AN INTEGRATED HUMAN FACTORS APPROACH TO DESIGN AND EVALUATION OF THE DRIVER WORKSPACE AND INTERFACE: DRIVER PERCEPTIONS, BEHAVIORS, AND OBJECTIVE MEASURES

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ABSTRACT

An ergonomic driver workspace and interface design is essential to ensure a healthier and comfortable driving experience in terms of driver perceptions, postures, and interface pressures. Developing more effective methods for driver-side interior design and evaluation, hence, requires thorough investigation of: 1) which perceptual responses are more relevant to ensuring ergonomic quality of a design, 2) the interrelationships among perceptual responses and objective measures, and 3) whether current assumptions regarding driver behaviors, and tools for specifying these behaviors, are valid for the design and evaluation. Existing studies, however, have rarely addressed these topics comprehensively, and often have been conducted with unsubstantiated assumptions. In contrast, this work sought to address these topics in a way that jointly considers characteristics of driver perceptions, behaviors, and objective measures to develop an improved design and evaluation methodology for driver workspace and interface, and that can also investigate the validity of implicit assumptions regarding perceptual relevance and drivers' behaviors.

The first part of this work investigated drivers' perceptions in relation to driver workspace design and evaluation. Specifically, it examined the efficacy of several perceptual ratings, when used for evaluating automobile interface design. Results showed that comfort ratings were more effective at distinguishing among interface designs, in contrast to the current common practice of using discomfort ratings for designing and evaluating interface designs. Two distinct decision processes to relate local to global perceptions were also identified (i.e., global comfort as an average of local comforts, and global discomfort predominantly influenced by maximal local discomforts). These findings were observed consistently across age and cultural groups. In

addition, this work provided empirical support for an earlier hypothetical comfort/discomfort model, which posited comfort and discomfort are complementary, yet independent entities.

In order to facilitate the integration of driver perceptions and dynamic behaviors into driver workspace design and evaluation, the second part of this work clarified the relationships between perceptual ratings and various types of driver-seat interface pressure. Interface pressure was found to be more strongly related to overall and comfort ratings than to discomfort ratings, which is also in marked contrast with existing work that has focused on identifying association between discomfort and interface pressure. Specific pressure interface requirements for comfortable driver workspace design and evaluation were also provided.

Lastly, this work specified more rigorous driving postures for digital human models (DHMs), based on actual drivers' perceptions, postural sensitivity, and static behavioral characteristics, to facilitate proactive design and evaluation that enables cost/time efficient vehicle development. Drivers' behavioral characteristics observed in this work were applied to the driver workspace design. First, postural sensitivity obtained by using a psychophysics concept has been applied to determination of core seat track ranges. Second, postural data have been used: 1) to review relevant industry standards on driver accommodation, 2) to investigate whether driving postures are bilaterally asymmetric, 3) to provide comfortable joint ranges, and lastly 4) to identify drivers' postural strategies for interacting with a vehicle.

Overall, this work identified three important behavioral characteristics, specifically a bilateral imbalance in terms of interface pressure, bilaterally asymmetric joint posture, and postural strategies identified by cluster analysis. Such characteristics can be embedded in DHMs to describe more accurately actual driver behaviors inside a driver workspace, which is deemed to be a fundamental step to improved virtual ergonomic vehicle design and evaluation. In addition, the strategy-based classification method used in this work can be extended to simulate and predict more complex human motions. Practical and fundamental findings of this work will facilitate efficient and proactive design and evaluation of driver workspace and interface, and will help provide a healthier driving experience for a broader range of individuals.

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I dedicate this work to my parents and in-laws who have waited so long for my study to finish successfully, and also to my wife, Hyung Sun Kim, who, despite unfamiliar living environments, supported, encouraged me in so many ways, and delivered the most precious, 8.2-lb gift, Minseok (Alex), on July 28th, 2007.

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Chapter 1: Overview

1. Introduction

To cope with customers' increasing need for and expectation of improved vehicle comfort, car makers have been seeking design and evaluation methods by which they can develop quality vehicles in more effective and proactive ways. Of particular importance, an ergonomic driver workspace design is essential to ensure a healthier and comfortable driving experience and to provide an improved overall vehicle quality for a wide range of people. A driver inside a driver workspace interacts in a seated posture with the automobile through driver-vehicle interfaces, and shows diverse perceptions and behaviors during the interaction. To better accommodate drivers' needs and expectations, the driver workspace and interface should thus be designed and evaluated with a thorough consideration of drivers' perceptions and behaviors associated with the driving task. Ergonomic quality of a driver workspace is largely determined by such factors as interior design (e.g., fit, support, and aesthetics), package geometry (i.e., harmonic placements of parts), postural comfort, interface pressure, and vibration.

Seated postures in general have been regarded as potentially unhealthy, and considered as one of the major contributing factors for several musculoskeletal disorders (e.g., in the neck, shoulder, back; Ebe and Griffin, 2001; Kelsey and Hardy, 1975; Magnusson and Pope, 1998; Schneider and Ricci, 1989). Due to frequent exposures to seated postures in the car (Cho and Yoon, 2001; Rajput and Abboud, 2007), comfort inside a driver workspace has become an important issue. Compared to the general public, the risk of low back pain is higher among vehicle drivers (Heliovaara, 1987), with the vibration between the road and vehicle as a major factor (Pope et al., 1986). Similarly, an epidemiological study by Gyi (1996) showed that people exposed to over four hours of driving per day were more than twice as likely to suffer from low back pain compared to those with over four hours of sedentary work per day. Among other factors, a driver's perceptions in a seated posture have been shown to be influenced by whether there is adequate support for preferred driving postures (Motavalli and Ahmad, 1993; Reed et al., 1994), even distribution of contact pressure (Helander et al., 1987; Sanders and McCormick, 1987), and mitigated vibration (Johnson and Neve, 2001). Subjective ratings and objective measures (e.g., joint angles, pressure, electromyography) have been used to improve sitting comfort and discomfort (de Looze et al., 2003).

As psychological constructs, similar to ‘fatigue’ or ‘effort’, comfort and discomfort have been suggested to require treatment as different and complementary entities in ergonomic evaluations and interventions (Helander and Zhang, 1997; Sauter et al., 2005; Zhang et al., 1996). Similarly, sitting comfort needs to be divided into sitting comfort and discomfort as each is placed at a different stage of human needs (Hancock and Pepe, 2005), and comfort and discomfort are regarded as not merely opposing constructs (Zhang et al., 1996). Since drivers perceive both comfortable and uncomfortable feelings in driving postures (Hanson et al., 2006), their perceptions of comfort and discomfort should be separately addressed. In addition, a driver’s sitting comfort needs to be distinguished from sitting comfort in home or office chairs, or in the non-vehicular workplace (Andreoni et al., 2002) due to their contextual differences (e.g., confined space, controlling task, vibration transmission, and visuomotor demands). Likewise, the driver’s and other in-vehicle occupants’ perceptions should be distinguished. The driver takes relatively more restricted and prescribed postures and needs more continuous visuospatial attention than the remaining occupants. Not considering these postural and attentional differences when designing experiments may lead to invalid measures of drivers’ sitting comfort and discomfort. Further, valid quantification of in-vehicle sitting comfort / discomfort requires that seats, seat belts, package geometries, driving postures, visual demands, and vibration dose be set close to actual driving situations.

Short-term and long-term sitting comfort / discomfort need to be distinguished. Sitting discomfort increases over time while sitting comfort tends to remain constant (Helander and Zhang, 1997). Increased discomfort seems largely associated with fatigue, which can result from one hour of driving (Uenishi et al., 2002). Gyi and Porter (1999) recommended at least two hours of testing to clearly assess discomfort (fatigue). However, fatigue in seated postures has diverse contributing factors, and can actually result from other sources than the seat. Even when the seat is a major factor, other aspects, rather than the seat’s function in providing support and distribution of body pressure, could be the major sources of any unpleasant feeling in sitting (e.g., aesthetics, micro-climate).

To promote musculoskeletal health, postural movement is essential. Several studies have shown that postural changes provide physiological benefits, such as relief of muscular fatigue (Dhingra et al., 2003; Jenny et al., 2001; Preuschen and Dupuis, 1969). In order to describe drivers' dynamic behaviors and the seat's supporting function, interface pressure is commonly used as an objective measure in the study of seat quality in terms of minimal discomfort, but evidence suggests that more careful consideration is needed for proper use given its limitations (e.g., creep, hysteresis) and potential confounders (e.g., a seat's sweat evaporation characteristic, noise, light, and air temperature). Aside from such technical issues, the means by which pressure data are integrated into subjective responses remains unclear.

