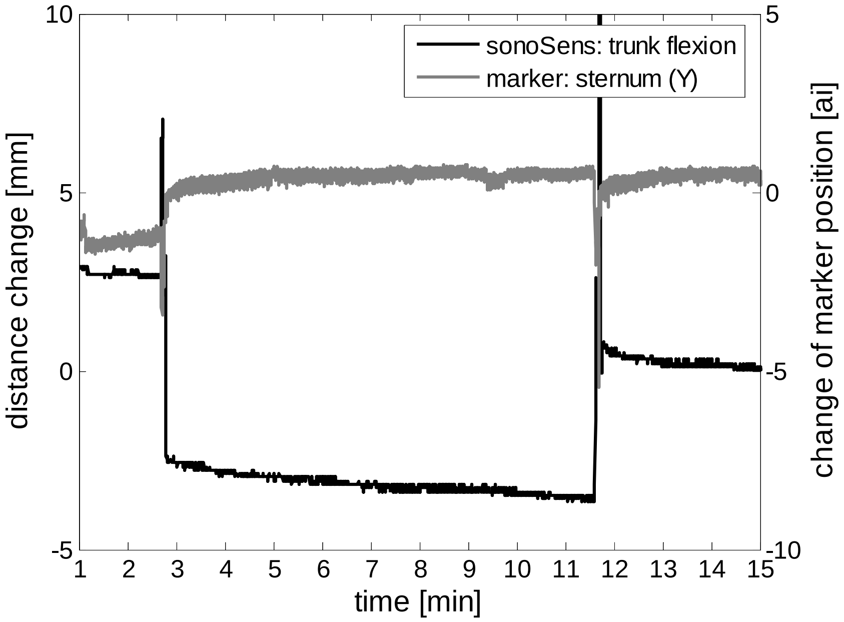

Figure 25: Comparison of sonoSens and video data for trunk movement in the sagittal plane. Data sample from the second test (long-term). Besides large displacements, small trend-like movements which are likely to be reduced by sensor contact are seen in both signals.

It appears from the above presented data that the validity of the measurement result is not influenced by the contact of the sensors with the backrest. It could be shown, that friction forces in the contact area of the sensors and the backrest are very low compared to assumed shear forces. Additionally, data from video and sonoSens for typical driver movements correlated significantly and showed high correlation coefficients. Nevertheless, clear evidence cannot be provided because neither shear forces at the backrest nor sensors movement could be directly measured. It must therefore be said that an influence of the contact on the results cannot be absolutely denied, but the sonoSens® Monitor can be used to assess driver movements.

2.5 Description of postural changes in prolonged driving

The study described in the following section was performed to evaluate the performance of the sonoSens® Monitor under field conditions and to gain basic knowledge about driver posture for prolonged driving. Based on the results, parameters are defined to basically describe the driver's behaviour modifications.

2.5.1 Methods

For the application of the sonoSens® Monitor, sensor positions recommended by the manufacturer were used (see Figure 18). The sensors were placed 5 cm left and right of the spinal processes at the level of the process of the third cervical vertebrae (C3, sensors L1 and R1), the second thoracic vertebrae (TH2, sensors L2 and R2), the twelfth thoracic vertebrae (TH 12, sensors L3 and R3), and the sacroiliac joint (SJ, sensors L4 and R4). The extension of the skin during body movements causes a change of the distance between the sensors. Through the continuous transmission of the ultrasonic signal between the sender and the receiver, these changes in body posture are measured. The device records the distances of twelve channels for each sample (Figure 26, channels A - L). In this study, a sampling rate of 1 Hz was used. The data was stored in the device during the test drive and transmitted to the PC after the measurement.

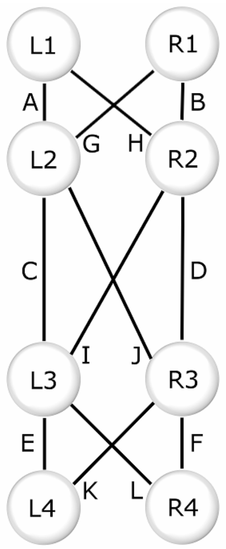

Figure 26: Scheme of sensor application and labels of measuring channels

Eight healthy male adults (age: 43.4 ± 7.2 years; height: 182.6 ± 6.7 cm; weight: 91.4 ± 24.0 kg) were investigated during a 120 minute drive on a monotone highway. Before starting, drivers adjusted their seats according to subjective preferences. Their setup was not changed during driving. They were then asked to drive to a given destination and were not provided with any other instructions. All drivers were aware that their movements were monitored during the test drive. All test persons used the same intermediate-sized car. The car was equipped with a standard seat. This seat had a leather cover and the following adjustments were available: distance to steering wheel, seat height, seat inclination, back rest inclination, 2-way lumbar lordosis. After the test drive, subjects were asked about any interference of the device with their normal driving habits. The compliance with the method was high. None of the test persons reported any interference from the device.

The initial sitting position (IP) of the driver, i.e. the mean posture of head, trunk and low back within the first minute of the test drive, after individually arranging the seat represents the basis for the interpretation of the data. Driver movements are calculated relative to the initial sitting position. The mean of the left (channels A / C / E depending on spinal part) and right channels (channels B / D / F) of each spinal segment represents movements in sagittal plane (MOV_{SP}), i.e. flexion and extension. The difference of according left and right channels indicates movements in frontal plane (MOV_{FP}), i.e. flexion to the right and left. To take into account different anthropometric measures of the test persons, the data is normalized by calculating the deviation from the initial posture in per cent. In the resulting Sagittal Index (SI, Equation VI):

$$SI = 100 - \left(100 * \frac{MOV_{SP}}{IP_{SP}}\right) \qquad \text{VI}$$

and Frontal Index (Equation VII):

$$FI = 100 - \left(100 * \frac{MOV_{FP}}{IP_{FP}}\right) \qquad \text{VII}$$

zero indicates the initial posture, positive values stand for flexion and side flexion to the right, and negative values for extension and side movement to the left respectively.

Driver posture is extracted from Sagittal and Frontal Index using a moving average filter, calculating the median from a window of 30 seconds.

It is assumed that the driver's behaviour modifications can be described by posture changes and driver activity (compare chapter 1.3). These parameters are therefore calculated from the posture data thus:

Posture changes are defined by two terms (Figure 27):

– The amplitude of the posture change must be greater than ± 2.5 times the overall activity (see below). This way, posture changes are only detected when their amplitude exceeds a significant value.

– The new posture must be held for at least 30 seconds. This constraint is introduced to ensure that driving related movements, e.g. looking to the side, cornering or resetting the stereo, are not interpreted as posture changes.

A maximum time period in which the defined amplitude change must be performed is not defined. Posture changes can consequently either be caused by sudden gross movements or by trend-like adaptations. They are used as separators to divide each data time series into a series of intervals. Intervals are defined as a series of data points between two posture changes.

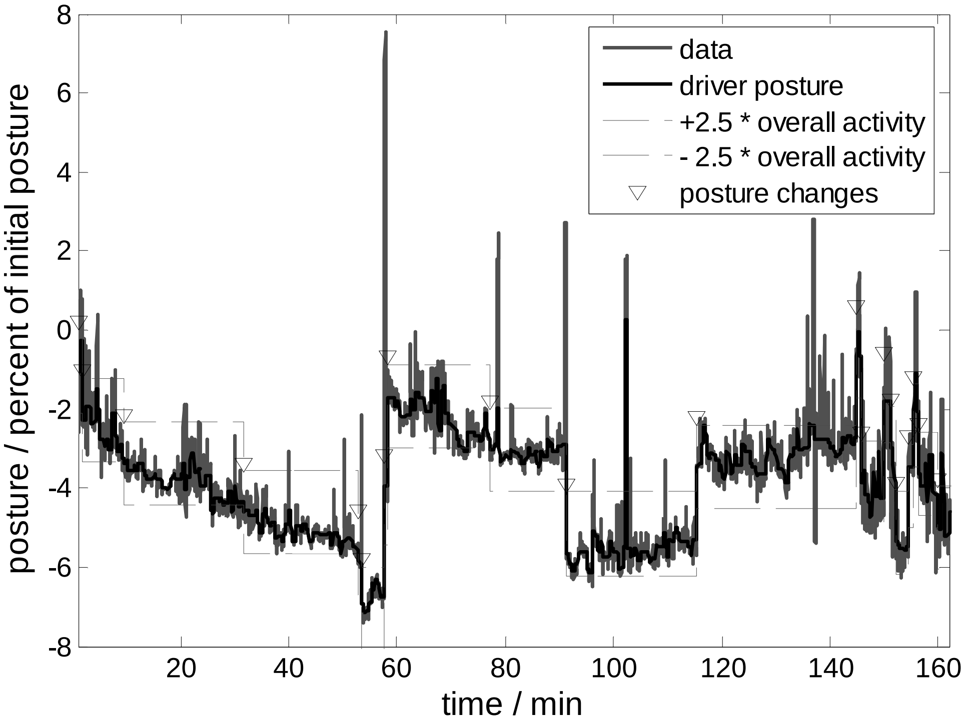

Figure 27: Detection of posture changes. Sample of a time series for trunk motion in sagittal plane (sample from a later study, chapter 3). Driver posture is extracted from the data by a moving average filter. Posture changes are detected if the driver posture moves outside the range of ± 2.5 times the overall activity (see below) and the new posture is held for at least 30 seconds. Posture changes are used as separators to divide the data time series into a series of intervals (▽).

Driver *activity*, i.e. small oscillating movements around the overall driving posture, is defined as the standard deviation of residuals after subtracting driver posture from the original signal. As defined above, driver posture is calculated by applying a moving average filter to the respecting Sagittal or Frontal Index. Activity is calculated for each interval.

First test measurements indicated that driver movements within each interval cannot be only described by activity. In some intervals, *posture adaptations*, i.e. trend-like movements, appeared that either caused posture changes or led to an adaptation of the driver's posture. Because most posture adaptations seem to have a linear slope the parameters of a linear fit of the interval data are used for their description (Equations IX). Additionally, an exponential fit is calculated to describe possible non-linear adaptations (Equation VIII, Figure 28). The parameters of both models are then compared to find out which fit leads to the better description of postural adaptations.

$$f(t) = ae^{bt} \qquad \text{VIII}$$

$$f(t) = xt + y \qquad \text{IX}$$

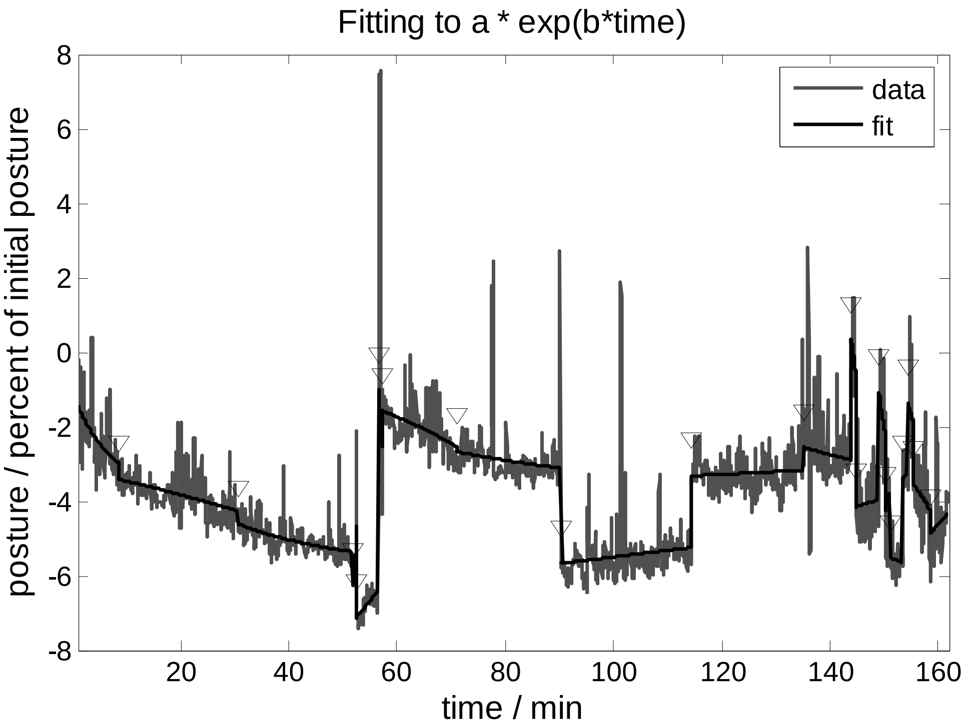

Figure 28: Measurement data and exponential fit of driver posture. A sample of the time series for trunk motion in sagittal plane is provided. The fit is calculated for each interval (compare Figure 27) with the model f*(t) = a*exp(b*t)* (Equation VIII).

The variables *a* / *b* and *x* / *y* of the best fit are determined using unconstrained nonlinear optimization. Zero is used as initial estimate for each variable. Because the shape of the exponential fit varies depending on the algebraic sign of the factors *a* and *b* (Figure 29), two optimizations for the exponential fit for each interval are calculated in order to allow every possible combination of factors *a* and *b* and thus the best fit. In the first case, interval data is shifted in positive direction so that all data points are positive. In the second case, data is shifted in negative direction. The positive and negative data of the time series is then fitted using the exponential model (Equation VIII). After that, factor *a*, the location of the initial data point of the exponential fit on the y-axis, is corrected by the amplitude of shifting. The parameters of the better fit are used for further analysis.

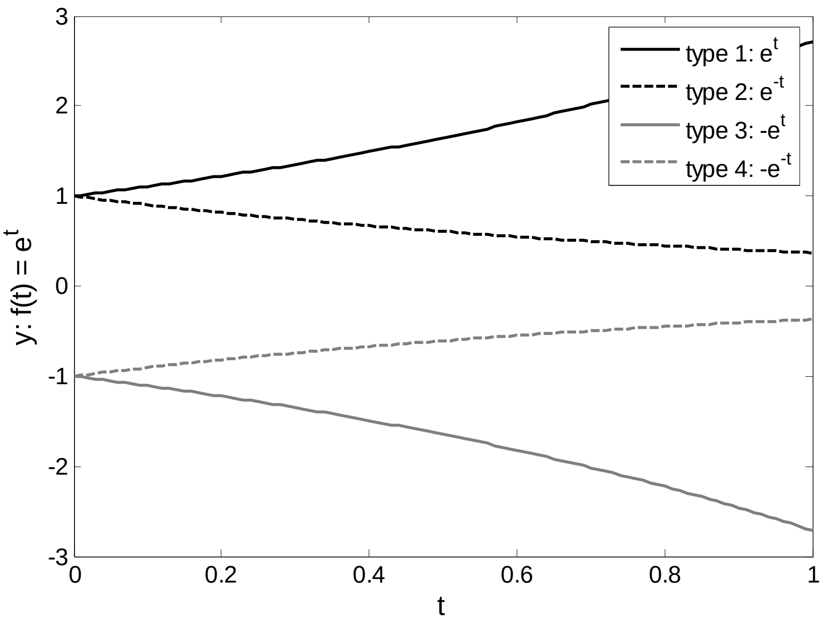

Figure 29: Various types of the exponential model (Equation VIII). The shape of the curve depends on the algebraic signs of *a* and *b*. Positive *a*'s give a concave, negative a convex shape.

The fit parameters can be used to evaluate posture adaptations, i.e. small, trend-like movements between posture changes that do not change the overall driving posture; and posture changes for each interval. The factors *a* and *y* describe the initial posture of the interval. The *delta* between adjacent intervals as difference of the last value of the interval and the first value of the next interval reflects the amplitude of posture changes. The factors *b* describes the time constant of posture adaptations, *x* reflects for the amplitude of posture adaptations within an interval. Time between postural changes correspond to the *length* of the interval.

Measurement data from the test drives is analysed according to the above described protocol. For statistical analysis, the median as well as the upper and lower quartiles of all parameters are calculated. The Statistics Toolbox of MATLAB® (version 7.0 R14, The MathWorks, Inc., Natick, MA) is used to nonparametrically compare all parameters of head, trunk, and low back with the Wilcoxon test. Parameters *a* and *n* provide posture information of the respective spinal parts and can therefore not be compared. P < 0.01 is defined as level of significance.

2.5.2 RESULTS

The data from the eight test drives indicate that driver posture is not static. It is found that the driver posture for all spinal parts and in all planes except frontal low back posture changes significantly during the test drive compared to the initial posture. Posture changes and posture adaptations could be measured for all drivers and are not significantly different between sagittal and frontal plane. Driver *activity* is higher in frontal plane than in sagittal plane. The parameters *b* | *x*, *delta* and *length* do not differ significantly between both planes and are therefore combined. Because *a* and *y* indicate the starting postures of the intervals, they cannot be compared between frontal and sagittal plane. Consequently, all parameters but *activity* and *a* | *y* were pooled for future analysis (Table 6).

Table 6: Lower quartile, median and upper quartile of the parameters *a* | *y*, *b*, *x*, *delta*, *length*, and *activity*. Values for parameter *activity* are given separately by plane because the sagittal values are significantly smaller than the frontal values. The parameters *a* | *y* cannot not be compared for both planes, values are therefore provided separately. The '*' indicates driving postures that are different from the initial posture. Data of all other parameters were pooled before the calculation of the median and the quartiles.

Parameter		**Head**	**Trunk**	**Low back**
n	sagittal	58	136	99
	frontal	86	134	78
	overall	144	270	177
a | *y* / percent				
	sagittal	-7.0 / -5.0 / -2.6 *	-5.8 / -4.1 / -1.5 *	-1.5 / 0.9 / 4.7 *
	frontal	0.5 / 7.3 / 12.5 *	-5.9 / -3.2 / 0.4 *	-5.6 / -0.6 / 7.1
b * 10^{-3}		-1.5 / 0.0 / 0.6	-2.0 / -0.4 / 0.4	-0.6 / 0.0 / 0.4
$\|b\|$ * 10^{-3}		0.1 / 0.7 / 3.3	0.4 / 1.4 / 3.8	0.1 / 0.6 / 2.1
x * 10^{-3} / percent		-10.3 / 0.2 / 3.5	-4.5 / -0.2 / 4.2	-0.6 / 0.2 / 1.9
$\|x\|$ * 10^{-3} / percent		1.3 / 6.6 / 29.3	1.6 / 4.2 / 11.0	0.3 / 1.1 / 4.2
delta / percent		-2.5 / 0.1 / 2.3	-1.3 / -0.1 / 1.5	-1.5 / -0.1 / 1.5

Parameter	Head	Trunk	Low back
|*delta*| / percent	1.0 / 2.5 / 4.7	0.6 / 1.3 / 2.6	0.9 / 1.5 / 2.9
length / minutes	2.2 / 4.7 / 10.8	1.9 / 3.7 / 7.9	2.3 / 4.3 / 9.6
activity / percent			
sagittal	1.1 / 1.2 / 1.6	0.4 / 0.5 / 0.7	0.1 / 0.2 / 0.4
frontal	1.4 / 1.7 / 1.9	0.5 / 0.7 / 1.0	0.2 / 0.3 / 0.7

Maximum values for *length* (95. percentile) are 40.3, 21.3, and 38.6 minutes for head, trunk, and low back respectively.

When comparing the absolute values, further significant differences between body parts were found (Table 7).

Table 7: Comparison between body parts. Significantly higher values are marked with “>” ($p<0.05$). The “=” sign indicates no difference between body parts.

Parameter		Head vs. Trunk	Head vs. Low Back	Trunk vs. Low Back
|*b*|		=	=	>
|*x*|		>	>	>
|*delta*|		>	>	=
activity	sagittal	>	>	>
	frontal	>	>	>

It is also found that the majority of postural adaptations can be better described by an exponential model. When comparing the best linear and exponential fit for each interval the Sum of Squares Due to Error (SSE) as well as the Root Mean Squared Error (RMSE) is lower for the exponential fit in more than 84 % of the cases depending on the body part and movement direction.

Table 8: Comparison of the goodness of linear and exponential fits. SSE and RMSE values for the exponential fit for each interval are lower than the respective values for the linear fit in the majority of cases.

Parameter	**Head**	**Trunk**	**Low Back**
Sagittal plane			
SSE and RMSE lower for exponential fit / percent of cases	75 %	89 %	89 %
Mean RMSE	1.3	0.6	0.3
Frontal plane			
SSE and RMSE lower for exponential fit / percent of cases	100 %	84 %	91 %
Mean RMSE	4.4	1.0	0.7

When looking at the best exponential fit, none of the fit types (compare Figure 29) appeared significantly more often than the others.

2.5.3 Discussion and Conclusion

It can be concluded from the results that drivers change their posture over time. This is indicated by the significant differences between driving posture and initial posture and by the high number of posture changes (Table 6). This was also found in recent studies. The average time between posture changes shows a great individual variance. Median values are approximately four to five minutes (parameter *length*, Table 7). The maximum time without posture changes ranges from 20 minutes for the trunk up to approx. 40 minutes for the head and low back. Since driving associated movements were not categorised as posture changes due to the definition (see above), the observed high number of posture changes may be interpreted as a reaction of the driver to increasing individual loads as done by other authors (compare chapter 1.3.2). In order to evaluate such a hypothesis, the time-related deviation of posture changes needs to be analysed. This was not done here because of the limited number of test drives but will be addressed in an additional study (chapter 3). So far, it can only be said that drivers change their posture quite often during prolonged driving. The exact cause for the observed posture changes is not clear, but since task-relevant movements were excluded through the parameter definition, a reaction on increasing loads seems to be a reasonable explanation.

Additionally, *b* and *x* values indicate that posture adaptations appear between posture changes. The amplitude of these adaptations is unique for every driver, but it can be said that it decreases in caudal direction, i.e. from head to low back (Table 7). A reason for this finding could be the seat's shape, which stronger limits pelvic and lumbar motion compared to trunk motion (chapter 1.3.1). Head motion is not limited by the seat at all except by the headrest in dorsal direction. When comparing the output of the linear and the exponential model, it is found that the majority of postural adaptations within each interval follows an exponential curve. An exponential model must therefore be used for future data analysis. Nevertheless, using a linear model for the description of the amplitude of postural adaptations seems reasonable, because the absolute *b* values found were very low. The estimated half life of postural adaptations, i.e. the natural logarithm of 2 divided by the rate constant *b*, is approx. 17 / 8 / 19 minutes for head / trunk / low back respectively. It can be concluded that postural adaptations are interrupted by posture changes early, because the median interval length is approx. four to five minutes. Moreover, postural adaptations in the low back take significantly more time compared to the trunk. It is therefore concluded that both parameters need to be calculated for future studies: *b* values to determine the time constant and *x* values to estimate the amplitude of postural adaptations.

Such posture adaptations were not described before. They may be an additional possibility to limit the total individual load, because continuous motion might alter load-increasing factors such as contact pressure and muscle load (compare chapter 1.3). This theory needs to be evaluated in an additional study, because seating comfort was not evaluated here.

It could also be found that the *activity* increases in cranial direction, i.e. from low back to head. This could be expected, because the hip and the low back are fixed by several seat features (1.3.1). Because of certain movements associated with driving like steering, trunk activity needs to be somewhat higher. Head motion is highest because it is indispensable for safe driving. Additionally, various driving associated head movements, e.g. looking in the mirror, raise head *activity*, because they are not categorized as posture changes. Posture changes were only detected when the new posture was held for at least 30 seconds, which is not the case for most head movements. The greater *activity* in the frontal plane compared to the sagittal plane is possibly a result of the backrest's shape and inclination, which stronger limits sagittal compared to frontal movements. In addition, lateral accelerations of the trunk because of steering manoeuvres etc. appear more often when driving on a highway than sagittal acceleration, e.g. caused by speed changes.

Based on the results, the following parameters can be used to describe driver behaviour:

1. posture changes
   a) the factor *a* of the exponential model (Equation VIII) for the newly adopted posture after a posture change
   b) the *delta* between adjacent intervals as difference of the last value of the interval and the first value of the next interval
   c) the interval *length* as time between postural changes
2. posture adaptations
   a) the factor *b* of the exponential model (Equation VIII) to describe the time constant of posture adaptations
   b) the *trend* within each interval as linear slope of the interval data to describe the amplitude of linear posture adaptations
3. *activity*, described by the standard deviation of the residuals after subtracting the mean driver posture from the original data

3 RELATION BETWEEN SYSTEM STRESS AND SEATING COMFORT

3.1 ABSTRACT

Postural adaptations play an important role in reducing static spinal loads but only limited information about driver movement is available for long-distance driving in field conditions due to methodological constraints. The first part of this chapter presents a detailed description of the driver's behaviour modification during prolonged driving. Seven different car seats were investigated by six healthy adults (age: 26.3 ± 3.1 years; height: 179.6 ± 8.6 cm; weight: 70.0 ± 12.2 kg, five male, one female) during a 180-minute drive on a highway. The movements of the upper body were measured using the sonoSens® Monitor (chapter 2.3.1). Driving posture, posture changes, posture adaptations and driver activity were calculated for 30-minute intervals. Additionally, subjective discomfort ratings were attained after the test drives. Driver posture is altered mainly by posture changes and posture adaptations. It could be shown that driver posture changes over time and that postural adaptation in the first 30 and last 60 minutes are greater than in the rest of the time. It can be concluded from the results that drivers use posture changes and continuous motion to minimize the total individual load. Additionally, continuous driver movement contributes to decreasing spinal loads. Behaviour modifications may therefore be used as objective measure to describe the total individual load.

In the second part of this chapter, a discriminant analysis of the calculated posture parameters is performed to predict individual discomfort ratings. Results show that a reliable prediction of subjective ratings is possible. A complex model was able to predict all ratings correctly, a much simpler model classified 86 percent of the cases correctly. The prediction can only be based on trunk and low back parameters. This proves that a relation between subjective ratings and stress-induced behavioural modifications exist. Additionally it is found, that driver posture and activity parameters are chi-square, parameters describing posture changes and adaptations are exponentially distributed. Based on these finding, a relatively simple description of driver behaviour in real-life driving can be made.

3.2 STRESS-INDUCED POSTURE MODIFICATIONS DURING PROLONGED DRIVING

Parts of this chapter are adapted from Adler et. al [2].

3.2.1 INTRODUCTION

The topic of driver posture has been widely studied. Even if results vary, basic criteria for an optimal posture are widely accepted (chapter 1.3.2). Most of the studies addressed static conditions, however. Consequently, the knowledge about driver posture in long-term driving is relatively narrow. A better understanding of the driver's postural adaptations in prolonged driving could help to optimise seat design and may provide additional information for the evaluation of seating comfort.

Driver posture is one of the most important issues for vehicle and seat design [72]. The layout of the car's interior and the seat is based mainly on ergonomic and comfort criteria derived from static experiments. Results of subjective long-term evaluations are used to optimise seat concepts, but the knowledge about posture changes for longer driving periods is limited. It was found, that the absolute posture among drivers varies and that drivers change their posture more or less frequently [141, 184]. Many causes for posture changes are reported, among them increasing individual load, fatigue or the adaptation of the driver to the car's interior [48, 57, 140]. An exact description of postural adaptations in prolonged driving is not available. It is therefore necessary to address this topic in an additional study. To find out whether different posture changing strategies exist among drivers and to gain information about the quantity and quality of posture changes, it is required to continuously monitor driver posture [52].

Moreover, a link between subjective comfort ratings and postural changes is reported [26, 35, 135, 166]. It was previously proposed that drivers may change their posture due to an increase of the total individual load with time [57]. The adoption of a different posture leads to load reduction because the driver-seat interaction and muscular loads are altered (chapter 1.3). If this is true for prolonged driving, posture changes, posture adaptations, and activity would increase with time. Moreover, drivers which report higher discomfort should show more posture variations than drivers with lower discomfort ratings. Additionally, detailed information about the time-dependent changes of driver posture could help to underline the proposed relation of stress-induced behaviour modifications to seating comfort (chapter 1.2).

In this chapter the previously proposed method for continuous and direct measurement of driver posture in long-term tests (chapter 2.4) is used to evaluate time-dependent posture changes. Based on a description of the driver's behaviour modifications, strategies which the driver uses to minimize the total individual load are extracted. The following research questions are addressed:

1. Does driver posture change significantly over time as found in a recent study (chapter 2.5)?
2. Is it possible to describe typical posture changing strategies in prolonged driving?
3. What strategies does the driver use to cope with the increasing total individual load?

3.2.2 STUDY DESIGN

Seven different car seats were investigated by six healthy adults (age: 26.3 ± 3.1 years; height: 179.6 ± 8.6 cm; weight: 70.0 ± 12.2 kg, five male, one female) during a 180-minute drive on a highway. Seats were randomly assigned to subjects so that every seat was used by one large, medium and small person. Before starting, drivers adjusted their seats according to subjective preferences. This setup was not changed during driving. They were then asked to drive on a predefined route to a given destination. No other instructions were provided. All drivers were aware that their movements were monitored during the test drive.

The movements of the upper body were measured (sonoSens® Monitor; Friendly Sensors AG, Jena, Germany) as distances between characteristic points on the back (chapter 2.4, Figure 18). The extension of the skin during body movements causes a change of the distance between the sensors, which is measured by the sonoSens® Monitor. Through continuous transmission of the ultrasonic signal between the sender and the receiver, changes in body posture are measured. In this study, a sampling rate of one Hz is used. The data is stored in the device and transmitted to the PC after each measurement.

The initial sitting position (*IP*) of the driver after individually arranging the seat represents the basis for the interpretation of the data. After the test drive, subjects were questioned about any interference of the device with their normal driving habits. The compliance with the method was high. None of the test persons reported any interference from the device.

To evaluate the driver's behaviour modifications, postural adaptations are calculated from the data as described earlier. The parameters will therefore only be characterized briefly here. A detailed description is provided in chapter 2.5. After calculating the Sagittal and Frontal Index for each body part, posture changes were calculated for each timeline. The data of each interval, i.e. the data between two posture changes, is then fitted using an exponential model (Equation VIII). The following parameters are used to describe driver posture for each interval. The factors *a* and *b* of the exponential fitting model describe the initial posture for each interval and the shape and amplitude of posture adaptations respectively. The *delta* between adjacent intervals characterizes the amplitude of posture changes. The *trend* describes the amplitude of postural adaptations within an interval. Time between postural changes corresponds to the *length* of the interval. Driver *activity* is defined as the standard deviation of residuals after the average mean is extracted from the original signal. To be able to basically analyze driver behaviour, absolute values of *b*, *delta*, and *trend* were used. Furthermore, the *maximum time* without a posture change was calculated for each timeline.

Additionally, discomfort ratings were obtained immediately after the test drive. This subjective data is not used in this study but for the further analysis of the relation of stress-induced behaviour modifications and seating comfort (see chapter 3.3).

For statistical analysis, the median as well as the upper and lower percentile of all parameters and 30-minute intervals is calculated. The Statistics Toolbox of MATLAB® (version 7.0 R14, The MathWorks, Inc., Natick, MA) is used to non-parametrically compare median values with the Wilcoxon test. Three tests are performed: the first to compare parameters for sagittal and frontal plane; the second to identify differences between initial posture and driving posture; and the third to identify changes in the course of the test drives between adjacent intervals. P<0.01 is defined as level of significance.

3.2.3 RESULTS

Data shows, that (1) sagittal and frontal movement parameters besides *activity* are comparable, (2) driver posture changes over time, and (3) the amplitude of postural adaptation in the first 30 and last 60 minutes are greater than in the rest of the time.

The comparison of the parameters for sagittal and frontal plane showed no differences besides a smaller *activity* in sagittal plane ($p < 0.01$). Parameter *a* can not be compared because it indicates the starting postures of each intervals. Consequently, all parameters but *activity* and *a* are pooled for future analysis (Table 9).

Table 9: Lower quartile, median, and upper quartile of all calculated parameters. Values for parameter *activity* are given separately by plane because data for sagittal plane is significantly smaller than for frontal plane. Parameter *a* can not be compared for both planes, values are therefore provided separately. The '*' indicates mean postures that are different from the initial posture. Data of all other parameters were pooled before calculation of the median and the quartiles.

Parameter		**Head**	**Trunk**	**Low back**
n	sagittal	542	573	478
	frontal	513	561	468
	overall	1055	1134	946
a / percent	sagittal	-11.6 / -7.0 / -3.6*	-8.0 / -5.7 / -2.7*	-4.9 / -0.1 / 5.7
	frontal	-0.3 / 4.1 / 9.3*	-1.4 / 0.8 / 3.0*	-2.3 / 1.3 / 5.2*
$\|b\| * 10^{-3}$ / percent		0.4 / 1.3 / 3.4	0.4 / 1.3 / 3.3	0.3 / 0.8 / 2.2
|*delta*| / percent		1.1 / 2.2 / 3.8	0.7 / 1.4 / 2.8	0.9 / 1.7 / 3.7
$\|trend\| * 10^{-3}$ / percent		2.8 / 9.3 / 27.0	2.0 / 5.1 / 15.1	0.8 / 2.4 / 7.3
length / minutes		2.0 / 3.4 / 7.7	1.9 / 3.6 / 7.1	2.0 / 3.8 / 9.9
activity / percent	sagittal	1.0 / 1.1 / 1.3	0.4 / 0.5 / 0.7	0.1 / 0.2 / 0.4
	frontal	1.2 / 1.4 / 1.5	0.5 / 0.6 / 0.9	0.2 / 0.4 / 0.6

The mean postures of all but low back segments for sagittal plane are significantly different from the initial posture (Table 9). This indicates that driver posture is not static but changes over time. In sagittal plane, head and trunk posture shows an extension compared to their initial posture ($p < 0.01$). Changes dominantly appear within the first 60 minutes (Figure 30). In frontal plane, head, trunk, and low back posture show a significant flexion to the right compared to their initial posture.

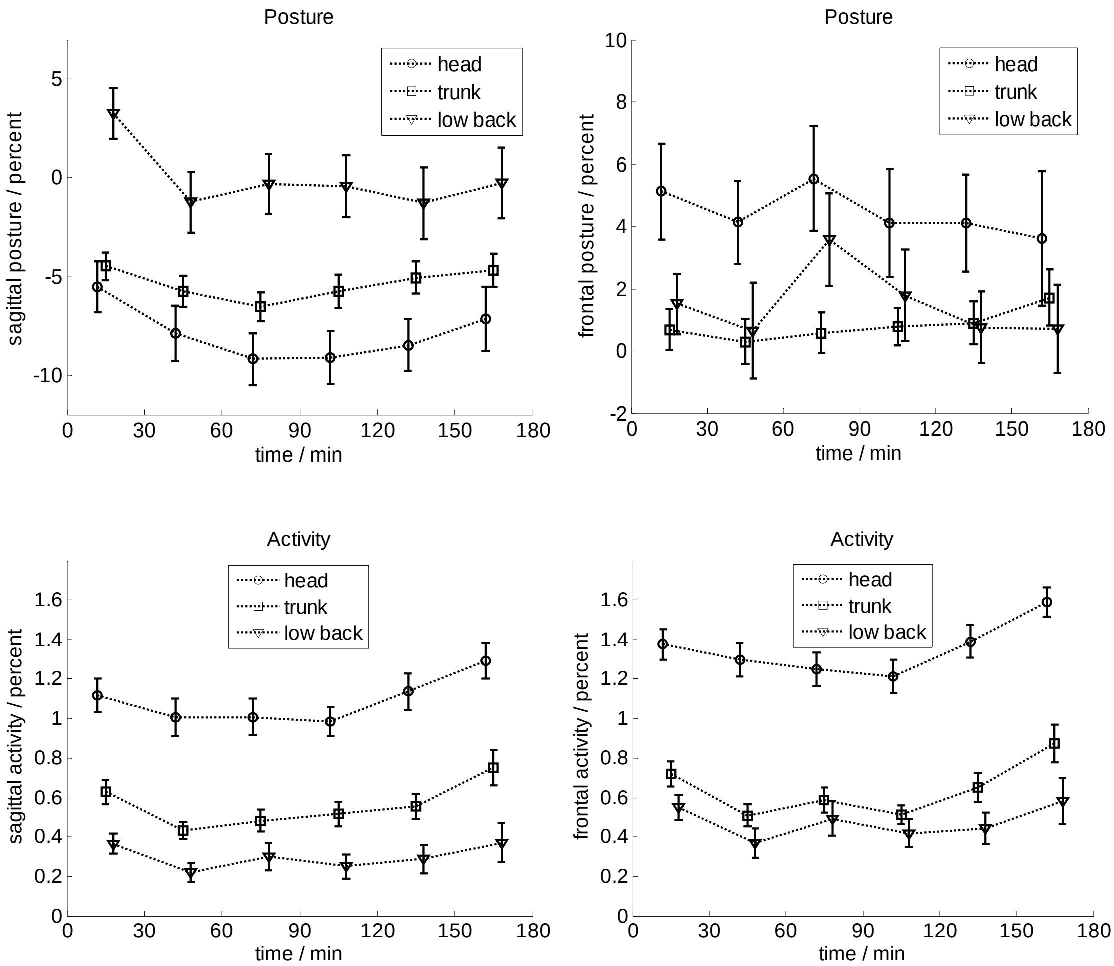

Figure 30: Parameter estimates and confidence intervals of *a* (upper graphs) and *activity* (lower graphs). Data of head (circles), trunk (squares), and low back (triangles) is chi-square distributed (chapter 3.3).