Different weightings of interface pressure or feelings at local body parts may be used by individuals in determining global levels of comfort and discomfort. While all the local body parts, regardless of whether they make contact with a seat, affect whole body perceptions, each local body part and local interface pressure are expected to weigh differently in the decision process used to obtain global perceptions. Therefore, it will be valuable to investigate whether some local body parts are more predominant in this process, and whether there is an ideal ratio in terms of pressure distribution among local surface areas of the car seat.

Physiological changes occur with age, such as slower reaction times, loss of muscular strength and dexterity, increased susceptibility to fatigue (Warnes et al., 1993), and loss of joint flexibility (Haywood et al., 1991) and visual acuity (Eby and Kantowitz, 2006; Nicolle and Abascal, 2001). Hence, older individuals might have different needs for driver-vehicle interface design, as these physiological changes are likely to adversely affect driving experience and posture. Less is known, however, whether there are differences between age groups in the perceptions of comfort and discomfort of sitting experience and/or in their driving posture.

Perceived comfort is assumed to be distinctive among consumers of different regions (Kolich and Taboun, 2004). Indeed, regionally different specifications have been used for car seats to account for regionally different preference for car seats (Leenslag et al., 1997). However, it remains unknown whether there are differences in effective subjective ratings of the improved seat-interface design for respective cultural groups and differences in relating local-to-global perceptions between cultural groups.

As one aspect of a driver's comfort, postural comfort plays an important role in determining driver workspace quality. In the age of virtual prototyping, the importance of accurately positioning a digital human model (DHM) in a virtual driving workspace has increased (Hanson et al., 1999), as it is the fundamental step for subsequent ergonomic tasks in terms of drivers' postural comfort, alertness (Diffrient et al., 1990), reach, visibility (Chaffin, 2007), easy operation, and collision safety. DHM tools provide such benefits as reduction of design/engineering costs and time, and improvement of ergonomic quality (Chaffin, 2005, 2007; Hanson et al., 1999; Park et al., 2004; Porter et al., 1993). A large body of work on driving postures has been reported, focusing on measurement and prediction of driving postures and determination of comfortable joint angle ranges (Andreoni et al., 2002; Bubb, 1992; DIN, 1981; Dupuis, 1983; Grandjean, 1980; HdE, 1989; Park et al., 2000; Porter and Gyi, 1998; Rebiffé, 1969; Vogt et al., 2005). However, no study has effectively addressed the potential problem of postural sensitivity, or the extent to which people might feel different when their seated postures are slightly changed by the movement of seat location (and, hence hip joint center location). This assessment is important, in that a quantification of sensitivity can be used to better or alternatively locate a DHM, and to effectively cope with common space or mechanical constraints arising during vehicle design. In addition, most studies have assumed bilateral symmetry of driving postures (e.g., Porter and Gyi, 1998; Reed et al., 1999), though other recent studies have shown different results (Andreoni et al., 2002; Hanson et al., 2006). Hence, additional study is needed to specify driving postures more rigorously.

Current methods for ergonomic vehicle design rely heavily on the Society of Automotive Engineers (SAE) recommended practices, such as SAE J1517 (Driver Selected Seat Position), SAE J941 (Drivers' Eye Locations), and SAE J826 (Devices for Use in Defining and Measuring Vehicle Seating Accommodation). When applying these practices, however, caution is warranted. In some cases SAE practices, though revised, are based on studies performed in the 1960's. This ignores changes in overall anthropometry that have occurred since then, and in most cases a gender-mixed population has been used for their guidelines, both of which increase the possibility that extremes in the population may not be well accommodated. For example, it should be verified whether the American female 5th and male 95th percentiles, regarded as appropriate extremes of population to take into account in automotive design (Hanson et al., 1999; Reed et al., 1994), are adequately accommodated by guidelines and equations provided by SAE recommended practices.

In order to compare alternative driving postures during the evaluation of driver workspace designs, and to ensure the reliability and quality of the final driving posture of a DHM, it would seem necessary to provide recommended joint angles, with which expected levels of perceptions are explicitly specified. In other words, it should be clarified whether recommended joint angles, based on ‘preferred posture’, are associated with sufficiently high levels of comfort and low levels of discomfort. In addition, a set of recommended joint angles should be available that can completely describe comfortable driving postures as well as maintain compatibility with relevant standards (e.g., SAE standards). Recommended ranges of joint angles should also be specified for different vehicle classes, and potential effects of driver attributes (e.g., age, gender, and stature) on driving postures remain to be clarified. DHM tools are acknowledged not to have a desirable level of sophistication or accuracy with respect to human posture and movement simulation (Chaffin, 2005, 2007; Chaffin et al., 1999). To increase the validity of ergonomic design and analysis using a DHM, characteristics of human behaviors in static posture and movement should be embedded in the DHM tool (Chaffin, 2005). In addition, it should be addressed whether there is a difference between comfortable and preferred driving postures, to ensure that the design of a driver workspace allows drivers to feel sufficiently comfortable in their preferred postures.

Though seated in a confined space, drivers adopt diverse driving postures. Even two drivers with a similar body size may sit in different postures (Kolich, 2007). Besides movements for reaching and controlling, drivers change their driving posture intermittently to reduce discomfort induced by postural fixity (Akerbloom, 1948; Andreoni et al., 2002; Dhingra et al., 2003; Jenny et al., 2001). Individual attributes (e.g., age, gender, and anthropometry) and vehicle factors (e.g., vehicle class, interior geometry, and driving venue) have been demonstrated to affect drivers’ reaching or sitting postures (Chaffin et al., 2000; Hanson et al., 2006; Park et al., 2000; Reed et al., 2000). Several distinct reaching or posturing techniques that might be involved in adopting a driving posture can be an additional source of this variability. If various driving postures, however, can be classified by inherent similarity, errors in specifying and predicting driving postures are likely reduced. Several studies have addressed sitting strategies (Andreoni et al., 1999; Andreoni et al., 2002; Beach et al., 2005), but their postural specifications do not effectively cover the entire driving posture. Hence, an expanded study on drivers' postural strategies is warranted to: 1) determine how many strategies are adopted by drivers for their driving postures, 2) investigate whether these strategies are associated with driver attributes (e.g., age, gender, stature), and 3) specify whole-body postures by the strategies identified.

In summary, designing an ergonomic workspace is a challenging and complex task that must meet multiple requirements, and consider the design trade-offs to harmonize drivers and vehicle. Within a confined space where vibration is generally present, the driver workspace is required to accommodate diverse groups of individuals by firmly supporting and physically fitting their preferred postures as well as allowing freedom to change postures. Hence, to develop a more effective driver-vehicle interface design and evaluation methodology, it seems necessary to investigate inter- and intra-relationships between drivers' perceptions, behaviors, and relevant objective measures, and to integrate them into the driver workspace and interface design and evaluation processes.

2. Objective and specific aims

The current work sought to develop methods for ergonomically designing and evaluating the driver workspace and interface. The overall objective of this work was threefold. First, it investigated the efficacy of several perceptual ratings, between diverse groups of people, when used for evaluating driver workspace and interface design. Second, it clarified relationship between perceptual ratings and interface pressure in order to integrate drivers' perceptions and behaviors into design guidelines. Third, it specified more empirically and ergonomically valid driving postures for digital human models (DHMs), based on actual drivers' perceptions, and behaviors, in order to facilitate proactive design and evaluation that enables cost/time-efficient vehicle development. Specific aims were as follows:

1. Construct a multiple-measures protocol that allows for a more comprehensive assessment of driver perceptions and behaviors. Toward this end, the current work incorporated a range of variables (i.e., vehicle factors, driver attributes, perceptions, behaviors, and objective measures). Driver perceptions were measured using diverse approaches, including comfort, discomfort, overall perception, alertness, design preference, and postural sensitivity. Comfort and discomfort were separately measured here to take into account recent findings in the scientific literature (i.e., they are complementary, yet independent entities, and are associated with different stages of human needs). Detailed measures of interface pressure and postures were included to describe drivers' dynamic and static behaviors.
2. Investigate effects of driver attributes (age, gender, culture, or stature) and vehicle factors (vehicle class, driving venue, or seat quality) on subjective ratings and objective measures (interface pressure, and driving posture).
3. Compare experimental results between lab and field settings to determine if and how close sitting comfort / discomfort rated in a relatively low-fidelity laboratory-based simulator environment corresponds to comparable results in a field environment.
4. Develop practical applications and provide design guidelines using experimental results, whenever possible.
5. Investigate which, among several, subjective rating schemes might be the most effective for use in designing and evaluating car seats and interior geometries, and what relationships exist among these schemes.
6. Identify the processes involved in determining whole-body perceptions from local body perceptions of comfort and discomfort.
7. Validate Zhang et al. (1996)'s hypothetical model of sitting comfort and discomfort (orthogonality between comfort and discomfort) using rating results.
8. Determine how well overall vehicle comfort is explained by seat comfort.
9. Determine the effectiveness of a set of 36 interface pressure variables (pressure levels, contact areas, and ratios of local to global pressure), which was derived for assessing, predicting and improving the sitting experience in terms of comfort, discomfort and/or overall ratings across a range of individual statures.

10. Determine what interface pressure levels and ratios are associated with a better sitting experience.
11. Compare pressure levels or ratios between two groups of people that have different levels of reported sitting comfort and discomfort.
12. Investigate effects of stature, vehicle class (sedan and SUV), seat, and venue (laboratory and field settings) on the set of pressure variables.
13. Investigate whether aging affects 1) the efficacy of each rating for use in designing and evaluating driver workspace, 2) the experiential difference between sedan and SUV settings, and 3) the processes of determining whole-body perceptions from local body perceptions of comfort and discomfort.
14. Investigate associations between interface pressure measures and three subjective ratings for two age groups.
15. Investigate whether cultural difference between North Americans and Koreans affects 1) the efficacy of each rating for use in designing and evaluating driver workspace, 2) the experiential difference between sedan and SUV settings, and 3) the processes of determining whole-body perceptions from local body perceptions of comfort and discomfort.
16. Determine if and to what extent a self-selected postural rating was affected by alterations in hip joint center (HJC).
17. Review two SAE recommended practices (i.e., J1517, J941), which mainly aim at accommodating 95% of a gender-mixed population, compare them with the results from this study, and suggest any adjustments requirements.
18. Propose a method combining SAE practices and the adjustments that could be used to locate the seat track and the driving posture more accurately and to accommodate a wider range of people.
19. Provide recommended driving postures with specific intended application to DHMs.
20. Provide comfortable ranges (angles) of all major joints, definitions of which are compatible with the pertinent standards.
21. Determine whether there are effects of vehicle factors (class, venue, seat) and driver factors (age, gender, stature) on joint angles.
22. Determine whether driving postures are symmetric.

23. Generate recommended ranges of joint angles, for two vehicle classes (sedan and SUV), that account for reported levels of postural comfort and discomfort.
24. Identify drivers' postural strategies for each of two vehicle classes (sedan and SUV).
25. Examine whether these postural strategies can be clearly divided by driver attributes (i.e., age, gender, and stature).
26. Use any identified strategies to increase accuracy of specification and prediction of driving postures.
27. Facilitate ergonomically valid proactive design and evaluation by specifying driving postures more accurately.

3. Literature review

3.1. Definitions of comfort and discomfort

Though the term 'comfort' is commonly used, there is still substantial debate in the literature regarding its definition (Bishu et al., 1991; Helander and Zhang, 1997; Richards, 1980; Zhang et al., 1996). Likewise, automobile seat comfort, as a science, still lacks a coherent, universally accepted definition (Baber, 2002). According to de Looze et al. (2003, p. 986), issues on comfort that are not debated are as follows:

- Comfort is "a construct of a subjectively-defined personal nature".
- Comfort is "affected by factors of a various nature (physical, physiological, psychological)".
- Comfort is "a reaction to the environment".

Merriam-Webster Online Dictionary (2007) defines comfort as a) "a feeling of relief or encouragement", b) "contented well-being", or c) "a satisfying or enjoyable experience", while Allen (1990) described it as a range of states from relief, well-being, and satisfaction to making life easier. The definition by Slater (1985) is "a pleasant state of physiological, psychological, and physical harmony between a human being and the environment" (p. 4). Richards (1980) emphasized that comfort is a state involving a sense of well-being, in response to an environment or situation. Summers (2000, p. 262) divides comfort into an emotional aspect, "a feeling of being more calm, cheerful, or hopeful after you have been worried or unhappy", and a physical aspect, "a feeling of being physically relaxed and satisfied, so that nothing is hurting you, making you feel too hot or cold etc". In summary, comfort is, as a subjectively-defined multi-faceted construct, a positive feeling in the form of relief, encouragement, enjoyment, well-being, satisfaction, and/or pleasantness that results from interactions with the environment.

Discomfort has been widely used and generally accepted as a proxy or risk factor for musculoskeletal disorders, and discomfort measures have been commonly used to evaluate ergonomic interventions (Sauter et al., 2005). It is also known that discomfort relates to poor biomechanics and circulation, restlessness, and fatigue (Zhang et al., 1996). Several definitions of discomfort are as follows:

- "Mental or physical uneasiness" (Merriam-Webster, 2007)
- "Lack of ease; lack of comfort" (Allen, 1990, p. 332)
- "A generic and subjective sensation that arises when human and physiological homeostasis, psychological well-being, or both, are negatively affected" (Shen and Parsons, 1997, p. 442)
- "An absence of comfort or ease; uneasiness, hardship, or mild pain" (Discomfort, 2007)
- "A feeling of slight pain or of being physically uncomfortable" (Summers, 2000, p. 383)
- "A feeling of embarrassment, shame, or slight worry" (Summers, 2000, p. 383)

3.2. Relationship between comfort and discomfort, their factors and models

Quite different viewpoints are also found in the literature regarding the relationship between comfort and discomfort, and indicating an overall lack of consensus:

- "In common parlance, comfort may refer to both comfort and discomfort" (Zhang et al., 1996, p. 377).
- "Comfort and discomfort need to be treated as different and complementary entities" (Zhang et al., 1996, p. 377).
- Comfort is "absence of discomfort" (Branton, 1966; Hertzberg, 1972, p. 41).
- Comfort "does not necessarily entail a positive affect" (Branton, 1966, p. 205).
- Comfort is one side of a continuum ranging from extreme comfort through a neutral state to extreme discomfort (Shackel et al., 1969).

As psychological constructs, similar to 'fatigue' or 'effort', comfort and discomfort more recently have been suggested to require treatment as different and complementary entities in ergonomic evaluations and interventions (Sauter et al., 2005; Zhang et al., 1996). Zhang et al. (1996) found that sitting comfort and discomfort are orthogonal (Figure 1), not merely the opposite of each other, and therefore should be treated as independent entities. They observed that discomfort is related to biomechanics and fatigue factors, whereas comfort is related to a sense of well-being and aesthetics. Similarly, Hancock et al. (2005) showed that discomfort relates to a lower-level need (prevention of pain), and comfort, as one of attributes inviting positive affect, relates to a higher-level need (promotion of pleasure). Paul et al. (1997) proposed the "nurturing and pampering paradigm" (p. 504), and claimed that different strategies should be used for reducing discomfort (nurturing) and increasing comfort (pampering) in the workplace. Based on these authors' views (Paul et al., 1997; Sauter et al., 2005; Zhang et al., 1996), it is a reasonable conclusion that these two different types of constructs should be investigated using two separate instruments.

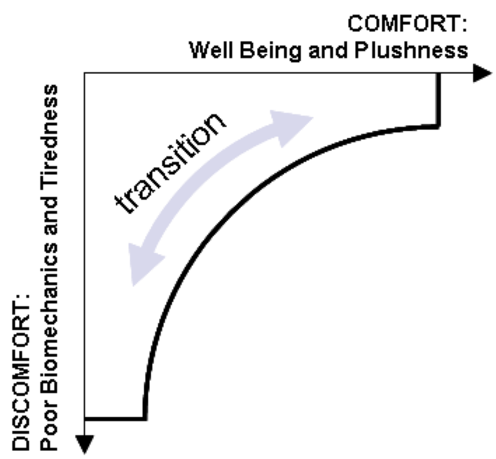


Figure 1. Hypothetical model for Comfort and Discomfort (adapted from Zhang et al., 1996). Reproduced with permission from Human Factors. Copyright 1996 by the Human Factors and Ergonomics Society. All rights reserved.