As described in a previous study (section 2.5), posture is dominantly altered using posture changes and posture adaptations (compare Figure 28). Postural adaptations in the first 30 minutes and at the end of the test drive are different from those in the rest of the time (Figure 31). Postural adaptation (*b* and *trend*) is greater at the start ($p < 0.01$)

and in the end than in the middle part except for |b| of head. The amplitude of posture changes (*delta*) of head and trunk significantly decreases after the start and increases towards the end. The time between posture changes (*length*) significantly increases after the start for trunk and low back and decreases in the final 60 minutes.

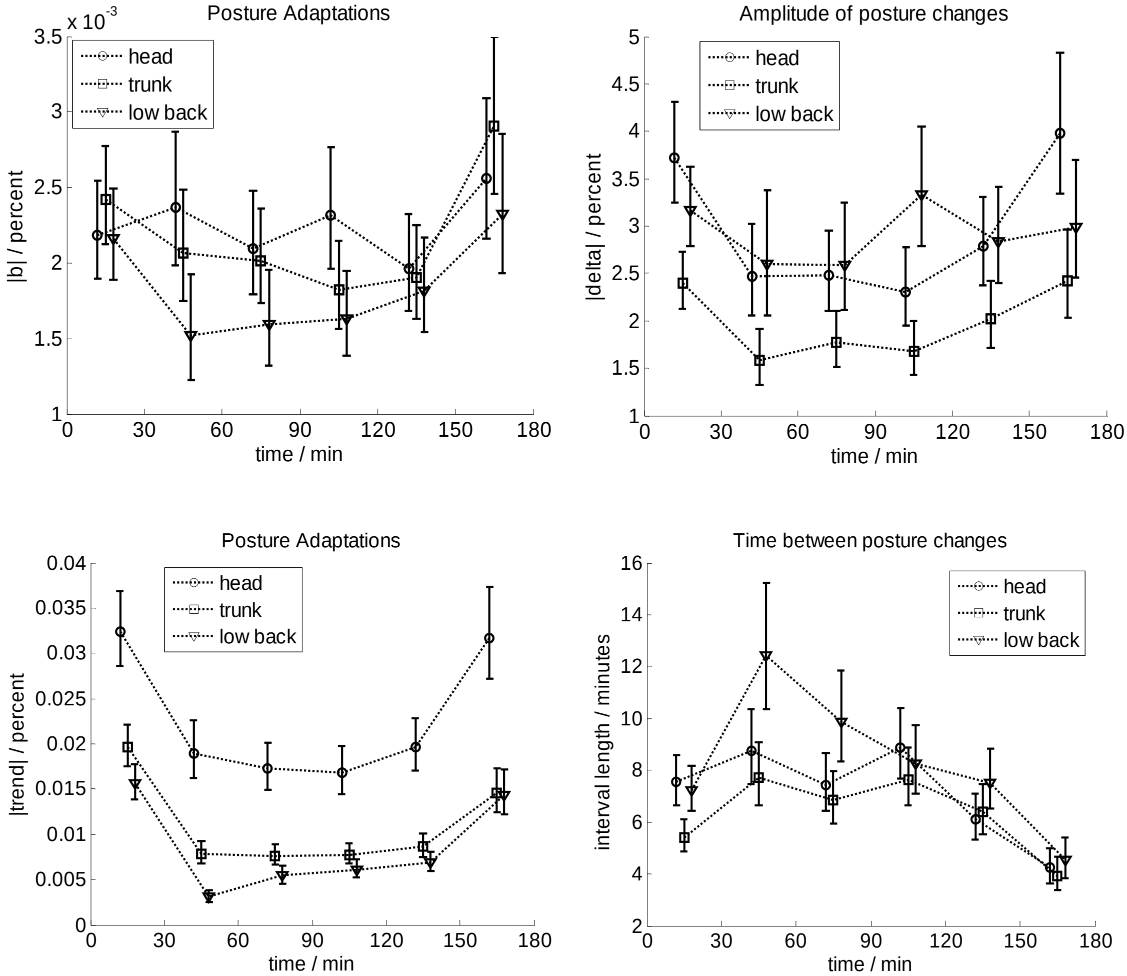

Figure 31: Parameter estimates and confidence intervals of absolute values of *b* (top left), *delta* (top right), *trend* (bottom left) and *length* (bottom right). Data of head (circles), trunk (squares), and low back (triangles) is exponentially distributed (chapter 3.3).

The median of the *maximum time* without a posture change is 13.8 / 12.8 / 18.3 minutes for head / trunk / low back respectively. Maximum values, i.e. the 95th percentile, are for 52.8 / 37.3 / 43.2 minutes for head / trunk / low back.

3.2.4 DISCUSSION

The automotive industry seeks for tools to objectively monitor driver posture and its relation to subjective comfort ratings [8, 72]. Previous studies assessed sitting posture either under static [8, 98, 181] or dynamic conditions [13, 42, 132], but not in a realistic driving environment. The present study aimed at monitoring driver posture and movements in prolonged driving under field conditions and at identifying typical movement patterns of the driver. A method for measuring driving posture and movements introduced in a previous study (section 2.5) was applied to healthy adults driving for three hours on a highway. The following conclusions can be drawn from the results:

Driver posture is not static and changes over time. It could be shown that some basic strategies for posture adaptation exist even if posture changes usually are unique for each subject. All drivers change their initial posture within the first 30 minutes of their driving time (Table 9). The space between backrest and shoulder is reduced by extension of the thoracic spine. It is believed that such movements may help to maintain the lumbar curvature, because backward movement of the trunk results in forward rotation of L5 [151]. Additionally, this strategy could help to shift the weight distribution on the backrest towards the upper trunk, since initially only seven percent of the body weight is exerted on the seat in this area [8]. The reduction of head inclination with respect to the trunk that was observed in the first 30 minutes could help to reduce strain in the neck region. Forward head posture increases disk pressure and activity of the neck musculature and is a common problem for drivers [75]. Backward head and trunk movements may also decrease the tendency to slouch, because this leads to forward rotation of the pelvis. When slouching, i.e. rotating the pelvis backwards, also the distance between head / headrest and shoulders / backrest increases [76]. Such an increase in trunk flexion could be observed after 90 minutes of driving in head and trunk (Figure 30 (top left)). This may be interpreted as a reaction to the increasing fatigue of the back muscles, which was described by other authors [103, 175]. A more kyphotic back posture reduces muscular load, because the influence of the ligaments on stabilizing the trunk is increased [50, 151].

The results also show that a significant part of the movements appears in the trunk region. In the recent literature, most attention is paid to lumbar or pelvic motion [39]. It is concluded, that trunk movements should be taken into account when assessing driver posture. Since measurement or simulation of driver posture is widely used for the seat design process [8, 29, 63, 71], the finding from this study should be considered for future measurements and simulations.

It takes approximately 30 minutes for the driver to adapt to his individual driving posture – this posture is then held for a long period of time. Reference postures for the seat design process should therefore be measured at least 15 - 30 minutes after the start of the test drive and not immediately after the seat has been taken.

Besides the initial posture adjustment, posture changes could be measured for all drivers. Posture changes appear on average every four minutes (Table 9). The maximum time without posture changes is approximately 15 minutes, but can be as high as 37 to 53 minutes depending on the body part. Sudden gross movements of seated individuals are also reported by other authors and are usually interpreted as a sign of the increasing individual load [13, 20, 24, 26, 52, 110, 166]. Posture changes were also found to play an important role in reducing the total load and consequently help the driver to maintain an acceptable seating comfort level [57]. In agreement with these findings, an increase of the number of posture changes with time was found in this study (Figure 31 (bottom right)). It could also be shown that the amplitude of posture changes increases with time, especially for head and trunk (Figure 31). Increasing total individual loads may therefore be considered as possible cause for the observed increase of the number of posture changes with time. However, further research is necessary to clearly correlate driver posture changes to seating comfort. One problem, that a clear connection between driver posture and comfort could not yet be established [39] might be the lack of a measurement system capable to continuously monitor driver posture under real conditions. Another reason could be that previous studies focused primarily on sagittal lumbar motion. A considerable part of posture changes and posture adaptations appears in the trunk region, however. The figures obtained in this study cannot be directly compared to other findings; because authors of previous studies did not provide exact numbers, used different measurement techniques, or the study design implied other driving conditions. It is believed, that these figures can only stand for the movements of a car driver under real driving conditions. This is because test measurements with a limited number of subjects and seats in simulated environments and different surroundings (e.g. train seats) showed a higher number and amplitude of posture changes. The figures obtained under real-life conditions appear to be reproducible, because the values of the calculated parameters in the two conducted studies are similar (compare Table 6 and Table 9). The observed lower overall number of posture changes in real-life driving compared to different environmental conditions seems to have its origin in the rather “fixed” position of the car driver (seat belt) and the more demanding conditions in road traffic compared to simulated environments. This assumption is supported by other studies which also found differences in driver performance in realistic compared to simulated surroundings [96, 139, 160].

The activity of the driver changes over time (Figure 30 bottom). Changes appear within the first minutes of the test drive (decrease) and in the course of time (increase). A higher activity at the start is believed to represent the settlement of the driver in the seat. As reported above, the final driving posture is reached after some minutes. A rise of the activity in the course of time as reported by other authors [20, 166] could also be seen. This underlines the above described relation between increasing motion and increasing load that was also concluded by the aforementioned authors. The slightly higher activity in frontal plane is believed to be due to seat dimensions, which allow smaller sagittal motion. The seatback angle might be an additional factor, because reclining increases contact forces between the upper body and the backrest predominantly in sagittal plane.

All drivers continuously vary their posture even if there are no posture changes. Posture adaptations can be seen in sagittal as well as frontal plane and appear in all body parts. The overall amplitude is very much smaller compared to posture changes (Figure 31: compare *trend* and *delta*). This indicates that not all posture adaptations lead to a posture change. Continuous motion might be a strategy of the driver to limit mechanical load in terms of pressure and shear forces, which have been identified as main causes for tissue ischemia [62] . In a recent study [13] using continuous pressure measurements, this ‘urge to move’ [24] was not described as trend-like behaviour but as small trunk movements. This difference is possibly due to the indirect assessment of the posture in the latter study. These findings indicate that posture adaptations might be an additional strategy of the driver to limit the increasing total individual load. This assumption is supported by the fact that postural adaptations, especially in the low back, continuously increase towards the end of the test drive (Figure 31, *b* and *trend*).

The findings of the study add new facts to the current discussion in literature and therefore help to identify and understand basic strategies of the driver to cope with the increasing total individual load associated with prolonged driving. Total loads that act on the driver were not directly assessed but are believed to increase with increasing time. Since an increase of postural adaptations could clearly be shown, it is assumed that the driver uses posture changes and posture adaptations to limit increasing loads. The described changes in driver behaviour can therefore be interpreted as stress-induced behaviour modifications as proposed in the seating comfort model (chapter 1.2). The presented method has the potential to become a powerful tool for engineers, because it is easy to use, does not affect seat parameters, and does not influence driver behaviour. Additionally, the provided information more accurately describes the starting conditions for mechanical models predicting driver posture.

3.3 PREDICTION OF SUBJECTIVE SEATING COMFORT RATINGS BY STRESS-INDUCED POSTURE MODIFICATIONS

The content of this chapter is adapted from Adler et. al [3].

3.3.1 INTRODUCTION

It has clearly been shown that stress-induced posture modifications of the driver and consequently system stress increase over time in prolonged driving. These finding have been linked to increasing loads. Three major means of the driver to limit individual loads have been identified: the increase of the frequency of posture changes, the increase of the amplitude of postural adaptations, and the increase of the movement amplitude. Based on statement of other authors, a direct relation between system stress and seating comfort was proposed (chapter 3.2). Such a relation could not be directly proven, however. The major aim of the following chapter is to examine this proposition and to evaluate whether subjective ratings can be predicted by stress-induced behaviour modifications. This would allow an objective assessment of seating comfort and could thus help to evaluate, compare and optimise car seats.

Many methods to assess seating comfort have been developed in the past years. The quality of subjective evaluations has improved [104, 150, 159], but there are still difficulties in reliably reproducing individual perceptions [9, 32]. Researchers therefore use the advances in technology to try to objectively analyse seating comfort. Commonly, contact pressure [34, 71, 102, 122, 136, 158] seems to be the most suitable parameter for this aim. Furthermore, EMG and posture changes as well as anthropometric variables have been found to allow an objective assessment of seating comfort [39]. Besides the widely used static experiments, the focus of recent studies has been set on assessing time-dependent changes of comfort-relevant parameters with long-term measurements. Time-dependent changes of interface pressure [13, 52, 152] or kinematics [153, 166] have been monitored. Most authors found an increase of the reported discomfort with time and a clear relationship between postural changes and subjective rating, but no exact relationship between measurement data and subjective ratings could be established [71]. Besides, knowledge about long-term driver behaviour under real driving conditions and strategies to cope with increasing loads is narrow, partially due to methodological constraints, partially because recent studies dominantly focused on short-term evaluations. Such knowledge, however, is essential for the understanding of basic coping strategies and for the design of appropriate seats. Additionally it would help to optimize current simulation models aiming at testing new seats virtually and predicting seating comfort, because a description of dynamic driver behaviour could be added.

The possibility to predict the seating comfort perception of a target group based on objective data attained from a small sample group of drivers would decrease the iterative seat testing time and consequently the development effort. Various models exist that estimate seating comfort based certain parameters, most commonly contact pressure [71, 136] and vibration [46]. A new approach is the prediction based on parameters calculated from virtual models [115]. The results help to optimize seats even in an early (virtual) prototype stage, but results are not fully satisfactory. A main disadvantage is the limitation of the models to short-term evaluations. An accurate prediction of driver posture and knowledge about stress-induced behaviour modifications could help to optimize yet existing models and to increase the accuracy of results. If basic parameters of postural variations were known, test driving time as well as the number of necessary test persons could be limited. An accurate prediction of the seating comfort perception of a target group could be estimated based on few measurements. Additionally, virtual prototypes could be evaluated by human models showing a comparable postural behaviour as the target group.

This chapter evaluates the relation between stress-induced behaviour modifications and subjective seating comfort ratings and presents a model to predict the ratings based on posture parameters. The posture analysis is based on a new method for continuous and direct measurement of driver posture in long-term tests under real driving conditions that was introduced in chapter 1.

3.3.2 STUDY DESIGN

The data obtained in a recent study (see chapter 3.2.2 for details) is used for this project. In addition to the kinematic data, subjective discomfort ratings were attained from each subject immediately after the test drive using a body area comfort method [32]. Each of eight body areas (neck, shoulder, upper back, lower back, buttocks, thighs, calves, and feet) was rated separately on a four-point bipolar scale of semantic differentials. For further analysis, the adjectives used were coded (no complaints – 1, almost comfortable – 2, uncomfortable – 3, very uncomfortable – 4) and an overall discomfort rating was calculated from the mean of all body area ratings. For the rating, subjects were questioned directly after leaving the car at the end of the test drive.

To evaluate changes in driver behaviour, posture changes were detected and used to divide each timeline into a series of intervals. For each interval the parameters *a*, *b*, *delta*, *trend*, *length* and *activity* were calculated as described earlier (chapter 3.2.2). The maximum time between posture changes (*tmax*) for each data sample was used as additional parameter.

A discriminant analysis was performed to find a relationship between postural adaptations and subjective discomfort ratings. Parameter estimates and confidence intervals for all parameters and the complete measuring time, both calculated based on the distribution type of the parameter, were used as prediction variables. Overall discomfort ratings were assigned to four groups as follows: 1.0 – 1.3: group 1; 1.4 – 1.6: group 2; 1.7 – 1.9: group 3; ≥ 2.0: group 4. Additionally, the data of each parameter was compared to a normal, chi-square and exponential distribution of random numbers with the same mean as the parameter data. The Kolmogorov-Smirnov test was used to compare the distribution of both samples. The aim of this test was find out whether the parameter data follows one of the defined distributions. The Statistics Toolbox of MATLAB® (version 7.0 R14, The MathWorks, Inc., Natick, MA) was used to carry out the statistical analysis.

3.3.3 RESULTS

It was found, that the parameters for the description of absolute posture (*a*) and *activity* are chi-square distributed; the absolute values of *delta*, *b*, and *trend* as well as the interval *length* are exponentially distributed. The discriminant analysis revealed, that subjective discomfort ratings can be reliably predicted from posture parameters.