Along with defining comfort and discomfort as two different entities, Zhang et al. (1996) identified two different factors for comfort, namely a sense of well-being and aesthetics. From a more macro view, it is known that there is a third type of comfort (i.e., psychosocial comfort, de Looze et al., 2003; Hsu and Wang, 2003). In the view of de Looze at el. (2003), psychosocial comfort is related to communication with other people, job satisfaction, and social support. Hsu and Wang (2003) identified job dissatisfaction, intensified work load, monotonous work, low job control, low job clarity and low social support, as major contributing factors for psychosocial comfort, and found associations between physical/ergonomics variables and psychosocial factors, and their interactions with visual and musculoskeletal discomforts. Similarly, Lu et al. (1996) found interactions between psychosocial factors and ergonomic workstation design factors, and argued that the psychosocial factors may contribute to physical discomfort. As such, the importance of psychosocial comfort should not be overlooked for a more comprehensive understanding of overall comfort perception, though this category is not considered in the present work.

Ideally, the optimal sitting experience will be a combination of maximal comfort with minimal discomfort (MCMD), where comfort (discomfort) is a combined entity of physical, emotional and psychosocial comforts (discomforts). Just seeing a seat without sitting can evoke a positive or negative feeling, which can affect the perception of comfort and discomfort during and after sitting (Eklund and Kiviloog, 2003; Helander, 2003). Therefore, emotional comfort and discomfort have a role in perception. Similarly, a comfortable seat should be complemented by a comfortable posture if it is to ultimately provide the sitter a positive feeling while occupied. Hence, the concept of physical comfort is required to describe this situation (relaxed feeling) while sitting, distinguished from emotional comfort that does not necessarily require physical contact. In summary, it is argued that physical and emotional aspects of both comfort and discomfort are necessary to describe overall perception of comfort/discomfort (Table 1), and that interactions likely exist among the different types of comfort / discomfort (Figure 2).

Table 1. Components of comfort and discomfort (Summers, 2000; Van Veelen et al., 2001; Zhang et al., 1996)

	Physical	Emotional
	Formed during/after use Physical contact required	Formed before/during/after use Physical contact not required
Discomfort	A state of ill-being Related to poor biomechanics and circulation, restlessness, and fatigue	Related to anti-aesthetics (unattractive, cheap, repellant)
Comfort	A state of well-being Absence of physical discomfort (relaxed, refreshed)	Related to aesthetics

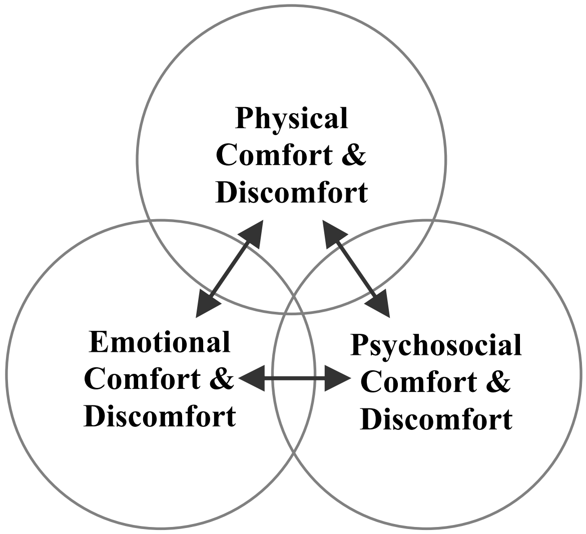


Figure 2. Compositions of comfort and discomfort and their possible interactions

Zhang et al.'s model (1996) considers only one type of discomfort (physical) and does not clearly divide comfort components. Given this, their model can describe only limited situations properly. With their model, for example, it is hard to describe the fact that even before sitting, there can be a negative feeling due to its design (e.g., unattractive color, cheap feeling, etc). Similarly, comfort can be evoked with and without the usage of the seat. Hence, it is necessary to have the concept of emotional discomfort to address the former example, and a distinction between physical and emotional comforts to address the latter. Consequently, the concept of total comfort and discomfort emerges, where physical, emotional and psychosocial comforts are combined into total comfort, and physical, emotional and psychosocial discomforts into total discomfort. There should be a transition between comfort and discomfort within any type, where comfort and discomfort are both present (Figure 3).

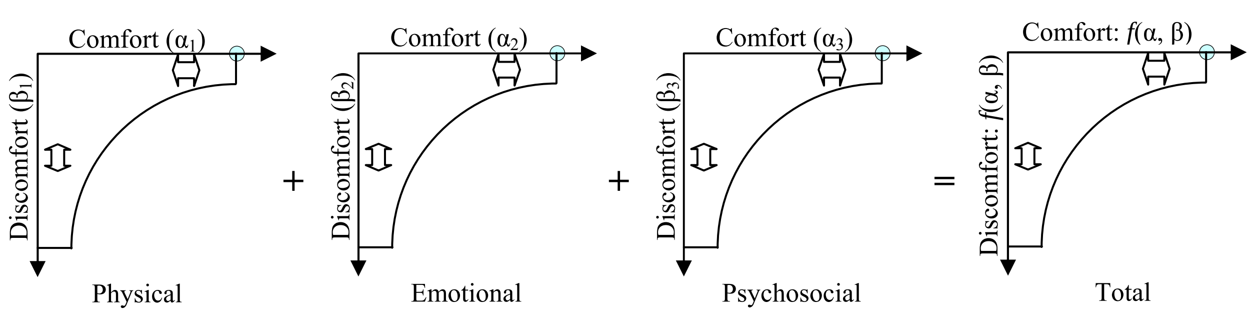


Figure 3. Proposed comfort/discomfort concept (Arrows: due to fatigue or adaptation, Circle: optimal point)

It is still not clear if, or to what extent, discomfort is dominant compared to comfort. Helander and Zhang (1997) found out that when discomfort was present, comfort became secondary, and observed that aesthetic design mattered with respect to comfort, but not to discomfort. Further, a full range of overall comfort ratings were found only when discomfort factor scores were low, and the range of comfort ratings was negatively associated with that of discomfort ratings. This indicates that, as the level of discomfort becomes more intensive, comfort factors tend to be unrecognized or become secondary. Hence, discomfort would seem to be a dominant factor in overall comfort / discomfort perception. However, Helander and Zhang (1997) did not investigate this issue quantitatively (i.e., to what degree comfort was reduced due to the presence of discomfort, or how they affected each other), nor did they address possible effects of comfort on discomfort. Similarly, referring to Helander and Zhang (1997), de Looze et al. (2003)'s sitting comfort / discomfort model (Figure 4) has two uni-directional arrows in the middle from discomfort to comfort to indicate the dominance of discomfort. They expected that "for discomfort the relationships of objective measures with discomfort would be stronger than for comfort, as the link between discomfort (and) objective measures of physical exposure, dose or response is more direct" (de Looze et al., 2003, p. 988). However, the validity and general applicability of this argument should be investigated further. Indeed, these authors mentioned that "the expectation that discomfort is more closely related to objective physical measures as compared to comfort cannot be verified" (p. 995).

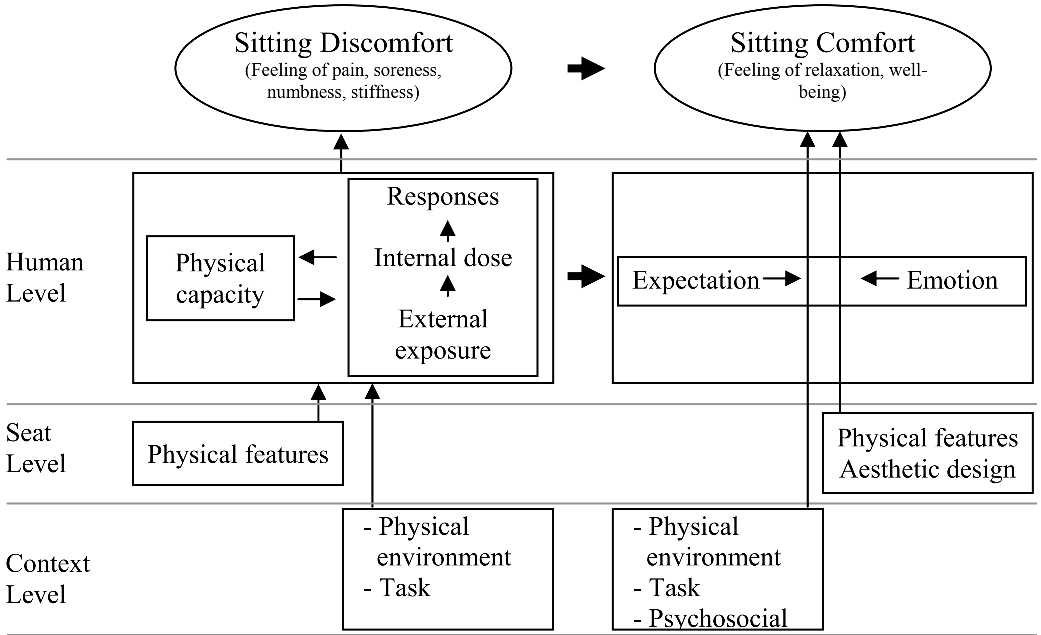
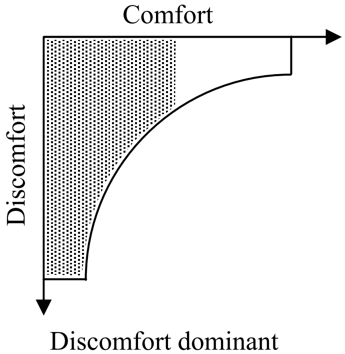
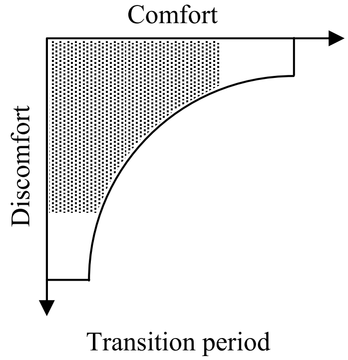
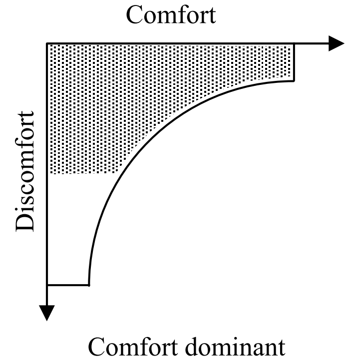


Figure 4. Theoretical model of sitting comfort and discomfort and its underlying factors at the human, seat and context level (adapted from de Looze et al., 2003). Reproduced with permission from Ergonomics.

As an alternative, the dominance of discomfort or comfort in evaluation of, or experience from, a product can be determined according to the overall maturity level of a product family of concern that is likely to change with the stage of a product family life cycle (Table 2). For example, if a group of products under consideration have a low level of quality on average and do not satisfy users' basic needs (prevention of pain, soreness, numbness, etc.), they can be evaluated more effectively with discomfort ratings. On the other hand, if they meet these basic needs, they should be evaluated by comfort ratings, as the levels of discomfort will not differ much, and hence product quality will be difficult to distinguish in terms of discomfort. A decrease in comfort level from Stage III_1 to Stage III_2 and from Stage III_2 to Stage IV can be partially explained by the temporal change in perceptions of comfort (Kolich and White, 2004).

Table 2. Proposed model of dominance of comfort and discomfort according to product life cycle - comfort/discomfort quality life cycle

Product Life Cycle*	Stage I/IV Introductory/Decline	Stage II/III_2 Growth/Maturity	Stage III_1 Maturity
Experience from the product			
Possible factors	I: low product quality of, and resistance to, a new product IV: increased expectation due to experience and satiation	II: increased quality and adaptation III_2: increasing expectation due to experience and satiation	III_1: higher quality and adaptation
Products in the market	- Basic needs not fulfilled (I) - Fall behind increased needs (IV) - Large variation in discomfort	- Meet basic and advanced needs partially	- Basic needs mostly fulfilled - Breakthrough required for further improvement - Small variation in discomfort
Dominant	Discomfort	-	Comfort
Effective scale	Discomfort	Discomfort, Comfort, or Overall^{+}	Comfort

*: Modified from Levitt (1965), +: Composite measure of comfort and discomfort

3.3. Combined model of comfort and discomfort

Some authors (e.g., Branton, 1969; Reed et al., 1994) have considered the seating experience to be only related to discomfort, and simply treated comfort as a discomfort-absent state. These authors further assumed that comfort had only two possible discrete states: existence or not. However, work by Hanson et al. (2006), in which participants described their preferred driving posture using adjectives, showed different results. In their study, a total of 119 descriptions were collected and classified into four groups: mental (comfortable, relaxing, restful, nice, peaceful and calm), environment (adjustable, adaptable, flexible, supportive, spacious, and good field of vision), generally positive (good, perfect, fantastic, and wonderful), and generally negative (troublesome and less good). This result indicates that experience in the driving posture indeed is related to both comfort and discomfort in diverse ways, as these adjectives correspond to either sitting comfort or discomfort descriptors given in Zhang et al. (1996)'s study. In addition, some authors (Wilson and Kolcaba, 2004; Zhang et al., 1996) have regarded comfort as a continuous factor, as with the case of discomfort. From this, it can again be argued that the seated experience should be rated in terms of both comfort and discomfort, using two separate continuous scales.

With comfort and discomfort being not merely opposing constructs, Zhang et al. (1996) identified well-being as one component of comfort. According to Warr (1999), however, well-being should also be treated as an independent construct. He showed that well-being can be measured on the three dimensions of comfort-anxiety, pleasure-displeasure, and enthusiasm-depression. A good state of well-being is partially related to comfort (e.g., at ease, relaxed), but not inclusively (e.g., enthusiastic and pleased are not part of comfort). Likely, an adverse state of well-being is partially related to discomfort (e.g., uneasy, fatigued), but again not inclusively (e.g., anxious and depressed). Shen and Parsons (1997) also related negatively affected well-being (i.e., ill-being) to discomfort. A combined view of Zhang et al. and Warr indicates that some components of comfort and discomfort indeed have opposite meanings, or are common, and that well-being is related to both comfort and discomfort, but is not merely part of comfort or discomfort. As summarized by Spirduso (1995), subjective well-being can be quantified using diverse measures such as Life Satisfaction Scales (Neugarten et al., 1961), Affect Scales (Bradburn, 1969), Indexes of General Affect and Well-Being (Campbell et al., 1976), General Well-Being Schedule (Fazio, 1977), and Affectometor 2 (Kammann and Flett, 1983).

3.4. Vehicle comfort and discomfort

People interact with a system within an environment, and this environment potentially affects, or is affected by, people and/or the system. Environmental ergonomics is concerned with interactions between people and the environment from the perspective of ergonomics (Parsons, 2000). Specifically, it deals with "the effects of heat and cold, vibration, noise and light on the health, comfort and performance of people" (Parsons, 2000, p. 581). All these factors along with spatial factors are determinants of vehicle comfort. More broadly, Corbridge (1987) classified automotive comfort into three domains:

1. Dynamic factors: vibration, shocks, and acceleration
2. Ambient factors: thermal comfort, air quality, noise, pressure gradients
3. Spatial factors: the ergonomics of the passenger's position (postural, physical fit)

Possible factors that can influence sitting comfort and discomfort are shown in Figure 5, with indications of how each factor is addressed in the current work.