Absolute posture (*a*) and activity parameters are chi-square distributed ($p<0.05$). If the degrees of freedom *k* of these parameters is calculated (equation X, 'Γ' denotes the gamma distribution), mean (*k*) and variance (2*k*) of the distribution can be estimated.

$$f(x,k)=\frac{\frac{1}{2}^{\frac{k}{2}}}{\Gamma\left(\frac{k}{2}\right)}x^{\frac{k}{2}-1}e^{-\frac{x}{2}} \qquad \text{X}$$

Posture change (*length*, |*delta*|) and posture adaptation (|*b*|, |*trend*|) parameters are exponentially distributed ($p<0.05$). Posture changes and posture adaptations therefore vary with constant probability per unit time λ, which can be used to predict certain events (equation XI), e.g. posture changes. Mean (λ^{-1}) and variance (λ^{-2}) can also be easily estimated.

$$f(x;\lambda)=\begin{cases}\lambda e^{-\lambda x} & ,x\geq 0,\\ 0 & ,x<0.\end{cases} \qquad \text{XI}$$

Regarding the prediction of subjective discomfort rating, a linear model (model 1, Table 10) was developed that significantly ($p < 0.05$) separated all four groups (compare section 3.3.2) and classified 100 per cent of the ratings correctly (Table 12). The prediction was made using trunk and low back variables only, namely the maximum *length* in both planes, the standard deviation of *a* in frontal plane, the standard deviation of lumbar *b* values and the mean of lumbar sagittal activity.

Table 10: Standardised canonical coefficients of the discriminant functions of model 1. λ^{-2} indicates the standard deviation of the exponential distribution, *k* is the mean and 2*k* the standard deviation of the chi-square distribution. The inferior letters specify the body part (l – low back | t – trunk) and the movement plane (s – sagittal | f – frontal).

Variable	Function 1	Function 2	Function 3
$\lambda^{-2}(\lvert b\rvert_{ls})$	-0.955	1.148	-0.408
$\lambda^{-2}(\lvert b\rvert_{lf})$	1.649	0.157	0.079
$2k(a_{tf})$	0.821	-1.153	-0.229
$2k(a_{lf})$	1.422	-0.392	1.091
$tmax_{ts}$	2.078	0.022	0.713
$tmax_{ls}$	-1.841	-0.039	1.736
$tmax_{tf}$	-2.024	-0.020	-0.005
$tmax_{lf}$	1.876	0.152	-1.559
$k(activity_{ls})$	-0.906	0.643	-0.381

For model 1, all three functions are needed to significantly predict the subjective discomfort ratings. Function 1 explains 69.0 percent of the variance, function 2 26.2 percent and function 3 6.8 percent.

A simpler model (model 2, Table 11) using only the interval *length* and the standard deviation of frontal *b* values, predicted 86 per cent (18 out of 21) correctly. Group separation still was significantly ($p<0.05$) different for model 2 (Table 12). In two of the overall three prediction errors, prediction indicated the adjacent class and subjective rating were at the respective edge of their class. One prediction was far away from the actual subjective rating.

Table 11: Standardised canonical coefficients of the discriminant functions of model 2. λ^{-2} indicates the standard deviation of the exponential distribution. The inferior letters specify the body part (l – low back | t – trunk) and the movement plane (s – sagittal | f – frontal).

Variable	**Function 1**	**Function 2**	**Function 3**
$\lambda^{-2}(\lvert b \rvert_{tf})$	1.352	0.435	0.300
$\lambda^{-2}(\lvert b \rvert_{lf})$	-0.504	-0.872	0.688
$tmax_{ts}$	1.446	-2.288	0.141
$tmax_{ls}$	-1.647	-0.036	0.961
$tmax_{tf}$	-1.764	1.987	0.156
$tmax_{lf}$	1.558	0.809	-1.043

For model 2, all three functions are needed to significantly predict the subjective discomfort ratings. Function 1 explains 69.1 percent of the variance, function 2 30.2 and function 3 0.8 percent.

Table 12: Results of predicting subjective comfort ratings with model 1 / model 2 (see text). Model 1 predicted 21 out of 21 samples correctly, model two 18 (86 per cent).

Discomfort		**predicted**				
		1	**2**	**3**	**4**	**correct**
original	**1**	10/9	0/1			10 / 9
	2		3/3			3 / 3
	3		0/1	3/2		3 / 2
	4	0/1			5/4	5 / 4

3.3.4 DISCUSSION

The automotive industry is seeking for tools to predict subjective seating comfort ratings. The present study aimed at examining a relation between system stresses and seating comfort as proposed earlier (chapter 1.2) and at evaluating whether subjective seating comfort ratings can be predicted by stress-induced behaviour modifications. From the results, the following considerations can be suggested:

A relation between the driver's postural adaptations in prolonged driving and subjective discomfort ratings was found in this study. Predictions strongly depend on the maximum time between postural changes of trunk and low back. Low maximum time spans between posture changes are associated with high discomfort ratings and vice versa. This corresponds to the results of studies which have been carried out recently [57, 152, 166]. It is believed that by changing posture, the driver is able to alter contact forces between the body and the seat. Moreover, the muscular load necessary to stabilize the upper body can be altered. Both effects temporarily decrease the total individual load (chapter 3.2.4). It can basically be said that the maximum time a driver can maintain his posture is related to his subjective discomfort impression and thus to seating comfort.

A satisfying prediction of seating comfort based only on the maximum time between posture changes cannot be achieved, however. The analysis revealed that additional parameters of trunk and low back are needed to reliably predict subjective ratings. Since parameter values are unique for each person, mean values cannot be used for comfort evaluation. A significant group separation (see chapter 3.3.2 for group definitions) could be achieved using only the maximum *length* and the standard deviation of frontal *b* values (model 2). Higher ratings are associated with lower variations in $|b|$ and vice versa. An increase of postural adaptations can be seen as additional strategy of the driver to decrease the total individual load. Continuous motion can reduce the impact of hard stressors in the same way as posture changes. Posture adaptations do not have the same power in reducing load, however, because posture changes still appear frequently. They are rather believed to increase the time between posture changes. The absolute amplitude of postural adaptations does not play an important role. It was shown that higher loads are associated with a higher variation instead of absolute higher values. Drivers, besides their individual level, increase postural adaptations with increasing loads. In contrast, a constant adaptation level indicates lower overall loads. In summary, posture changes as well as posture variations are important to significantly separate comfort groups.

For a precise prediction of subjective discomfort ratings, additional parameters, i.e. the standard deviation of the frontal trunk and low back posture and the mean of lumbar sagittal activity must be taken into account (model 1). As with posture adaptations, increasing posture variations (*activity*) are associated with increasing loads independent of the absolute posture. Additionally, lumbar sagittal activity was found to account for different ratings. This result underlines the finding of other authors, who linked increasing pelvic or lumbar motion to increasing discomfort ratings [57, 152, 165]. It must be said that subjective discomfort ratings cannot be predicted by a single parameter, but when including data of posture changes, posture adaptations and activity in the model, an accurate prediction is possible. This rather complex relation might be a reason why recent studies failed to identify a clear relation between posture parameters and subjective discomfort ratings [39].

Parameters describing head motion do not allow a reasonable prediction of subjective discomfort ratings. This might be the case because of the limited interaction between head and seat. Moreover, head movements are directly linked to the driving task. Even if a connection between head movements and the total individual load existed, patterns would be overruled by movements necessary for safe driving. Head motion consequently cannot be used to assess subjective ratings in realistic environments.

Besides the prediction of subjective ratings, it was found that all parameters used in the prediction models can be described by either an exponential or a chi-square distribution. This allows estimating postural adaptations of a larger group from measurements of a representative sample. The mean and standard deviation as well as the distribution of the parameter values can be specified. On the one hand, this makes it possible to define the typical range of stress-induced behaviour modifications for a target group or a seat model. On the other hand, robust parameters can be used for the simulation of the driver’s postural adaptations with human models. Also, a prediction of certain events, e.g. posture changes, is imaginable. With the current results this is not possible however.

It could be proven, that subjective discomfort ratings can be predicted by stress-induced behaviour modifications. A second aim of the study was to evaluate whether a relation between system stress and seating comfort exists. The main results support such a relation, but a direct verification could not be provided. This is mainly due to the fact that seating comfort was not directly measured. Because of the complexity of determining individual seating comfort levels and the ongoing debate in literature about an adequate definition (chapter 1.2), subjective discomfort rating were assessed instead of seating comfort in this study. Because of the parabolic relation between comfort and discomfort, increasing discomfort rating may indicate decreasing comfort even if discomfort is associated with different factors (Figure 1). Additionally, seating comfort is defined as the result of stress-induced impression changes caused by an increasing total individual load. The subjective rating attained in this study therefore may be interpreted as an indicator for the evaluation of stress-induced impression changes. Consequently, a relation between stress-induced impression changes and stress-induced behaviour modifications could be circumstantiated. Thus, a relation between system stress and seating comfort may be assumed.

3.4 CONCLUSION

A method for continuous monitoring of driver posture presented in a recent study has been used to evaluate stress-induced behaviour modifications of the driver. The method may be applied to objectively analyse postural changes in long-duration driving under various conditions, especially real road travel. The findings of this study underline the relation between stress-induced impression changes and stress-induced behaviour modifications and thus may be used to predict seating comfort from system stress. Parameters describing driver motion of trunk and low back can be used to reliably predict subjective discomfort ratings. The parameters with the strongest correlation to subjective impressions are the maximum time between posture changes, the standard deviation of posture adaptations and frontal posture, and the mean sagittal lumbar activity.

Moreover, all drivers show continuous time-dependent postural adaptations. Parameters describing posture changes and posture adaptations are exponentially distributed. The absolute posture as well as the activity follows a Chi-square distribution. Based on these finding, a relatively simple description of driver behaviour in real-life driving is possible. Additionally, existing human models can be trained to simulate the driver's movements in extended duration travel.

4 NEW METHODS TO ANALYSE AND INFLUENCE THE DRIVER'S BEHAVIOUR MODIFICATIONS

4.1 ABSTRACT

Continuous monitoring of the driver's posture plays a vital role for safety, i.e. airbag deployment, and comfort features such as automatic adaptation of seat side bolsters to lateral translation of the upper body. A detailed analysis of the driver's upper body posture is, however, not possible with available systems. As it was shown in chapter 3, drivers continuously adjust their posture to minimize the total load. Further comfort enhancement therefore was possible, if detailed information about trunk and pelvis motion would be available throughout the ride. The necessary steps to achieve this goal are (1) to develop a system for posture measurement that can be integrated in the seat, (2) to examine posture changing strategies and influencing variables, and (3) to analyse the possibilities for manipulation of driver posture in order to reduce the total load.

A system for driver independent posture measurement was developed, that can be implemented in up-to-date car seats without altering its parameters or influencing the driver. The system uses continuous local pressure measurement to assess postural changes of the driver. Adjustment variations of the seat are monitored with inclination sensors. Sensory information is processed by a microcontroller. It could be shown that the system is capable to monitor individual driver behaviour and seat adjustments.

In a second step, a study using local pressure measurement and sonometry was conducted to further evaluate the initial posture change that was found in a recent study (chapters 2.5 and 3.2). Posture of ten persons (age: 25.8 ± 4.0 years; height: 178.5 ± 6.3 cm; weight: 71.7 ± 8.7 kg, eight male, two female) was monitored during a 30-minute simulated test drive. Immediately after the test drive, subjects were questioned about the perceived discomfort. The results indicate that drivers significantly changed their initial posture within the first minutes. This initial posture change is independent of the driving conditions, because it can be seen in real as well as simulated environments. The direction and amplitude of this change is unique for every person. Individual changes can be, however, categorized in two different strategies: thoracic extension with lumbar flexion and vice versa. Additionally it could be shown that postural variations can be derived with local pressure measurements. It can be concluded, that the initial posture change and further posture variations can be assessed using a seat-integrated measurement system.

In the third part, a study was carried out aiming at describing the effect of small changes of seat-back inclination on spine kinematics. 19 healthy adults (12 male, seven female, age: 25.1 ± 3.4 years; height: 177.2 ± 7.4 cm; weight: 69.8 ± 10.1 kg) were investigated during a 30-minute simulated driving test. Upper body movement and local contact pressure were recorded. Seat-back inclination was varied every five minutes (18, 21, 24, 21, 18 degrees). The results of the study are that posture can be altered by small changes of backrest inclination and that the absolute posture change depends on the direction of the change of the backrest angle. Posture and pressure values significantly change if the backrest inclination is altered by three degrees. Data for similar seatback inclinations are different, however. It can be concluded that the absolute driving posture does not correlate with the seatback angle, if the inclination is changed during the drive. Also, strategies of the driver to adapt to changes of the backrest angle are not unique. A modification of current models is necessary to adequately describe spinal kinematics for continuous changes of the seatback angle. A change of driver posture and contact pressures, induced by a minimal change of seatback inclination, could help to limit physiological loads, e.g. static pressure or muscle loads, associated with decreased seating comfort.

4.2 DEVELOPMENT OF A DRIVER-INDEPENDENT SYSTEM FOR THE ASSESSMENT OF LOAD-INDUCED POSTURE MODIFICATIONS

As shown in the chapter 3, the continuous assessment of the driver's posture can be used to predict subjective discomfort ratings and thus estimate seating comfort. Moreover, time-dependent changes of certain parameters, i.e. posture changes, posture adaptations and activity, can be interpreted as the driver's reaction to changing total loads. Continuously monitoring of the driver's posture could therefore help to estimate the current total individual load and initiate load reducing mechanisms. The methods used today are not capable of detecting the appropriate parameters, because they only aim at detecting out-of-position situations. The information when the driver is not in his desired position is needed for safety, i.e. airbag deployment, as well as comfort features such as automatic adaptation of seat side bolsters to lateral translation of the upper body. The aim of this project was to develop a system for continuous posture monitoring that can be easily integrated into the driver seat. The characteristics of such a system can be derived from analysing the automotive environment. The system therefore:

- needs to be small and light-weight, so it can additionally be integrated in the seat without interfering with other structures;
- must run on as stand-alone application, preferably on a microcontroller;
- uses as few sensors as possible, so data can be processed in real-time with limited hardware sources;
- works with the car's electrical system;
- and may not interfere with driver behaviour and perception.

An according prototype was developed in cooperation with the Brandenburg University of Technology Cottbus, Chair of Distributed Systems / Operating Systems; integrated in a modern production seat, and its output validated against posture measurement with the sonoSens® Monitor.

Since direct measurement techniques could not be used because of several constraints, pressure sensors are chosen to indirectly analyse driver posture. Pressure measurement is a standard tool for industrial seat analysis and has recently been used to assess the driver's posture, e.g. to assess load-induced behaviour modifications [39]. The analogue force sensing resistors (FSR) used in this project (Figure 32) work similar to membrane switches, but change resistance when pressure in normal direction is applied.

Figure 32: Force sensing resistors (FSR) of various sizes (source: www.conrad.de).

When pressure in the range of 10 g up to 10 kg is applied, the resistance decreases from about 2 MΩ down to approximately 3 kΩ. Pressure values can therefore be calculated from resistance changes. Sensors can be used up to 10^6 times which seems suitable for the attended application. For the system prototype, sensors with circular contact areas (diameter 18 and 38 mm) were used. They were connected to the system according to the manufacturer's specifications.

Additionally, two dimensional acceleration sensors (see attachment for details) are used to measure seat adjustments, e.g. the backrest inclination angle. The acquisition of the actual seat adjustment is necessary because it acts as a hard stressor influencing the total individual load (chapter 1.3.2). Additionally, load reducing mechanisms must be adapted to the actual seat position in order to not disturb the driver, e.g. by choosing seat angles out side the comfort range (Figure 5). Acceleration sensors can be described as follows (Figure 33a): A small seismic mass surrounded by a viscous fluid is included in a closed system. The mass is connected to the system by a resistance strain gauge. When a force acts on the mass, a resistance change of the strain gauge can be measured. It is additionally possible to use these sensors as inclination indicators by measuring the influence of the gravitational force on the seismic mass (Figure 33b). The outputted resistance changes according to sensor tilt. When the gravitational force exactly acts along one direction of the sensor, meaning that the sensor is not tilted according to vertical, and no other forces are applied, the measured resistance in this direction is maximal (U_g). If the sensor is positioned horizontally, resistance would be minimal (U_0). For an inclination angle of 45 degrees, the acceleration (a) is half the g-force and the measured resistance (U) consequently half the difference between U_g and U_0 (ΔU) (Figure 33b). Assuming a linear relationship, the inclination angle (α) can therefore be calculated as follows (Equation X).

$$\alpha = 90° \frac{U - U_0}{\Delta U} \qquad \text{X}$$

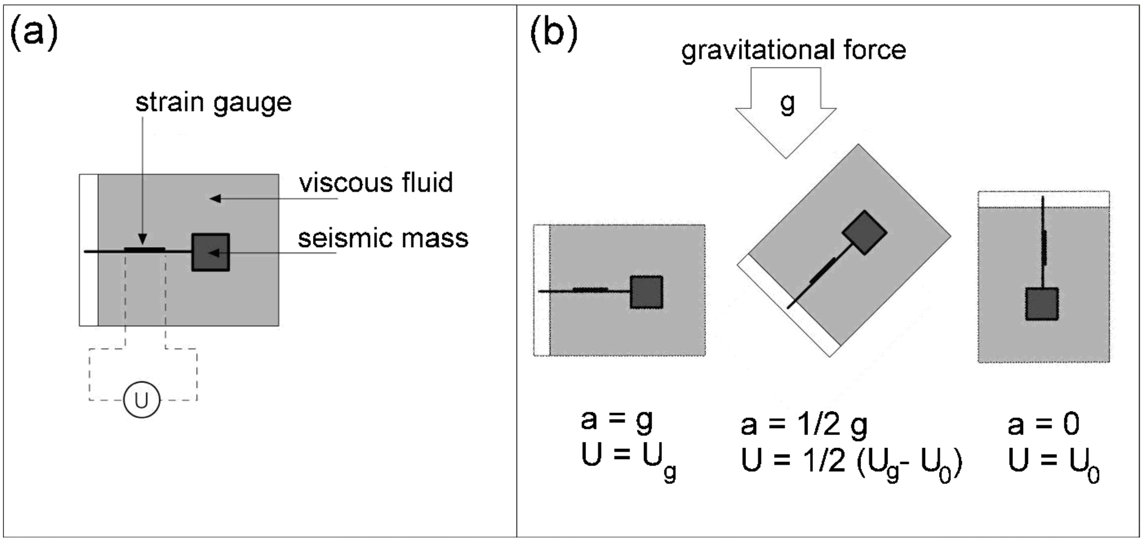

Figure 33: (a) Illustration of the basic parts of an acceleration sensor. When a force acts on the mass, a resistance (U) change of the strain gauge can be measured. (b) The use of acceleration sensors to measure inclination. The sensor angle relative to the direction of g-force influences the acceleration (a) of the mass the measured resistance (U).