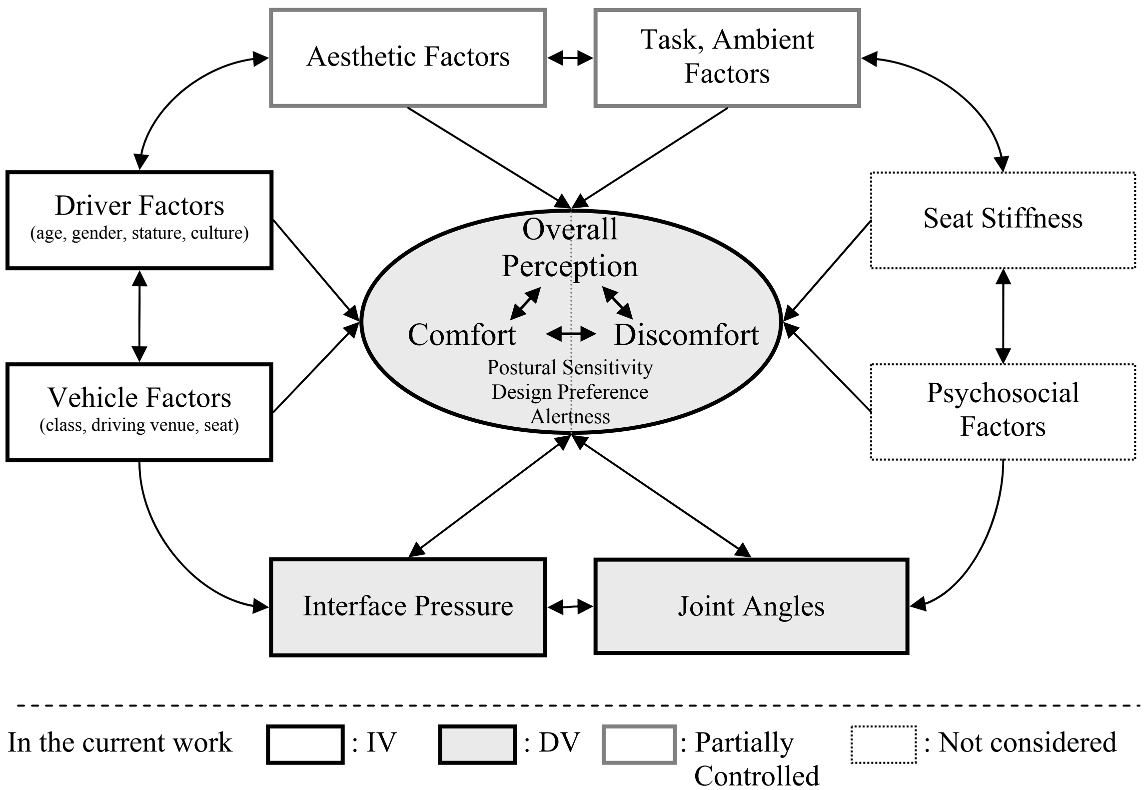


Figure 5. Factors affecting sitting comfort and discomfort

3.5. Measuring in-vehicle sitting comfort and discomfort

3.5.1. Contextual issues

Precise quantification of driver comfort / discomfort, a fundamental step for improving the driver-vehicle interface design, requires that seat and package geometries, driving postures and visual demands should be set close to actual driving situations. Troup (1978) showed that the car seat is one major factor affecting a driver's comfort, and can play a positive role in prevention of back pain by alleviating vibration and road-shock. Rebiffé (1969), on the other hand, indicated that ergonomic vehicle packaging, specifically harmonic layout of relevant parts, is more important for overall comfort than the seat itself. Anshel (2005) indicated that visual information in human-machine systems was so dominant that its deficiency could often result in awkward body postures. Driving involves high visual demands (Wierwille and Tijerina, 1996), which can thus change the driving posture and result in postural discomfort (Pheasant, 1992). Seat and package geometries and driving postures, in turn, likely influence interface pressure distributions, one of commonly used measure for seat comfort investigations.

Besides ensuring realistic conditions, in terms of seat, posture, task, and environment, which are necessary (especially in a laboratory-based study) for their contextual effect on the human response as generally discussed by Annett (2002), a safety belt should also be incorporated for the same reason. During the past five years (2000~2004), safety belt usage rates in the U.S have risen from 72% to 81% (BTS, 2006). Thus, to better represent driving conditions, a safety belt should be worn during an experiment. Further, without a proper restraining system, participants are more likely to slip forward and to be in (more) slouched postures, called sacral sitting (Andreoni et al., 2002; Savage, 2006), or submarined (Arrowsmith, 1986), which will result in changes in pressure distribution and joint angles. Motavalli and Ahmad (1993) further suggested a backward inclined seat cushion, seat covering with high friction, and sitter's muscular effort in order to prevent forward slipping.

3.5.2. Temporal effects on sitting comfort / discomfort

Short-term and long-term sitting comfort / discomfort need to be distinguished. Sitting discomfort increases over time while sitting comfort tends to remain constant (Helander and Zhang, 1997). Increased discomfort seems largely associated with fatigue, which can result from one hour of driving (Uenishi et al., 2002). Some authors have suggested using long-term test durations for the assessment of seat discomfort. For example, Gyi and Porter (1999) indicated that at least two hours of testing was required to clearly assess discomfort, which seems mainly focused on measuring fatigue in seated postures. Fatigue in sitting, however, could be simply due to "the passage of time" (Helander and Zhang, 1997, p. 912), and not necessarily due to the seat design. Further, fatigue in vehicle has been shown to be affected by multiple other sources such as temperature, air quality, noise (Gameiro da Silva, 2002), seat cover ventilation (Hawkins, 1974; Reed et al., 1994; Temming, 1993), and circadian factors (Brown, 1994; Moore-Ede et al., 2003; Van Dongen and Dinges, 2000). Measure of interface pressure does not effectively account for any of the above factors (temperature, air quality, noise, seat cover ventilation, and circadian factors), but rather accounts for the seat's support and pressure distribution characteristics and postural changes. Therefore, in using pressure data for assessment of sitting comfort / discomfort, a method is required that can determine their levels within a relatively short period of time. Moreover, a compiled version of the 1990 Nationwide Personal Transportation Survey (NPTS) data by Reed and Massie (1996) showed that about 82 percent of trips taken in the U.S. were ≤ 20 minutes. Hence, short-term driving is also more representative of actual driving patterns than long-term driving, and long-term driving is not the normal level of driving exposure found in the non-occupational population.

A long-term, discomfort-oriented investigation on drivers' sitting experience seems appropriate for the study on the assessment and prevention of professional drivers' musculoskeletal risks, whereas short-term, comfort-oriented study seems to be more relevant and effective for improving the general drivers' experience. Similarly, according to Makhsous et al. (2005), a theoretical length of driving before "entering the caution zone (where there is a possible health risk)" (p. 1193) was 2.5 hours, which amounted to less than 1% of travel-day trip durations made by non-professional drivers in 1990 (Reed and Massie, 1996). However, it should also be emphasized that sitting duration is one of the most important factors contributing to discomfort (Helander and Zhang, 1997; Lee et al., 1990), rather than vehicular factors including seats. Interestingly, a field study by Oliver (1970) showed that there was no difference between preference ranking orders after short-term (two miles) and long-term (60 miles and two hours) driving, and that the difference in vibration levels among seats was also not perceivable due to other confounders such as individual differences and complex road situations.

Discomfort seems to be time-dependent due to the effect of fatigue. Michel and Helander (1994) observed that discomfort increased with time. Helander et al. (1997) showed in their seat comfort study that the rank order of preference established among a set of chairs during the first assessment did not change until the end of experiment. However, this result was only regarding statistically significant differences. Indeed, with a closer examination of the results, they found that there was time effect on comfort descriptors related to well-being and most discomfort descriptors, whereas no time effect was found in comfort descriptors related to chair design (aesthetics). Hence, comfort due to aesthetics seems relatively time-resistant, compared to other comfort and discomfort factors. Similarly, Kolsch et al. (2003) also included the time effect on discomfort in their comfort zone model, with comfort being defined as absence of discomfort.

As noted, physical discomfort increases with time, and physical comfort also seems affected by time and/or by the presence of discomfort, especially when discomfort is substantial. As opposed to Helander et al. (1997), some researchers have found that emotional comfort is also time-dependant. For example, Eklund and Kiviloog (2003) observed that an initially attractive seat became more attractive over time, whereas an unattractive one became more unattractive over time. However, no indication was provided whether these results were statistically significant. It thus appears that the relationship between instantaneous and long-term comfort ratings depends on how dominant aesthetic comfort and other comfort aspects are in the initial formation of total comfort, how strong the relevant stimuli are, and how long these comforts last as a result. Summarized in Figure 6 are the potential stimuli and the formation order of comfort and discomfort, and their interactions. In contrast to Zhang et al. (1996) and de Looze et al. (2003), a comfort effect on discomfort should be taken into account and vice versa.

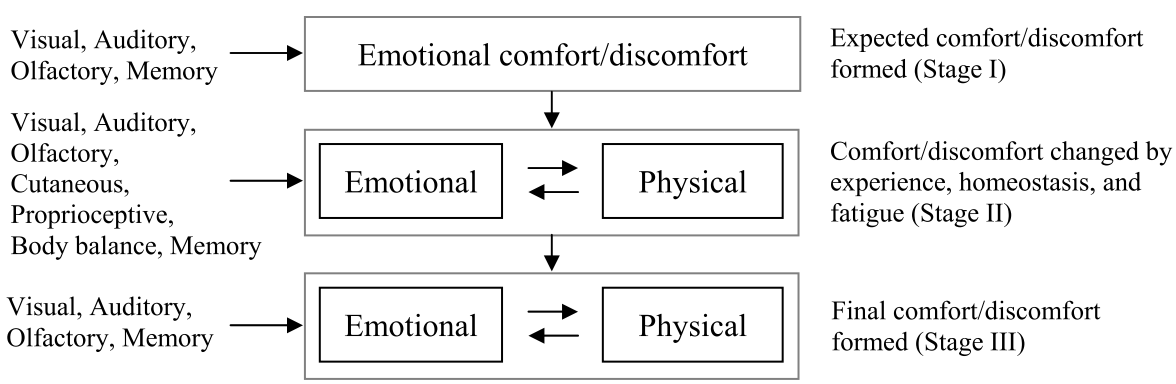


Figure 6. Relationship between components of comfort/discomfort

3.5.3. Aging effects on sitting comfort and discomfort

With age there is a deterioration of function, including poor eyesight, slow reaction time, loss of muscular strength and dexterity or susceptibility to fatigue (Warnes et al., 1993), and these have a potential to negatively affect individual driving postures and forward visibility. In Milne and Lauder's study (as cited in Reynolds, 1993), different forms of spinal curvature (i.e., "flatter and more kyphotic", p. 106) were observed in the sixth decade of life. Hence, to the contrary of its intention, a commonly adopted contoured seat back could actually make the elderly uncomfortable. Burger et al. (1977) showed that the design of the vehicle interior contributed to at least 7.5% of all accidents. Similarly, visual (dis)comfort affected by vehicle in/exterior design is related to hazard misperception (e.g., gap, distance) as well as hazard non-perception (e.g., vision obstruction, reduced visibility), both of which are regarded as major crash contribution factors (Wierwille and Tijerina, 1996). In particular, the elderly have slower and restricted abilities in static and dynamic visual acuity (Eby and Kantowitz, 2006; Nicolle and Abascal, 2001). Therefore, a study on potential aging effects on sitting comfort and discomfort is warranted. Anshel's study (2005) on man-computer systems showed that visual information is so dominant that its deficiency could be readily compensated by changing the body posture. Hence, though not investigated in this work, it should be addressed that visual discomfort can affect postural ratings as the former can lead to postural change.

The older population has different needs due to the following physical and psychological changes that occur with age:

- Range of Motion (ROM) changes: ranges of flexion and extension shrink and hence functional reach is also shortened (Spirduso, 1995)
- Stature shrinks (~2cm/decade, Spirduso, 1995)
- Eyesight and hearing worsen (Nicolle and Abascal, 2001) and muscles are weaken, all of which are related to postural balance (Spirduso, 1995)
- Information processing slows (Nicolle and Abascal, 2001; Spirduso, 1995)
- The sensitivity to different joint angles possibly differs due to more flexed posture (Spirduso, 1995)

Besides these aging effects, there are two other reasons to consider the older population separately from other population groups. In the U.S., 20% of licensed drivers are currently over the age of 60, and this percentage is expected to increase rapidly between now and 2020 since baby boomers (aged 42~60 as of 2006) have been starting to enter this population. They are also known to have the largest consuming power, an amount of $900 billion per year (Gobe, 2001). Therefore, it is prudent to consider their capabilities and limitations systematically in product design and development for their safety as well as for vehicle salability. Two age groups (younger: ≤37 years old, older: ≥ 60 years old) are particularly of interest, as these groups have relatively high involvements in fatal crashes compared to the middle-age group (Evans, 1998). The high fatality rate of car accidents in the younger group is attributed to inexperience and risky driving such as speeding (Williams, 2006), whereas the older group has a higher fatality rate largely due to age-related deterioration in cognitive and sensory functions (Baldwin, 2002).

3.5.4. Subjective rating scales for in-vehicle sitting comfort and discomfort

Most studies that have quantified subjective responses in seated postures have included only a discomfort scale (e.g., Hsu and Wang, 2003; Jung and Choe, 1996; LeBlanc et al., 2003; Smith et al., 2006; Straker et al., 1997), largely due to their primary focus on pain prevention (Hancock and Pepe, 2005). Other studies have used one scale to measure mixed feelings by placing comfort and discomfort on opposite end of a continuum (e.g., Genaidy et al., 1995; Genaidy and Karwowski, 1993; Kee and Karwowski, 2001, 2003, 2004). In other studies comfort was not measured, and only a discomfort scale was used with supplemental objective measures such as electromyography (EMG), center of pressure (COP), or interface pressure (e.g., Fenety et al., 2000; Seigler and Ahmadian, 2003). Comfort is not usually measured without discomfort being measured. In the perianesthesia setting, Wilson and Kolcaba (2004) measured only comfort by defining discomfort as a detracting factor from comfort, and used a visual analogue scale (VAS) with a range from 0 (no comfort) to 10 (highest possible comfort). In a review of literature on sitting comfort and discomfort, de Looze et al. (2003) observed that in none of the reviewed studies had comfort and discomfort been simultaneously but separately rated using two different scales.

As with the debate on the definition of comfort and discomfort and their relationship, it is still under debate whether or not anchors used for comfort/discomfort rating can be equally spaced (Borg, 1982; Corlett and Bishop, 1976; Ebe and Griffin, 2000a, 2000b; Stevens, 1975). Corlett and Bishop (1976) argued that there would be a linear relationship between the perception of postural pain and the exposure duration. According to Borg (1982), on the other hand, the perception follows a logarithmic law in the form of $R = a + c(S - b)^n$, where R is the intensity of the response, S is the stimulus intensity, a and b are constants showing the starting point of the function, c is the proportionality constant, and n is the exponent. As a result, Borg's (1982) discomfort rating scale shows a nonlinear relationship between the intensity of the response and the stimulus intensity (when $n \neq 1$). Steven's psychophysical power law (1975) also indicated the possibility of a nonlinear relationship between sensation magnitude and the stimulus magnitude (when the exponent $\neq 1$). Moreover, Russell et al. (1992) suggested that "the use of relatively coarse Likert scales to measure fine dependent responses can cause information loss, and greatly reduce the probability of detecting true interaction effects" (p. 336). Indeed, some researchers have investigated the relationship between dynamic and static factors and seating discomfort (Ebe and Griffin, 2000a, 2000b), and found that there was a nonlinear relationship between them.

Diverse subjective rating scales have been used to quantify perceived levels of comfort and discomfort. Some of them are: General Comfort Rating ('completely relaxed' to 'unbearable pain') (Shackel et al., 1969); Body Area Comfort Ranking (forced-choice ranking method with iterative selection of 'three most comfortable and uncomfortable areas') (Shackel et al., 1969); Chair Feature Checklist (CFCL, rating each seat feature using the scale of 'too much - correct - too little') (Shackel et al., 1969); 10-Point Comfort Rating ('very comfortable to very uncomfortable') (Oliver, 1970); ASDQ ('No objections to extreme objections', 'No discomfort to extreme discomfort') (Smith et al., 2006); and, CP-50 (Shen and Parsons, 1997). The CP-50 (Shen and Parsons, 1997) is a category partitioning scale, and consists of 'no discomfort (0)', five categories (1 to 50, 10 points for each) of 'very slight', 'slight', 'medium', 'high', and 'very high discomfort', and finally 'maximal (>51)' (note: no wording of 'maximal' available in the original scale).