Since only trunk and low back movements are needed to predict subjective ratings (chapter 3.3), at least six pressure sensors are needed to monitor trunk and pelvic motion (Figure 34). Based on test measurements it is concluded that two sensors should be placed at the level of the lower scapulae tips (diameter 38 mm), two at L5 level (18 mm) and two under the ischial tuberosities (18 mm) orientating at the anthropometry of a 50th percentile adult. Additionally, one acceleration sensor is placed at the backrest frame to assess seatback inclination.

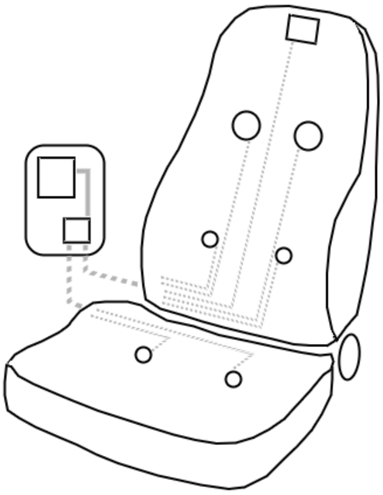

Figure 34: Minimal setup to monitor driver posture. Six pressure sensors (O) and one acceleration sensor (☐) are used to monitor pelvic and trunk posture as well as the seatback angle. Raw data is processes by a microcontroller and then send to a flash memory for storage.

Measurement data is continuously recorded at a predefined frequency. Data recording and processing is controlled by the operating system REFLEX which runs on a microcontroller. After processing, the data is stored on a flash memory or directly transferred to a connected PC. The heart of the system is the operating system (OS), which was developed by the Brandenburg University of Technology Cottbus, Chair of Distributed Systems / Operating Systems [170, 171]. The following description is given to provide a brief overview:

> Most small devices are more or less control loops for some processes in the real world. Therefore the operating systems on these devices do not need to be general purpose systems. Other requirements rule that world, namely a small memory footprint, robustness, real-time capabilities and of course resource sparing. REFLEX (Realtime Event FLow EXecutive) is a generic event driven OS for embedded devices. Event handlers and control functions are all represented by passive objects that are scheduled preemptively according to an earliest deadline first (EDF) strategy. All sensors, control functions and actuators of a typical

embedded control system are represented by objects that can communicate with each other by means of events. Synchronization and scheduling of events is based on an event flow model that is in principle very similar to the data flow paradigm. The implementation of control systems that are described by means of state machines or SDL-graphs is therefore particularly easy. REFLEX has a small memory footprint (only a few KB of RAM for complete control applications) and is entirely implemented in standard C++. It has been ported so far to several CPU types including Motorola HCS12, Atmel ATmega128 and Hitachi H8/300.

Since sensor parameters are provided by the manufacturer, further sensor validation was limited to assessing the drift of the pressure sensors and the relation between the output of the acceleration sensors and the seatback angle. The pressure sensors showed no drift within a 30-minute interval. Seatback inclination could be accurately measured using the output of the acceleration sensor. When varying seatback inclination within ±10 degrees starting at a 20 degree backward inclination from vertical, the sensor's output and the inclination angle were significantly correlated ($p < 10^{-3}$, $r = 0.98$). The ability of the system to monitor the driver's posture system was than evaluated in a driving simulator. This was done due to an easier evaluation process and because data attained in a driving simulator is proven to be valid [139]. Results showed that postural changes can be derived from local pressure measurements. A final test was performed under real driving conditions. The data showed a similar pattern than the posture data assessed with sonometry. Additionally, the proposed system reliably recorded data without altering interfering with seat parameters and driver behaviour. A detailed description of the recorded data is provided in the next chapters.

4.3 EVALUATION OF THE INITIAL POSTURE CHANGE OF THE DRIVER

4.3.1 BACKGROUND

A previous study (chapter 2.5) indicated that driver posture significantly changes within the first 30 minutes. It could be shown that the space between backrest and shoulder is reduced by an extension of the thoracic spine. It was concluded that such movements can help to maintain the lumbar curvature, because backward movement of the trunk results in forward rotation of L5 [151] and a free shoulder space of at least six centimetres is required to effectively use the lumbar support [66]. Additionally, this strategy could help to shift the weight distribution on the backrest towards the upper trunk, since initially only seven percent of the body weight is exerted on the seat in this area [8]. A reduction of head inclination with respect to the trunk was also observed, which could help to reduce strain in the neck region.

The exact causes for this initial posture change are not known, however. A further study was therefore carried out to better understand the phenomenon. Particularly, the following questions were addressed:

1. Does the initial posture change only occur under dynamic driving conditions or can it also be found in a simulated environment?
2. Does the initial sitting posture affect the initial posture change?
3. Do all drivers show the same kinematics?

4.3.2 EXPERIMENTAL DESIGN

The initial posture change was evaluated in a self-build driving simulator using sonometry (chapter 2.4) and local pressure measurement (chapter 4.2). Pressure sensors were placed directly underneath the covering fabric, the acceleration sensor was fixed to the metal seat frame at the upper part of the backrest (Figure 34 of a regular car seat. The seat was fixed onto a platform including a steering wheel and a computer screen. Distances and dimension of all parts were set up according to a standard car cockpit. Posture of ten persons (age: 25.8 ± 4.0 years; height: 178.5 ± 6.3 cm; weight: 71.7 ± 8.7 kg, eight male, two female) was monitored during a 30-minute simulated test drive using sonometry (see chapter 2.4) and the new system (chapter 4.2) with a measurement frequency of one hertz.

None of the test persons had back problems; all had a valid driver's license. Before starting a virtual test drive on a round trip (two minutes per round, 15 rounds for each test person), test persons adjusted the seatback's inclination and the distance to the steering wheel according to subjective preferences. Their setup was not changed during driving. Interaction with the virtual car was allowed through the steering wheel only. Acceleration and deceleration were available through rocker switches at the steering wheel, which could be used with either the index or the middle finger.

For the evaluation of time-dependent posture and pressure changes, mean and standard deviation of sagittal posture and pressure changes for five minute intervals are calculated. The amplitude of posture adaptations within each interval are derived from the slope of the linear fit of the Sagittal Index (compare chapter 2.5). Pressure changes were calculated accordingly, using the mean pressure of the sensor pairs. SPSS (version 11, SPSS Inc., Chicago, USA) was used for the statistical analysis. Time dependent differences of posture and pressure changes were analysed using a Student T-Test. A cluster analysis was performed to identify different posture-changing strategies. To find parameters for posture prediction, a discriminant analysis was carried out. Finally, a Pearson correlation coefficient (r) of various parameter pairs was calculated to identify relations between parameters. $P < 0.05$ was defined as level of significance.

4.3.3 RESULTS

An initial posture change could be observed as well as correlations between posture and pressure parameters. The driver's posture 15 minutes after the start can be predicted by earlier posture changes.

Initial posture and posture change

Significant changes compared to the initial posture can be seen in head and trunk posture as well as in the pressure under the ischial tuberosities. Significant changes in trunk posture appear after five minutes, head posture changes can be observed after ten minutes (Figure 35). Both body parts show an extension. The pressure under the ischial tuberosities rises significantly within the first 15 minutes. All other parameters are not significantly different from the initial values. Because all significant changes of the measurement data could be seen within the first 15 minutes, all further evaluation was limited to this time period.

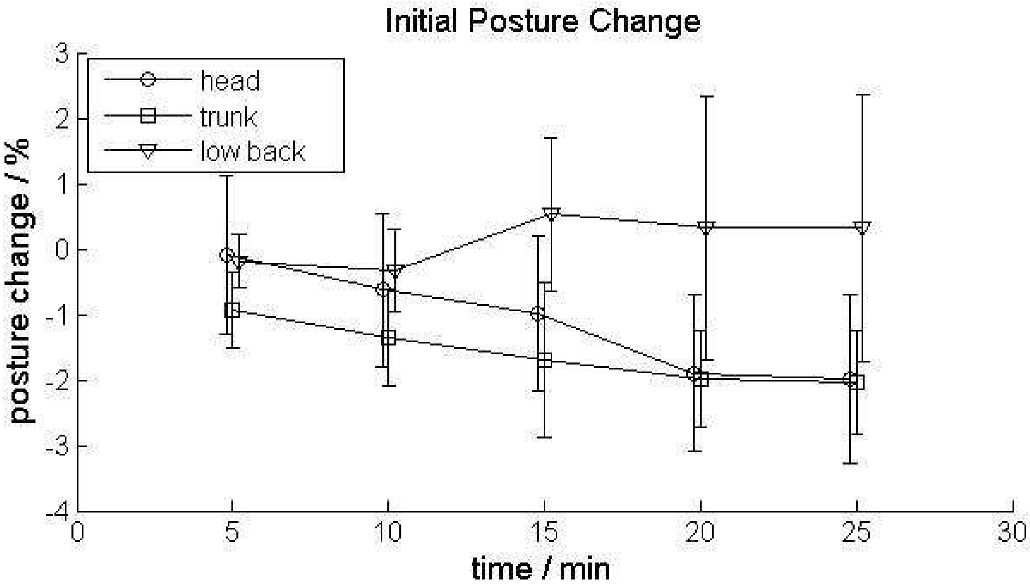

Figure 35: Initial posture change: mean and standard deviation of head (○), trunk (□), and low back (▽) posture for all test persons (n=10). In average, all test persons showed a significant trunk extension after five minutes and a head extension after ten minutes. Average low back posture was not different from the initial posture.

A cluster analysis (hierarchical clustering of pressure changes of five-minute intervals, three tests with a number of two / three / four clusters) revealed two different posture changing strategies (Figure 36). Both groups could be separated using the data of the first five minutes. Because trunk and low back pressure changes within the first five minutes show an opposite behaviour, each of the parameters can be used alone to significantly separate both strategies. The majority of the test persons (n=7) showed an increase of pressure in the trunk region and a decrease in the low back area (type I). The opposite strategy (type II) could be observed by the remaining test persons (n=3).

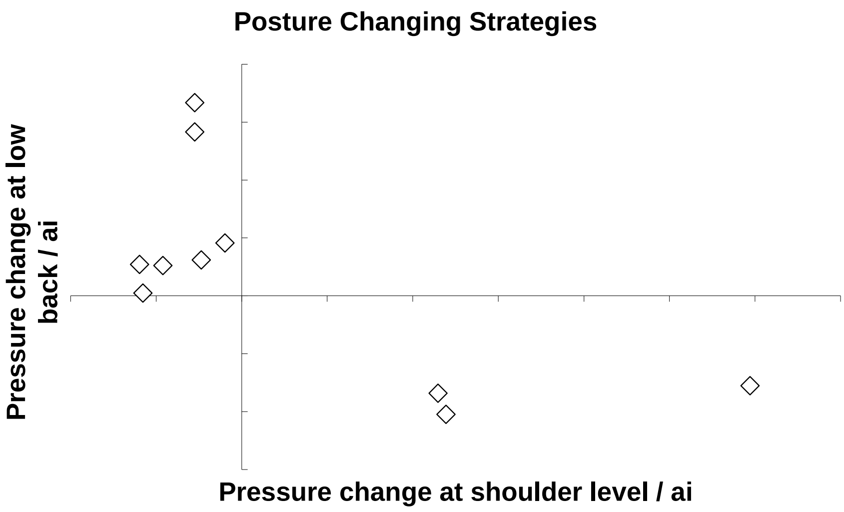

Figure 36: Different posture changing strategies. Posture-related contact pressure changes of low back and trunk within the first five minutes are inversely related. Predominantly, a trunk extension resulting in higher contact pressures together with a low back extension (lower pressure) is found. Three test persons showed an opposite behaviour.

The direction of pressure changes within the first 15 minutes can be predicted from the changes within the first five minutes. The pressure change after five and 15 minutes is the same, if the pressure level changes by more than ±1.5 percent within the first five minutes.

The seatback angle correlates with trunk posture ($r > 0.7$, $p < 0.02$; exact values depend on the interval time) as well as with trunk pressure values ($r > 0.7$, $p < 0.02$). Furthermore, a connection between trunk posture within the first five minutes and low back posture after ten minutes could be found ($r = 0.75$, $p = 0.01$). Lumbar posture changes therefore seem to be initiated by early trunk posture changes, which themselves are influenced by the seatback angle.

Pressure changes of the trunk and low back are inversely related ($r = -0.69$, $p = 0.03$), pressure changes of the low back and seat pan show a positive correlation ($r = 0.74$, $p = 0.02$). Trunk posture changes, which seem to initiate low back posture changes, consequently also affect the pressure under the ischial tuberosities.

4.3.4 DISCUSSION

The results indicate that drivers significantly change their initial posture within the first minutes. This initial posture change is independent from the driving conditions, because it can be seen in realistic (chapter 2.5 and 3.2) as well as in simulated environments. Even if the direction and amplitude of this change is unique for each person, individual changes can be categorized in two different strategies of the drivers to cope with the seat's character: thoracic extension with lumbar flexion and vice versa. Additionally it could be shown that postural variations can be derived with local pressure measurements.

The initial posture change of the driver is independent from individual and environmental conditions. In average, all drivers show an extension of the head and trunk within the first minutes of the test drive. It can be concluded (compare chapter 3.2.4) that this strategy on the one hand can help to maintain the lumbar curvature and limit slouching. On the other hand, trunk extension shifts weight distribution on the backrest towards the upper trunk, which reduces the contact pressure under the buttocks. A reduction of head inclination with respect to the trunk could help to reduce strain in the neck region. Such strategies limit the total individual load (chapter 1.3) and therefore may have a positive impact on seating comfort. Backrests and headrest should consequently be designed in such a way that they allow some extension of the upper body. These finding correlate with results of previous studies, e.g. that a "free shoulder space", i.e. the horizontal distance between shoulders and backrest at the initial sitting posture, of at least six centimetres is needed to maintain lumbar lordosis and not to overrule lordotic support [66]. This is, however, not easy to achieve. Seat design must primarily be focused on the driver's safety. Studies of rear-impact crashes showed that injuries are less severe if the driver is located close to the backrest and headrest [58, 156]. Consequently, increasing distances between body and seatback would reduce safety. In contrast, a decreased seating comfort would induce more posture changes of the driver and thus lead to a higher percentage of out-of-position cases, which would increase the injury potential. A good compromise between both safety and comfort must therefore be found.

It was also seen that posture changes affect the contact pressure between back and backrest as well as between buttocks and seat pan. Based on local pressure changes two different effects could be identified. The majority of test drivers showed an increase of pressure in the shoulder region and a decrease in the low back area (type I). In the experimental setup with a fixed backrest recline, the only possibility to change trunk pressure values in such a way, is to extend the trunk and rotate the pelvis forward. As described above, trunk extension was observed as one part of the initial posture change. An initial forward rotation of the pelvis could not be found however. This might be due to the rearward pelvic rotation in the typical sitting posture. In such a position, higher forces are needed for forward and for rearward pelvic rotation. It therefore seems reasonable to believe that pressure of the low back area was decreased by a small change in the lumbar curvature due to higher contact forces between trunk and backrest. Forces were not big enough, however, to affect pelvic position. This findings partly underline the above-mentioned result from Goossens et al.[66] saying that trunk extension leads to forward pelvis rotation. It could be shown that trunk extension leads to a decrease of low back contact pressures, but a forward pelvis rotation cannot always be found.

In contrast to the type-I-strategy, some test persons showed an opposite change of the pressure pattern (type II). A significant trunk flexion, which would have led to a decrease of the contact pressure in the shoulder region and an increase in the lumbar area, could not be seen in the sonoSens data. A reduction of the pressure at trunk level without a trunk flexion might appear when the trunk is passively shifted forward by a flexion in the low back. Such a flexion can be found for the three test persons of type II. The two different strategies could also be identified being the reason for the fact that initially no posture change of the low back could be seen. When looking at the persons of each type separately, a significant extension and flexion was seen for type I and II respectively. It can therefore be concluded the initial posture change also affects the low back posture, but the direction of the posture change varies for different persons.

The initial posture change is unique for every test person. The direction of postural changes, once initiated, is kept constant, however. It was shown that the posture after 15 minutes of driving can reliably be predicted from the posture change in the first five minutes. Significant posture changes after 15 minutes did not occur. This indicates that it takes up to 15 minutes until the driving posture is found independently of using a driving simulator or driving on a real road (chapter 3.2). This must be taken into account when aiming at predicting driving posture. To attain reliable results, continuous measurements of driver posture of at least five minutes must be performed. The final driving posture can then be estimated from the derived changes. As demonstrated earlier this posture is only held for limited time. Additionally it must be said that a general prediction of the driver's posture without any measurement is not possible, because at least two different posture changing strategies are present.

Low back posture is significantly related to the contact pressure under the ischial tuberosities. Higher pressure under the buttocks may be associated with trunk flexion (type II), because the centre of mass is shifted forward and the contact forces between back and backrest are decreased. It can be concluded, that slouching leads to a higher contact pressure under the buttocks, which is generally being seen as a major hard stressor increasing the total individual load and consequently decreasing seating comfort (chapter 1.3.3). The typical initial posture change, which has an opposite direction compared to slouching, may therefore be interpreted as a strategy to reduce the contact pressure under the buttocks and thus limit increasing total individual loads.

4.3.5 CONCLUSION

The initial posture change and further postural adaptations can be assessed using the developed seat-integrated measurement system. Correlations exist between postural changes, changes of contact pressure, and seat adjustment. If continuous information of postural changes is available, individual and interactive alterations of the seated posture through manipulation of seat adjustments would be possible. As demonstrated earlier, posture changes and posture adaptations reduce the total individual load. One possible solution is a dynamic change of the seatback angle, because this influences driver posture as well as contact pressure. Further research must be carried out to evaluate this possibility.

A short measurement of posture and contact pressure will not lead to optimal results for the evaluation of the typical driver posture. Measurements should therefore last at least five minutes and should, besides mean values, also detect time-dependent changes. The results can then be used to predict the individual driving postures.

4.4 THE EFFECT OF SMALL CHANGES OF SEATBACK INCLINATION ON SPINE KINEMATICS

Parts of this chapter are adapted from Adler et. al [4].

4.4.1 BACKGROUND

Postural adaptations have been proven to limit total loads when driving. It was found, for example, that changing their posture regularly may extend the amount of time persons can safely remain seated without damaging tissue or become fatigue [35]. Since motion while driving is limited, various strategies have been introduced to apply continuous passive motion to the driver. Micro adjustments of the lumbar posture were used to reduce the incidence of low back pain and enhance seating comfort by delaying the onset of low back fatigue [101, 142]. A similar "lumbar massage", i.e. the cyclic change of the position of the lumbar lordosis, was proven to have a beneficial effect on the EMG of lumbar muscles [103]. Another approach used continuous small rotations of the seat pan, resulting in less spinal shrinkage and pain relief [161-163]. The benefits of this technique were confirmed by other authors [109]. Various other similar techniques exist to alter the pelvic position, for example the use of air-inflated cushions in the seat pan to affect pelvic tilt. One problem of the described approaches is the definition of the exact frequency and amplitude of passive posture changes. General values could not be defined predominantly because of subjective differences. Moreover, all systems aimed at applying motion to the low back or pelvis only. Additional movements of the trunk, which have been proven to limit total individual loads (chapter 3), could improve system performance.

One possibility to avoid the described problems is to apply passive trunk motion based on continuously recorded posture data. This approach would have the advantage of reacting according to the individual driver behaviour. Additionally, low back posture and contact pressure at seat pan and backrest could be altered because of their interaction with trunk movements (chapter 4.3). An alteration of the backrest angle may be easily achieved, because an increasing number of modern car seats is equipped with an electric recliner.

Furthermore, seat angle changes have been found to increase seating comfort [68]. Periodic changes of the seatback angle were successfully used to increase long-term comfort for pilots sitting for 12-16 hours [107]. A change in the backrest's inclination is recommended for wheel-chair users to adopt different sitting postures [41] in order to reduce the risk of developing pressure ulcers. Posture and seatback angle show a direct relationship [75]. When moving the trunk to the back stepwise with support at shoulder level, the lumbar lordosis is decreased [151]. According to Anderson et al. [7] the influence of the seatback angle on the lumbar lordosis seems to be small, however.

The concept of dynamic posture changes based on the person's behaviour has already been successfully used to increase subjective comfort. An intelligent micro-controlled seat, that makes posture adaptations based on parameters derived from continuous contact pressure measurements has been shown to improve seating comfort [128]. The compliance was high; subjects felt the self-adjusting seat was more comfortable, providing a better fit. To limit pressure scores in paraplegic patients, a micro-processor-based weight shift monitor is used for long-term monitoring of patient posture [37]. The device emits an alarm, when a certain period of time without a postural change is detected. Patients are then repositioned manually by an assistant.

A study was carried out to evaluate the possibility of influencing driver posture by using small changes of the seatback angle. Based on the results of recent studies and previous chapters of this work, two assumptions are made: (1) trunk and low back posture as well as contact pressure can be altered using small changes of seatback recline; and (2) driver posture and seatback angle show a direct relationship.

4.4.2 Experimental Design

The possibility of altering the driver's posture using small changes of the backrest angle is evaluated in a simulated environment using sonometry (chapter 2.4) and local pressure measurement (chapter 4.2). The same setup as in a previous study is used (4.3). Pressure sensors are placed directly underneath the covering fabric, the acceleration sensor is mounted onto the metal seat frame at the upper part of the backrest (Figure 34). The seat is fixed on a platform including a steering wheel and a computer screen. Interaction with the simulated car is only available through the steering wheel, acceleration and deceleration could be controlled through wheel-mounted rocker switches. Distances and dimension of all driving simulator parts are set up according to a standard car cockpit. The posture of 19 persons (age: 23.1 ± 3.4 years; height: 167.8 ± 7.2 cm; weight: 66.1 ± 9.8 kg, 12 male, seven female) is monitored during a 30-minute simulated test drive using sonometry (see chapter 2.4) and continuous local pressure measurement (chapter 4.2) with a measurement frequency of one hertz. None of the test persons had back problems; all had a valid driver's license. Before starting a virtual test drive on a round trip (two minutes per lap, 15 laps for each test person), test persons adjusted the seatback's distance to the steering wheel according to subjective preferences. The seatback angle is initially set to 18 degrees for all test persons and manually changed by an assistant every five minutes. Seatback angles are varied in three degree steps as follows: 18 – 21 – 24 – 21 – 18 degrees. The absolute inclination is measured with an acceleration sensor mounted at the upper seatback frame to assess possible errors in adjusting the seatback angle. If errors were detected, the deviation was taken into account when interpreting the data or data was excluded from the results if the deviation was bigger than one degree. A variation of three degrees is used because greater changes could influence driver behaviour. It has been found that people are not sensitive to changes of the backrest angles smaller than three degrees [80]. This means that smaller changes of the backrest angle do not interfere with the driver's behaviour and driving habits. The use of smaller changes than three degrees would have been possible. The maximum possible threshold is chosen for this study to maximise the effect on the driver's posture.

For the evaluation of time-dependent posture and pressure changes, mean and standard deviation of sagittal posture and pressure changes for five minute intervals are calculated. Posture is derived from the mean of the Sagittal Index (chapter 2.5, equation VI) within the respective interval. Pressure levels are calculated accordingly using the mean pressure of the sensor pairs. MATLAB® (version 7.0 R14, The MathWorks, Inc., Natick, MA) is used for the statistical analysis. To evaluate whether driver posture and contact pressure can be altered by small changes of the backrest's inclination, a Student-T-test is carried out to compare the mean values of adjacent intervals. Additionally, posture and pressure values of the same backrest inclination are compared to find out if a connection between posture and backrest angle exists. $P < 0.05$ is defined as level of significance.

4.4.3 RESULTS

The results of the study are that posture can be varied by small changes of the backrest's inclination and that the absolute posture change depends on the direction of the change of the backrest angle. Posture and pressure values significantly change if the backrest inclination is altered by three degrees (Figure 39). Pressure and posture parameters are weakly correlated ($r_{Trunk} = -0.63$, $p = 0.26$; $r_{LowBack} = 0.60$, $p = 0.28$).

The contact pressure under the ischial tuberosities is weakly correlated to the seatback angle ($r = -0.55$, $p = 0.34$). It is not related to backrest contact pressure, i.e. the sum of low back and trunk pressure values ($r = 0.18$, $p = 0.77$). Overall pressure values, i.e. the sum of contact forces at seatback and seat pan, remain constant when the seatback angle is increased and increases if the seatback angle decreases again (Figure 38). The increase of the overall pressure is dominantly caused by an increase of the contact pressure at the seat pan.

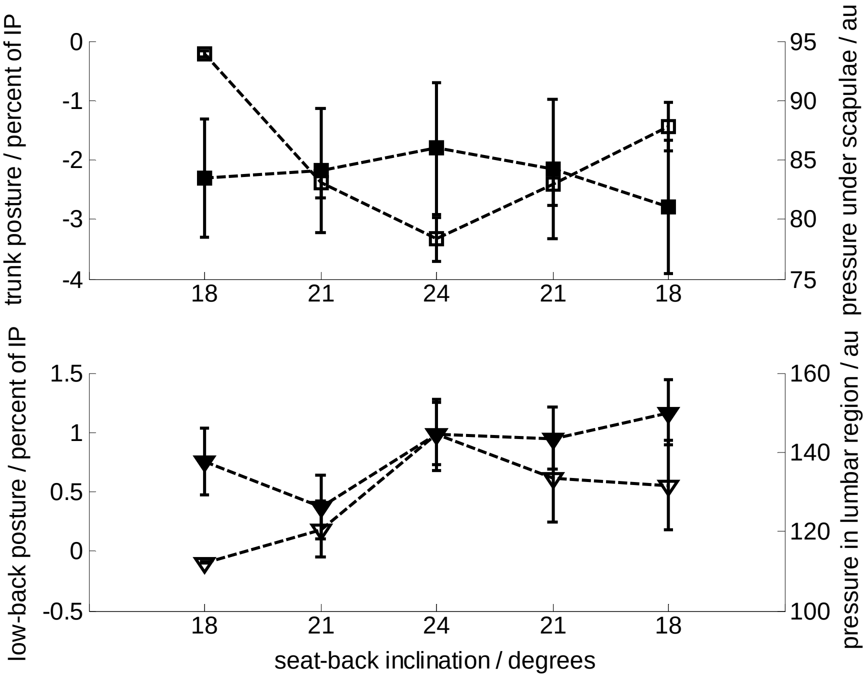

Figure 37: Mean and standard deviation of posture (transparent markers) and contact pressure (solid markers) for trunk (□) and low back (▽) for various seatback angles. Posture changes are shown relative to the initial posture (IP). Posture and pressure values show are correlated (r_{Trunk} = - 0.63; $r_{LowBack}$ = 0.6).

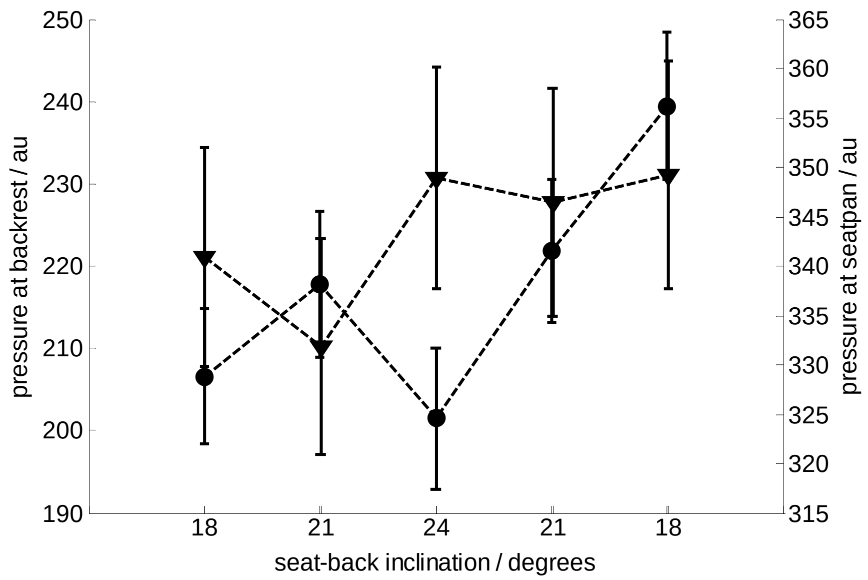

Figure 38: Mean and standard deviation of contact pressure at backrest (sum of low back and trunk pressure values ●) and seat pan (▼) for various seatback angles. Pressure values at backrest and seatpan are not related (r = 0.18).

The absolute driver posture cannot be inferred from the seatback angle directly. The variation of the seatback angle significantly changes posture and pressure parameters for the majority of test persons, but the direction of the change varies among drivers (Figure 39). The direction of the posture change of trunk and low back depends on the direction of the variation of the seatback angle. An increase of the backrest inclination leads, in average, to a trunk extension and a lumbar flexion and vice versa. There are, however, a limited number of test persons that show an opposite or no posture change. Additionally it is found, that the amplitude of the induced posture changes is greater when the backrest inclination is increased compared to a decrease of the backrest angle (Figure 37). These effects lead to significant posture and pressure differences for the same seatback inclination (Figure 39). Consequently, posture and pressure can not be derived from the absolute seatback angle, if it is changes during driving.

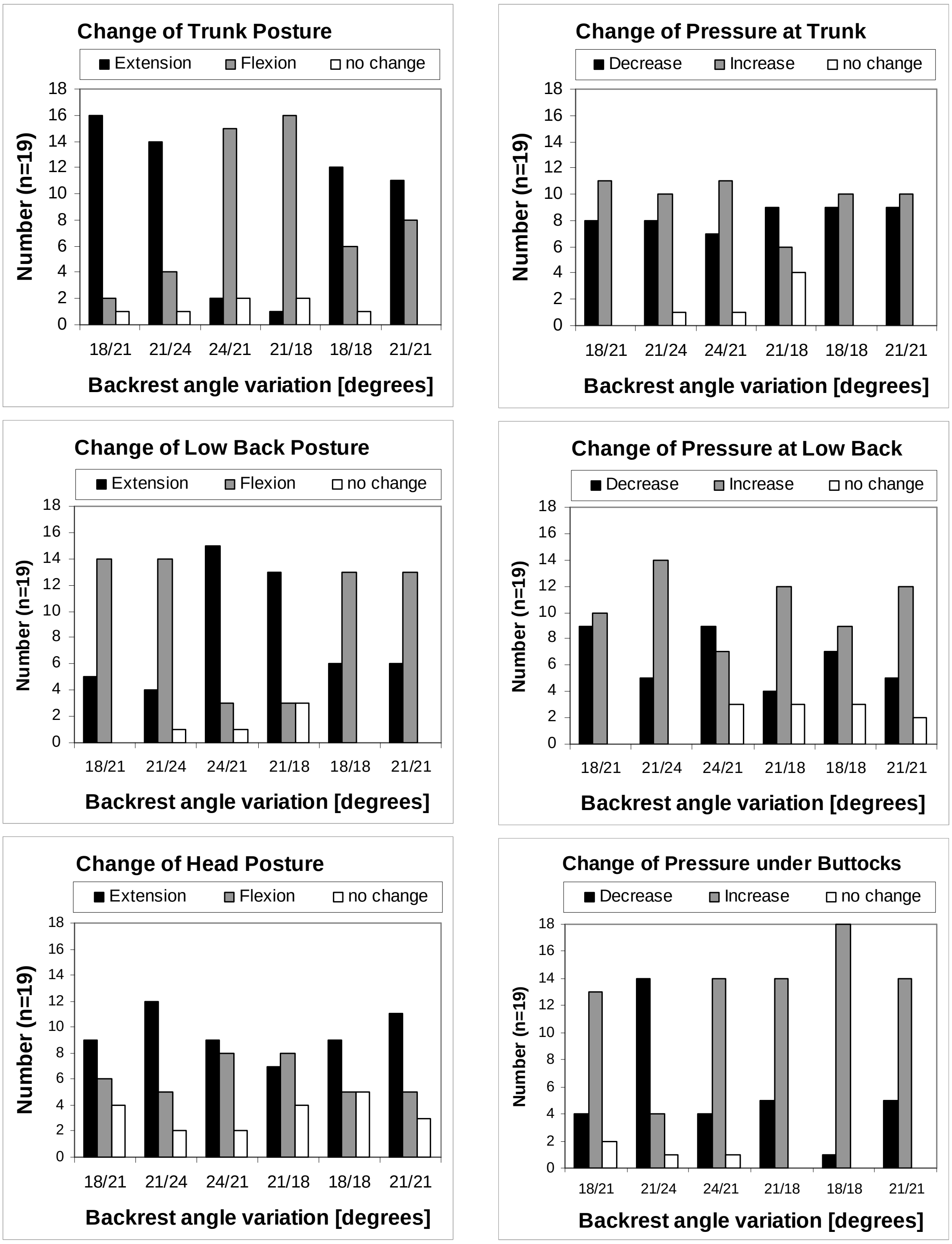

Figure 39: Number and direction of significant changes of posture (left) and contact pressure (right) for all test persons. Significant changes are detected if the posture or pressure after the variation of the seatback angle differs significantly from the posture or pressure before the seatback angle change. The alteration of the seatback's inclination changes the contact pressure and posture for the majority of the test persons.

4.4.4 DISCUSSION

The study evaluated the influence of small changes of the seatback angle on driving posture and contact pressure. The following suggestions can be made based on the results:

As expected, small changes of the seatback's angle lead to significant changes of driver posture and contact pressure. It is therefore possible to actively alter the driver-seat interaction by minor variations of the seatback angle, for example to limit the increasing total individual loads associated with prolonged sitting. The head's posture is also affected. A change of the head's posture is necessary to maintain the eye-level and to focus on the screen or the road respectively. Since trunk and low back posture changes, the different locations of the eyes must be balanced by changing the head's posture.

Driver posture and contact pressure are related. Posture variations may be – to some extend - derived from local pressure measurements. It is therefore possible to continuously monitor driver posture with seat integrated sensors instead of sensors applied to the driver's body which makes it substantially easier to monitor stress-induced posture modifications in real-life situations. Continuous information about the driver's postural variations could be used for safety applications such as airbag deployment and for detecting increasing loads leading to lower seating comfort (compare chapter 3). One main cause for the differences between the results of both systems possibly is the location of the pressure sensors. Since sensor location was chosen based on a 50th percentile male in a normal driving posture (chapter 1.3.2), differences occurred between the actual location of the body parts and the sensors for different test persons. Additionally, initial seating postures vary among the tested population. This leads to a different sensor output for comparable movements, because movements may cause an increase or decrease of the sensor's distance to the point of the highest pressure based on the initial position. For example, a backward rotation of the pelvis could lead to a decrease of pressure, if initially the ischial tuberosities were located directly above the sensors. An increase of pressure may occur for the same movement, if the ischial tuberosities were located slightly forward compared to the pressure sensors' locations. A placement of a sensor matrix at specific locations could assumingly help to limit these effects. A second cause may be the ratio of the change of pelvic inclination to backrest inclination. A recent study has shown that an increase of the seatback angle is not equal to the increase of pelvic tilt and vice versa [105]. This will affect the ability to monitor posture with local pressure measurements. If a backward pelvis rotation was smaller than the simultaneous backrest angle change, the pressure at the low back would decrease even if the pelvis rotated backwards. The expected pressure increase associated with this movement does only occur, when the change of the pelvic angle is at least as big as the backrest angle change. Moreover, methodological differences between both systems lead to different results. Sonometry is a direct method for posture measurement compared to the indirect pressure measurement. Since different effects are measured deviations are to expect. It must therefore be concluded, that an exact match of local pressure readings and driver posture is not possible in all cases. Besides, the results indicate that the measurement of pressure variations can be used to evaluate changes in the driver's posture. Additionally it must be mentioned, that sonometry – even if being the better method to measure postural adaptations of the driver – cannot be used to routinely assess driver posture in realistic environments. This is because sensors need to be applied to the driver which is only possible in set-up measurement situations.

The assumption that changes in the trunk and low back are related to the seatback angle must be reconsidered. Posture and pressure values are significantly different for similar inclination angles for most test persons. The different behaviour compared to other studies may possibly be explained with the differences in the interaction between the low back and backrest (Figure 40). The position of the ischial tuberosities remains constant in the current study (situation I) because test persons did not leave the seat during the experiment. The repositioning of the test persons – the subjects gets out of the seat, the seatback angle is changed, and subjects sit down again (situation II) - in other studies (e.g. Goossens et al. [66]) certainly causes a change of the contact point between pelvis and seat pan, which leads to a different driver posture. If the angle is increased, a gap between the low back and the seatback occurs in situation I, because the seatback moves backward according to the pelvis. This decreases the force of the seatback ($F_{Seatback}$) acting against the rearward pelvis torque (M_{Pelvis}) and consequently allows a greater rearward rotation of the pelvis than if the pelvis was moved backwards (situation II).

Additionally, a difference in the amplitude of posture changes was observed. If a 'free' movement of the pelvis and low back was allowed, which appears when increasing the backrest angle with the person sitting in the seat, the amplitude would be greater than if the lower back was pushed forward ('guided') by a decrease of the seatback's inclination. The result is a reduced lumbar lordosis when the backrest is moved back in the initial position (Figure 37). It can be concluded, that the greater change of the lumbar lordosis produced by the backward torque of the pelvis cannot be reversed by a decrease of the backrest inclination, because the pelvis torque acts against the force applied by the backrest. This finding may be a direct cause of the measurement protocol which started with increasing the backrest angle. It cannot be said, if the same effect also appears when the backrest angle is reduced at the beginning. Further measurements are needed to underline the finding of this study.

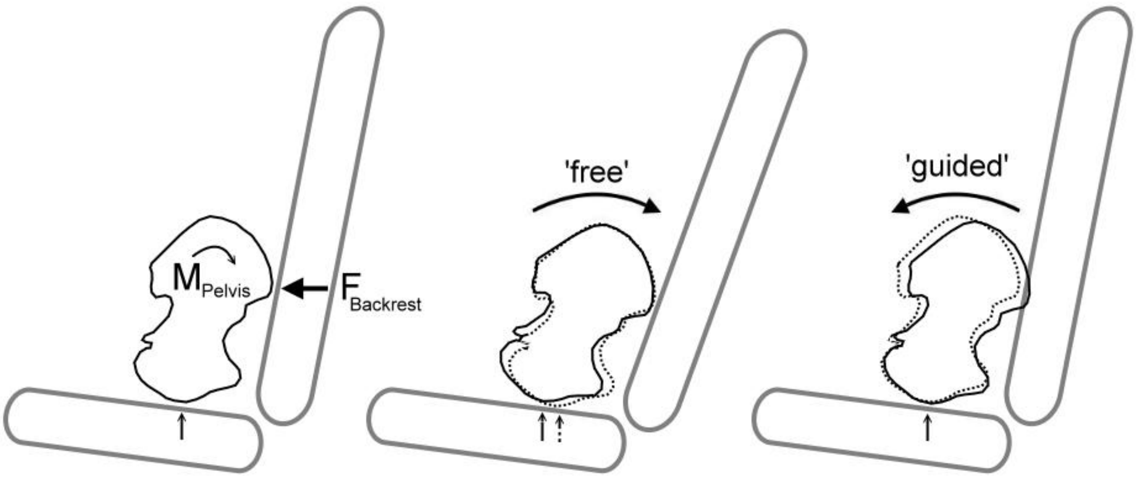

Figure 40: Pelvic posture in relation to the seatback angle and contact point at the seat pan. If the subject is repositioned between trials, i.e. the contact point of the ischial tuberosities is changed (situation II, dotted line); pelvic posture corresponds to seatback inclination. If the contact point is not changed (situation I, solid line), the pelvis inclination is increased compared to situation II.

A reduced lumbar lordosis is associated with an increased thoracic kyphosis [146, 147]. This would result in higher contact pressures at the low back and lower contact pressures at the trunk when comparing identical seatback inclinations. A tendency towards such a movement pattern can be seen in the data (Figure 37). Other behaviours are, however, also be found among the test population. It must be concluded that posture changing strategies vary among drivers. A similar result was found in a recent study (chapter 4.3), where two opposite strategies could be identified.

Besides posture, the contact pressure between seat and body can also be altered by small variations of the seatback angle. A continuous variation of the seatback angle could therefore help to partially decrease pressure especially under the buttocks which could help to reduce the occlusion of blood flow and degeneration of tissue associated with prolonged pressure under the buttocks [67]. High pressure is a main hard stressor increasing the total individual load and consequently decreasing seating comfort [62]. Another advantage of the proposed method is that the passive posture variation could be adapted to the individual driver behaviour instead of applying a fixed routine as seen in available methods (see chapter 4.3.1). The ability to predict increasing loads (chapter 3.3) offers additional opportunities for reducing individual loads. A load-reducing postural change could be triggered even before the subjective load limit is reached (compare Figure 4), if continuous information about the drivers posture modifications was available. This concept was not validated so far, therefore further investigations are needed. It must be noticed, however, that pressure values under the ischial tuberosities predominantly increased in the actual study, which would add additional load on the tissue. To some extent, the increase of pressure due to foam compression accounts for the observed increase. Besides, pressure is applied to a different area because of pelvic and upper body motion, which still produces some relief for previously loaded tissue.

A variation of the seatback angle of three degrees does not disturb the driver. All test persons stated that the passive inclination change did not affect their behaviour and were non-disturbing. This corresponds to the result that drivers are insensitive to seatback angle changes of up to three degrees [80]. The change of the backrest position was noticed by the test persons in this study, but was not reported to have any negative effect. The absolute backrest inclination was critical, however. The majority of test persons disliked the highest inclination of 24 degrees. It was said that due to the increased distance to the steering wheel, the load of arm and trunk muscles needed for stabilisation reached a critical value. It is therefore recommended to alter the seatback's inclination by not more than three degrees in both directions according to the self-chosen driving posture. Changes should not be made suddenly as in this study but by a smooth increment over a short period of time. Tests under real driving conditions and with the individually preferred seatback angle are needed to validate these findings. This is necessary because the experiments were performed under simulated conditions and with a predefined inclination angle, which may have influenced the results.

4.4.5 CONCLUSION

The absolute driving posture does not correlate with the seatback angle, if the inclination is changed during driving. A modification of current models is necessary to adequately describe spinal kinematics for continuous changes of the seatback angle. It must also be concluded that no uniform posture changing strategy exist among drivers. At least two different ways of adapting to different backrest inclinations were noticed. The strategies seemed to be constant for each person and may have their origin in the initial posture and seatback angle. Further investigations are necessary to validate these findings and to identify the exact causes.

Driver posture and contact pressures can be varied by changing the seatback's inclination minimally. This can help to limit individual loads, e.g. static pressure or muscle loads, associated with decreased seating comfort. Using continuous local pressure measurement in combination with the knowledge about physiological limits and the ability to predict stress-induced posture variations, subject-dependent alterations of load patterns could be generated by individual variations of the seatback angle. This could help to reduce common disorders associated with prolonged sitting. Additionally, information about driver behaviour could be used to optimize safety applications such as airbag deployment.

5 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The present thesis consists of a series of studies aiming at defining a method for the continious monitoring of driver posture, describing various aspects of the relation between seating comfort and system stress, and developing new methods to analyse and reduce the total individual load. All objectives could be realised. The main results are discussed in the respective chapters. The advantage of such a cumulative approach is the ability to incorporate the results of one study into another. However, general results are only attained if all aspects are merged. The aim of this chapter therefore is to reconsider the conducted studies and to define general results. This is done in three steps: First, the applied materials and methods are critically reviewed. Second, the proposed seating comfort model (chapter 1.2) is discussed and adapted to the results of the previous chapters. Third, the relevance of the results for the automotive industry is described.

5.1 MATERIAL AND METHODS

The posture of the driver was measured to evaluate typical movement patterns. The major aim of all studies was to investigate characteristic driver behaviour in prolonged driving. The tests conditions were defined to reflect the reality as close as possible. The focus was set on selecting a wide range of drivers and seat models, choosing test durations of up to three hours, and measuring in real-life situations:

– *Selecting a wide range of drivers and seat models*: The variety in anthropometry and age of the selected test drivers (14 persons; approx. 170 – 190 cm / 55 – 120 kg / 20 – 50 years) for the road trials reflects the typical driving population. Shortcomings are the small number of the subjects and the small percentage of female drivers. Additionally it must be said that the test population for the laboratory tests was rather young (20 – 30 years). Furthermore, eight different up-to-date seat models were used in the road trials. Standard- up to premium-class models were chosen as test seats. These classes reflect a great portion of sold cars and are dominantly used for extended-duration travel. Economy- to intermediate sized cars were consequently not used. Luxury models were simply not available. It can be concluded that the results are valid for a wide range of drivers and seats. Additional measurements could underline the results and enhance the understanding of stress-related movements and their relation to long-term seating comfort.

- *Choosing test durations of up to three hours*: Long-term seating comfort is regarded as the subjective impression appearing after 30 minutes or more of continuous driving [121]. Significant changes in the driver's response to prolonged seating are found for even longer durations. According to this, measurement time spans between two and three hours were chosen in the field studies. It was clearly seen that a test durations of two hours and more is needed to find significant stress-induced behaviour modifications. Longer periods are likely to increase the total load and thus induce greater postural adaptation. Because of the safety risks associated with such long driving periods, e.g. accidents caused by sleepiness or inattention, the time span for the tests was limited to three hours. Another advantage is that the found results can clearly be related to increasing loads instead of been regarded as the driver's conscious reaction to the end of the test drive. The changing test conditions in the final phase of the test drive, e.g. changing road types when approaching the final destination, is likely to influence the driver's behaviour. Because behavioural adaptations were not just seen at the end of the test drives but already after 60 minutes, they can be linked to influencing factors other than the testing conditions. A test duration of three hours as chosen in the main trials can consequently be regarded suitable and is recommended for further studies.
- *Measuring in real-life situations*: Tests in realistic environments are needed to assess the driver's behaviour in real driving situations. Even if the results attained in driving simulator studies seem to be valid [139], several finding indicate significant differences to real driving [96]. Nevertheless, the use of driving simulators increases rapidly due to technical advances and several constraints associated with road trials. The major shortcomings of field tests are the increased effort, the limitation of suitable measurement equipment and the difficulty to standardise the tests. Nevertheless, driving on a real road was chosen for the long-term studies due to the known result deviations compared to driving simulators. The testing protocol was optimized to reduce the effect of the disadvantages. Besides a short phase at the start and end of each test, the test persons drove on a highway all the time. Additionally, frequently used sections as well as the typical rush hours were avoided. Nevertheless, differences in traffic and weather conditions could not be eliminated

which might have an influence on the results. However, the use of a driving simulator is not an alternative, because the results are believed to be different to those attained in road tests. Simulated driving conditions were consequently only used to address certain specific questions, for example to validate additional measurement equipment (chapter 4.3) or to analyse the effect of applying passive motion to the driver which would have been to dangerous to be initially tested in a real life situation (chapter 4.4). Besides an increased effort and lacking ability to standardise tests, it must be recommended to conduct further measurements under realistic conditions.

Despite the described shortcomings, the study results are believed to reflect the characteristic driver behaviour. The corresponding parameter values of the two field studies indicate that the described driver behaviour is constant among drivers and is not limited to single seat models. Posture changes, posture adaptations and certain activity were found in all tests; the exact values differ however. It could also be shown hat the initial posture change of the driver takes place in real-life as well as simulated tests. Additionally, subjective discomfort rating could reliably be predicted by parameters describing posture modifications and it could be shown that the parameter values follow either a chi-square or an exponential distribution. Consequently, a certain predictability of the driver behaviour could be proven.

To be able to assess driver posture under the above defined constraints, an adequate measurement technique had to be selected. Among available systems suitable for the mobile analysis of the driver's motion under realistic test conditions, the sonoSens® monitor appeared to be the best choice (chapter 2.3). The setup of the system is easy and does not take much time, long-term measurements can be conducted without the need of additional equipment, and the device does not influence or distract the driver. Also the measurement results were proven to be reliable and valid (compare chapter 2.4). Nevertheless, the contact of the sensors with the backrest was identified to influence the results. Even if the likelihood of attaining false results is small, no figures could be given to quantify the exact influence. It is possible that the free movements of one or more sensors may be limited leading to a misinterpretation of the actual posture change. The described influence is limited to movements of the trunk and low back, because the upper sensors assessing the neck motion do not have contact with the backrest due to their position (Figure 41). The sensors L1 and R1 do only touch the headrest when it is adjusted to low and the driver leans his head backwards. This is usually not the case. The sensors L2 and R2 are not likely to touch the backrest because of the convex shape of the upper part of most backrests and the typical kyphotic trunk posture.

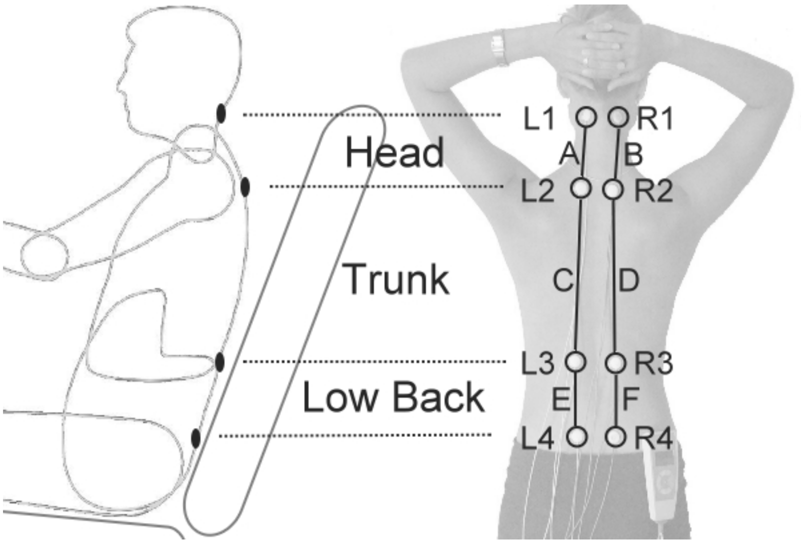

Figure 41: Standard sensor position to measure postural adaptations of head, trunk and low back. A detailed description of sensor positions and denotations is given in Figure 18 and Figure 26.

The following errors may occur caused by the contact between the sensors and the backrest:

– *Driver posture*: The calculated driver posture may differ from the actual posture, especially in the frontal plane. For example, a displacement of R3 in cranial direction would lead to a calculated side flexion to the left for the low back and to the right for the trunk, because the Frontal Index is calculated as the difference of the according left and right channel (compare Equation VII). A displacement of the same sensor in lateral direction had no effect, however. Also, errors in the calculation of the sagittal posture may appear, if both sensors in one level would be shifted simultaneously. This is unlikely to appear, however. The influence of such effects on the results is limited, because the absolute driver posture was only used to describe the initial posture change, which appeared in sagittal plane. Its use for the prediction of subjective ratings was limited to the standard deviation, which is not likely to be changed by single incidents.

– *Posture changes*: The contact of the sensors with the backrest may indicate additional posture changes, which actually did not take place. This can be the case if the posture is slightly changed and the sensors remain in position, e.g. when sliding with the pelvis forward. A slight pressure relief in the low back area could then cause a sudden sensor movement even without a respective lumbar or trunk movement. Moreover, the amplitude of posture changes could be detected wrong, if the sensor movement is limited by the contact with the backrest. Both cases will not affect the results of the studies greatly, however. Additional posture changes will not appear often in single measurements. Therefore, they will not effect the total number of posture changes, which has been found to be higher than 30. An influence on the maximum time between posture changes is possible. Such errors would only carry weight for the evaluation of single measurements and if the overall number of posture changes would be low. This must be regarded when interpreting the data but does not affect the general findings which are drawn from approx. 25 long-term measurements. Generally it can be said, that the evaluation of posture changes is not much affected by the influence of the contact, because when changing posture, the pressure at the sensors usually is relieved allowing free sensor movement.
– *Posture adaptations*: The contact of the sensors with the backrest may alter the evaluation of posture adaptations dominantly by decreasing the assessed amplitude. Because continuous trend-like movements are carried out without pressure relief at the backrest, the sensor movements are likely to be affected. If this is the case, the calculated amplitude as well as the time constant would be influenced. Presumably, the amplitude would decrease and the time constant would increase. In the first case, the attained results would be amplified. The second case would not affect the results much, because the calculated time constants already are many times longer than the interval length. The time-depended increase of both parameters would also not be different, because the probability of errors due to the contact is constant over time. In summary, the error may affect the evaluation of posture changes predominantly in terms of underestimating the parameter values.

– *Activity*: The influence of the described error on the calculated activity is believed to be comparable to the effect on the posture changes. It can be assumed that some small movements will not be measured because the movement of one or more sensors is restricted. Since this effect is not time specific but may rather appear throughout the measurement, the described results are not affected.

It would be possible to further evaluate the exact effect of the contact of the sensors with the backrest on the posture measurement. This can be achieved by measuring the relative movement of the sensors to the backrest. Because of the many influencing factors, attaining reliable results would require extensive effort and the development of a new or adaptation of an existing measurement technique. Regarding the assumingly small influence of this error on the results, such an effort does not seem to be legitimate. An exact quantification is necessary for the reliable interpretation of single measurement, however. An additional study must therefore be carried out to precisely define the influence of the contact of the sensors with the backrest on the measurement data.

It was shown that postural adaptations of the driver are related to subjective seating comfort impressions and that the driver behaviour can be predicted based on this relation. Basically it can be said that the driver uses postural adaptations to limit the total load. Additionally, various methods are described in the literature and in this thesis that can be used to passively induce driver movements. It is concluded that continuous information about the driver’s postural modifications could be used to optimise the settings of such systems. This can, however, not routinely be realised using the sonoSens® Monitor, because sensors need to be applied to the subjects skin. A seat-integrated system consisting of various pressure and inclination sensors was developed to demonstrate the possibility of continuously monitor driver movements without influencing driver behaviour. Generally it can be said, that analogue systems already exist and could have been used. The idea of developing a new system was to optimize the output and minimize the influence on the seat’s properties. Additionally, the new system was designed to be able to not only assess driver motion but also process the data and consequently provide an individual interaction with the driver. The latter aspects were not addressed in this thesis, however, and are only theoretically possible in the current state. Besides that, such attributes need to be kept in mind when discussing the idea of developing such a system. It could be shown that postural adaptations of the driver can be assessed with the proposed method and that a relation between pressure and posture changes exists. Nevertheless, an exact match of the results is not possible because of the different sensor location and measurement techniques. As described in chapter 3.3 subjective discomfort rating are dominantly related to the maximum time between posture changes and the standard deviation of the time constant of posture adaptations in frontal plane, i.e. side movements. The maximum times can easily be attained from pressure measurements, because a pressure relief is associated with posture changes. To assess the time constants of lateral movements in the same way as done in this work is most likely impossible, but a similar parameter may be derived from the variations between paired pressure sensors (compare Figure 34). Because of the limited measurements and the lack of long-term data, additional measurements are needed to validate this assumption. Another advantage is that head movements are not relevant for the prediction of subjective impressions, because they could not be assessed by seat-integrated pressure sensors. Consequently it must be concluded that the newly developed system must be further evaluated in future studies. The results attained here only indicate that an additional investigation is justified and worthwhile.

5.2 A NEW SEATING COMFORT MODEL

A major aim of the present work was the evaluation of the relation between system stress and seating comfort. It was proposed that the impact of soft and hard stressors results in a certain total individual load (Figure 2) which acts on the driver. The driver shows subjective as well as objective reactions caused by the total load. It was proposed that the amount of these reactions is related to the total load level and thus increases with increasing loads. These assumptions were thoroughly underlined by recent studies. No additional information could be added by this thesis, because only subjective and objective reactions but not the absolute load level was assessed in this work. Nevertheless, an increase of the total individual load with time is taken for granted, because it is sufficiently supported by several studies (compare chapters 1.2 and 1.3). It can therefore be concluded that a relation between increasing loads and the driver’s reaction exists (Figure 42), because increasing postural variations were clearly seen in the conducted measurements (chapter 3.2).

Based on the described relation between the load level and the driver’s response, a new seating comfort model was proposed. The basic assumption is that the total individual load caused by the influence of soft and hard stressors leads to stress-induced impression changes and stress-induced behaviour modifications which themselves are related to seating comfort and system stress (chapter 1.2). Seating comfort may consequently be evaluated by assessing the level of system stress. The results of the studies described in the present thesis emphasise this assumption. Comprehensive evidence can not be provided, however, due to the limited assessment of system stress. It could be proven that postural adaptations increase with time. This is interpreted as objectively measurable reaction of the driver to the increasing total individual load. Postural adaptations are believed to be one criteria symbolizing stress-induces behaviour modifications. The above assumed relationship between increasing loads and aggravating driver reactions could therefore be directly demonstrated. Similar reactions are being reported in the literature for postural adaptations [52] as well as for other parameters, e.g. the increase of lumbar stiffness and the back muscle EMG level [15], muscle oxygenation and blood flow of back muscles [45], an increase of the eye blink rate and decreased driving performance [87]. When regarding all references, it can be said that changes in the postural behaviour are related to the total load level (Figure 42).

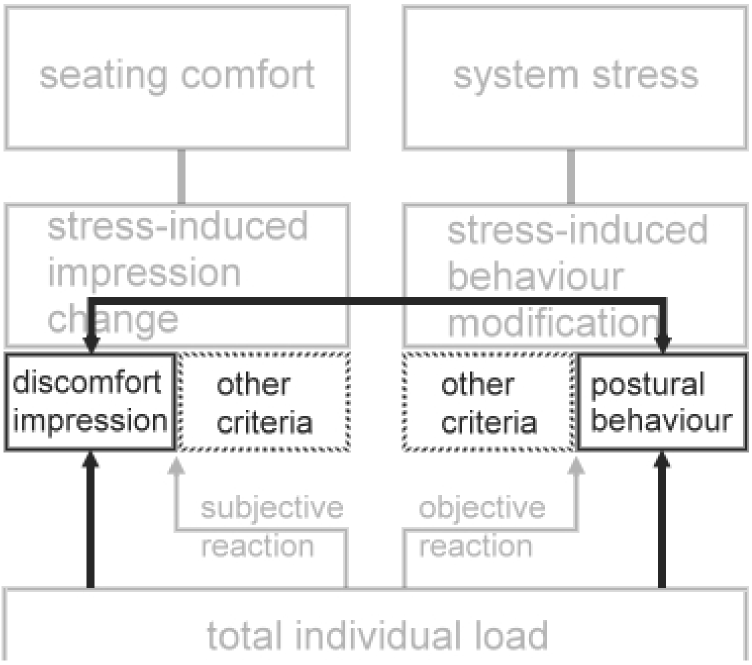

Figure 42: Relations between various parameters supported by the results of the studies described in this thesis (black arrows). Increasing individual loads lead to increasing subjective discomfort as well as increasing postural modifications. Both parameters symbolize stress-induced impression changes or behaviour modifications, respectively. The findings can be used to indirectly confirm the proposed relation between seating comfort and system stress (chapter 1.2).

In addition to this, subjective discomfort ratings could be reliably predicted by stress-induced posture changes. Direct evidence for the proposed relation between system stress and seating comfort was not provided, however. Nevertheless it is believed that such a relation exists. On the one hand, this is because an indirect verification is given by the results of this thesis. The fact that the overall seating comfort is related to subjective discomfort is well documented in literature and thus widely accepted [39]. Additionally, the level of system stress can be derived from stress-induced behaviour modification, from which one, i.e. postural changes, was assessed here and linked to subjective discomfort impressions. Some evidence for the relation of seating comfort and system stress could therefore be provided in this thesis; even if the absolute levels of both variables were estimated only by partially assessing the influencing factors, i.e. subjective discomfort ratings and postural behaviour (Figure 42).

Contrary to the assumption at the beginning of this thesis, the above described findings are only true for the assessment of long-term seating comfort. Whether the model is also valid for short-term seating comfort, i.e. the subjective impression for sitting periods of up to 30 minutes [121], cannot be said. It is assumed that this is not the case, because dominant postural variations appeared after longer sitting periods. As a result of the described findings, the proposed model must be adapted (Figure 43).

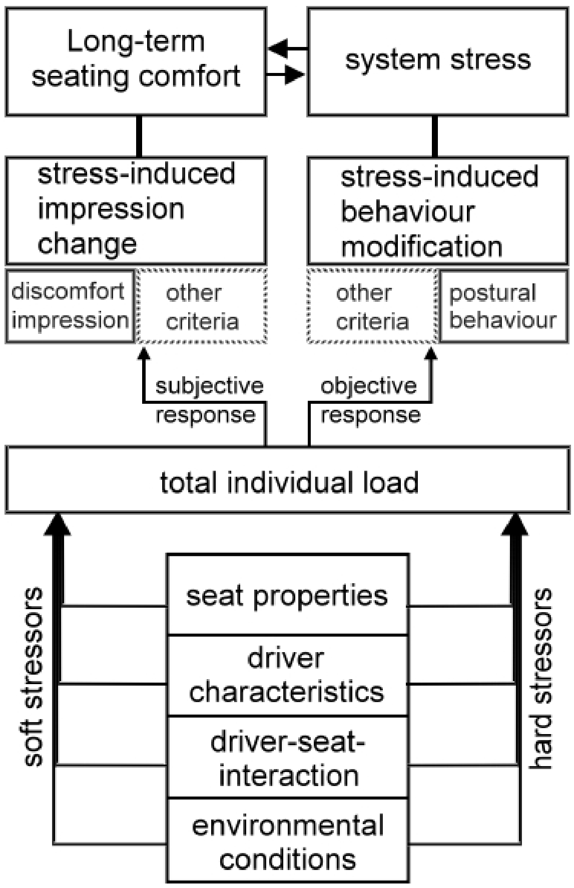

Figure 43: Detailed model for the description of the genesis of long-term seating comfort and its objective evaluation (adapted from Figure 3).

The main assumptions could be underlined, however. Generally it can be concluded that the level of long-term seating comfort seems to be related to the level of system stress. Long-term seating comfort can be estimated by subjective discomfort impressions, system stress by stress-induced posture modifications. Because of the direct relation, long-term seating comfort can objectively be assessed from system stress. A more reliable estimation of long-term seating comfort may be attained by including additional criteria into the calculation of the level of stress-induced behaviour modifications and thus attaining a more precise description of the level of system stress. The definition of seating comfort presented in chapter 1.2 needs to be adapted to the following:

LONG-TERM SEATING COMFORT IS THE SUBJECTIVE RESPONSE TO THE TOTAL LOAD GENERATED BY THE IMPACT OF SOFT AND HARD STRESSORS ON THE INDIVIDUAL.

Furthermore, the following can be defined:

LONG-TERM SEATING COMFORT IS DIRECTLY RELATED TO SYSTEM STRESS.

SYSTEM STRESS IS THE OBJECTIVE RESPONSE OF THE INDIVIDUAL TO THE TOTAL LOAD AND CAN BE DERIVED FROM STRESS-INDUCED BEHAVIOUR MODIFICATIONS.

These definitions led to the development of a basic model describing the relation between the total individual load, system stress and long-term seating comfort (Figure 44).

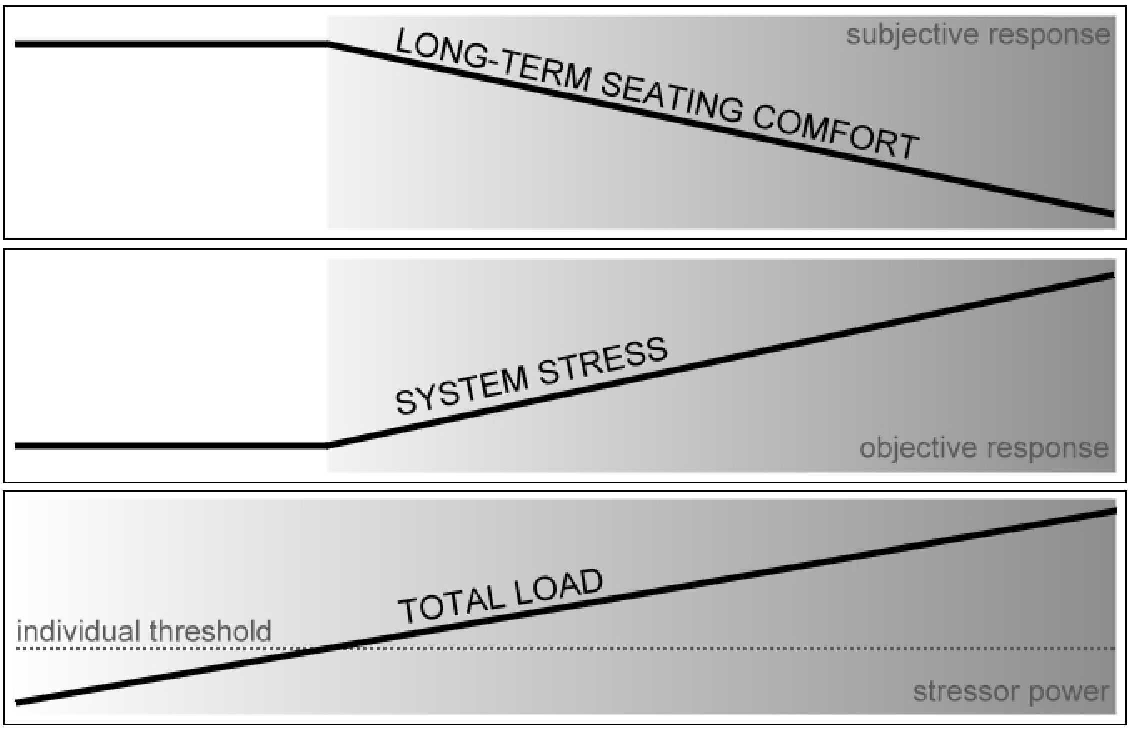

Figure 44: Model for the basic description of the relation between the total individual load, system stress and long-term seating comfort.

Because postural adaptations of the driver for prolonged sitting periods were assessed under field conditions, additional aspects can be said regarding the postural behaviour. It was found that all drivers change their posture throughout the time. Postural variations can be described by posture changes, posture adaptations and activity. Moreover, an initial posture change was found for all test persons independently of the seat model and was mainly caused by posture adaptations. Some movements are related to subjective impressions, some are task-oriented. It must therefore be concluded that comfort-related driver behaviour exists in addition to task-oriented behaviour. It is certainly possible that other categories are present besides the two described above. A more general description can not be given at this point, because only upper body movements were assessed here. With the current knowledge, the following can be concluded:

DRIVER MOTION IS THE SUM OF TASK-ORIENTED, COMFORT-RELATED AND FURTHER MOVEMENTS.

5.3 RELEVANCE FOR THE AUTOMOTIVE INDUSTRY

The results described in this thesis can directly be used by the automotive industry, mainly in terms of optimizing existing products and developing new systems. They can also be applied to related fields, e.g. the commercial vehicle and the office chair industry. Details are described for automotive applications only; they can however easily be adapted to other fields. In the following section, the main results are outlined and their practical relevance described:

– *Measurement of the driver's posture and movement*

  The presented method for the measurement of the driver's posture and postural adaptations can directly be used in field test. No additional equipment is necessary to reliably assess driver movements in realistic environments. Also no adaptations of the seat and car interior are needed. The method can therefore by applied in test drives which are carried out frequently in the development phase of new seating systems. Additionally, the proposed method for data processing and evaluation can directly be used to analyse the data. One the one hand, the results attained from the data provide a basic understanding of the driver's postural adaptations in long-duration travel. This can help to design seats which allow both task-oriented as well as comfort-related driver movement. On the other hand, information about the driver's posture can be used to optimize the ergonomics of the car interior. The assessment of typical movement patterns of test persons in a certain car / seat helps to identify problem areas. By applying the described method, the typical use of the car by a test population can be objectively analysed and utilised for the optimization of the interior. Moreover, the driver's response to adapted seat features, e.g. a changes backrest shape or a different lumbar support mechanism, can directly be measured. This allows for a fine tuning of several features and thus the performance enhancement of the complete seat.

  The main advantage for the automotive industry is the possibility to easily assess new data describing the driver's postural behaviour in real driving situations. The method can routinely be applied in the development process.

– *Evaluation of long-term seating comfort*

One main result of this thesis is a basic description of the genesis of long-term seating comfort and its influencing parameters. The definitions and the provided models expand the knowledge about this topic. The increase of seating comfort is a major goal for the seat development. A general definition as given here can help to find new means for the optimisation of current and future seat models.

Additionally, it is now possible to objectively evaluate long-term seating comfort based on the assessment of driver movements. From the results, existing seat models can be rated and compared. Also, the progress of the development process can be measured. This enables engineers to identify benchmark seats, rate the performance of their product in comparison to competitors, and thus attain important information about further optimization potential. The importance for the automotive industry consequently is the ability to objectively analyse and evaluate long-term seating comfort in realistic environments.

– *Prediction of long-term seating comfort*

It was demonstrated that subjective ratings can be predicted by certain parameters describing postural adaptation in prolonged driving. This knowledge can be utilised to estimate the comfort perception of the seat’s target group and thus assess whether the defined quality standards are met. By using the proposed method subjective comfort evaluations, which still are the most widely used seat evaluation practice, can be supplemented by objective parameters.

Moreover, a description of comfort-related postural adaptations is provided. This can be employed to model and predict typical driver movements. Also, the knowledge can be implemented in existing human models aiming at predicting seating comfort. The currently used models can only be used to evaluate the applied load in static and short-term conditions or estimate the influence of vibrations. Broader applications are possible with the described findings, enhancing the possibilities of using virtual models for the optimisation of seat models and thus reducing the number of iterations and the development time.

– *Reducing the total load level*

The results of this thesis clearly indicate that the driver uses postural applications to temporarily reduce the total individual load and to maximise the time he or she can comfortably sit in a car seat. Information about the driver's postural adaptations can therefore be utilised to optimise comfort-relevant seat features, e.g. lumbar massage. This can be done by passively inducing postural adaptation using mechanical or pneumatical systems. Such systems are available in modern car seats; their optimal settings, i.e. frequency and amplitude, are not well described however. This leads to several different approaches. Using the information provided here, a fine-tuning of available systems is possible, because typical movement frequencies and amplitudes of the driver are described. An approach which would simply imitate the driver's typical movements could assumingly help to reduce the loads associated with prolonged driving and thus increase the long-term seating comfort. Additionally, it seems to be possible to predict the point in time where posture changes are initiated by the driver, if informations about driver movements is continuously available. Load-reducing actions could then be initiated even before the driver itself feels the need to adapt his posture. This could further increase the efficiency of available systems. Additionally, an individual fine-tuning of comfort-enhancing features based on continuous posture monitoring would possibly increase the compliance of the users.

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EHRENWÖRTLICHE ERKLÄRUNG

Ich erkläre hiermit, dass mir die Promotionsordnung der Fakultät für Sozial- und Verhaltenswissenschaften bekannt ist.

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Weder früher noch gegenwärtig habe ich an einer anderen Hochschule eine Dissertation eingereicht. Ich versichere, dass ich nach bestem Wissen die reine Wahrheit gesagt und nichts verschwiegen habe.

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