3.5.5. Interface pressure as an objective measure for sitting comfort / discomfort

Interface pressure data was regarded by de Looze et al. (2003) as an objective measure having a clear association with subjective ratings. Previous studies showed that preferred pressure levels were different between body parts as well as between anthropometric groups (Dunk and Callaghan, 2005; Kamijo et al., 1982; Kolich, 2004), and that there were associations between interface pressure and sitting discomfort. On the other hand, some studies have failed to find this association. For example, Gyi's study (1996) indicated that sole use of interface pressure was not successful in predicting car seat discomfort. Therefore, use of different types of pressure data, and quantifying comfort instead of discomfort, may be more successful at identifying associations between pressure and human responses. If so, such associations would facilitate determining seat design and evaluation criteria for diverse groups of people in terms of pressure levels. However, there are also critiques on using the pressure distribution alone as seat design criteria. For example, Reed et al. (1994) pointed out the shortcoming in the use of interface pressure of not accounting for surface shear, which is "an important factor in determining the critical pressure at which blood vessel occlusion will occur" (p. 32) and hence a potential cause of "tissue ischemia and discomfort" (p. 32).

Different pressure levels between bilateral lower body parts in a driving posture are expected due to the different task and postural requirements placed on each lower extremity. For example, the right foot, used to control pedals, is required to take more restricted postures with less consistent support, while the left foot, unless a clutch pedal is considered, is relatively free and consistently supported by the car floor and/or the foot rest. Due to this, the left foot (and the left lower limb) might be involved more dominantly in postural balance, which would result in a bilaterally asymmetric posture and pressure. Indeed, preferred driving postures have been shown to be asymmetric (Andreoni et al., 2002; Hanson et al., 2006).

Most previous studies on sitting comfort / discomfort have made restrictions on seat configuration (e.g., seat back/cushion reclining angle) and/or sitting posture (e.g., torso/knee angle). However, it is necessary to measure seat pressure data while the participants are in the most comfortable (preferred) postures possible according to their sitting strategy, which would ensure natural, necessary adjustments of the seat and other parts.

Many authors have shown an effect of seat pressure on seat evaluation (e.g., Habsburg and Middendorf, 1977; Iwasaki et al., 1988; Kamijo, 1982; Kamijo et al., 1982; Ng et al., 1995). Based upon a review of several studies, Dhingra et al.(2003) identified that a soft seat provided more evenly distributed pressure on a larger effective contact area than a rigid seat, a condition that has been considered more comfortable and preferable in general, but this also can lead to the problem of postural fixity (Akerbloom, 1948; Grandjean, 1980; Grieco, 1986). Postural fixity impairs transfer of essential nutrients (e.g., "oxygen, glycogen, and creatine phosphate", p. 377) and waste products (e.g., "carbon dioxide and lactic acid", p. 377) through blood vessels by preventing natural blood flow, and as a result expedites muscular fatigue (Kolich and Taboun, 2002).

3.5.6. Joint angle as an objective measure for sitting comfort / discomfort

Many studies have been conducted to quantify driving postures (e.g., Andreoni et al., 2002; Dupuis, 1983; Grandjean, 1980; Hanson et al., 2006; Porter and Gyi, 1998; Rebiffé, 1969; Reed et al., 1999; Vogt et al., 2005). However, most of these considered only one side of the driving posture, many neglected to measure perceived comfort / discomfort levels, and none included all joint angles required for a complete description of driving posture.

By using more accurate measures of driving postures to overcome these drawbacks, the following benefits are expected:

- Complete description of driving posture by including both sides and all joint angles
- Optimized space allocation inside digital mockups: right location and right range
- Improvement of user satisfaction by meeting users' needs in terms of minimal discomfort and maximal comfort
- Facilitation of safe driving by reducing postural fatigue

3.5.7. Other objective measures

Besides interface pressure and joint angles, other objective measures have been and are being used that can be further divided into three categories: vibration, physiological measure, and seat properties. However, these measures have been exclusively used to measure discomfort.

- Vibration
  - Standards: ISO 2631-1 (1997), ISO 2631-5 (2004) , BS 6841 (1987)
  - Driving-point impedance
  - Apparent mass
  - Transmissibility
- Physiological Measure
  - Adrenaline concentration in urine (Inagaki et al., 2000; Uenishi et al., 2002)
  - Electromyography (Bush et al., 1995; Inagaki et al., 2000; Kolich and Taboun, 2002; Lee and Ferraiuolo, 1993)
- Seat Foam Property
  - SAG factors: "the ratio of the forces required to compress a specimen to 65% and 25% deflection with a plate of specified diameter (normally 200 mm)" (Ebe and Griffin, 2001, p. 902). 2.8 or higher level is recommended (Wolfe, 1982).
  - Seat stiffness: "a static characteristic given by the gradient of a force-deflection curve obtained according to ISO 3386 (1986)" (Ebe and Griffin, 2000a, p. 772). A study by Ebe and Griffin (2000a) showed this value was more highly correlated with the discomfort score if the magnitude of vibration was low or in static conditions (i.e., R^2 = 0.772 vs. 0.902 at bumpy and motorway roads, respectively).

3.5.8. Multivariate approach (composite index)

Some authors have used more than one factor to investigate perceptions and feelings. Examples are Yamazaki et al. (1998) using temperature, light and sound, Howart and Griffin (1990) using noise and vibration, Alcobia and Silva (1999) using thermal comfort, air quality, noise, and vibration, and Humphreys (2005) using warmth, lighting, humidity and air quality. All of these exemplar studies focus on environmental factors. Inagaki et al. (2000) used two physiological measures (adrenalin and EMG) and vibration in the evaluation of riding comfort. Andreoni et al.

(2002) used interface pressure and joint angle. The current work focuses on multivariate approaches using internal and biomechanical factors (interface pressure and joint angle).

3.6. Standards and guidelines for in-vehicle comfort / discomfort

3.6.1. Occupant packaging

Occupant packaging seeks a harmonic layout of relevant parts, considering both users' limitations and capabilities (in terms of vision, hand reach, anthropometry, and force) and design constraints (e.g., available space, collision safety, aesthetic design, and size of each part). Several standards related to occupant packaging are available from SAE (Society of Automotive Engineers) in the forms of recommended practices (SAE J287, J941, J1052, J826, and J1517, Figure 7). Among them, SAE J941 and SAE J1517 are especially of interest. SAE J941 is related to drivers' eye locations, and SAE J1517 is related to drivers' hip locations. More details on these two SAE practices are described in Chapter 6, where these are reviewed and compared with the results of the current study to yield revised recommendations.

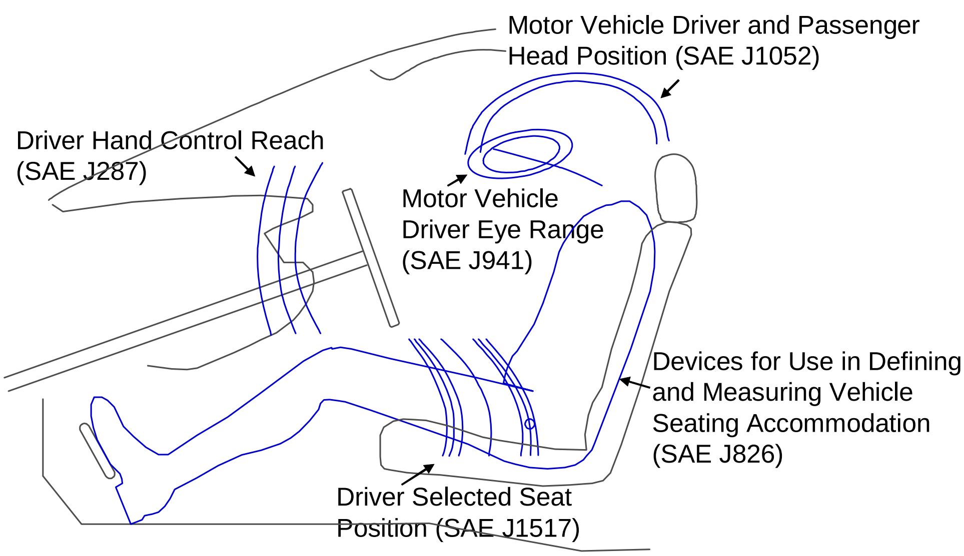


Figure 7. SAE accommodation design tools and recommended practices (adapted from Roe, 1993)

3.6.2. Vibration

ISO 2631 - 1 (1997), ISO 2631 -5 (2004), and BS 6841 (1987) are widely used for whole body vibration (WBV) assessment and specify vibration measuring and evaluation procedures including the location of the accelerometers, the vibration evaluation method and the frequency weighting for accelerations. The former defines SEAT (Seat Effective Amplitude Transmissibility) and VDV (Vibration Dose Value), which are objective measures for seated discomfort (Ebe and Griffin, 2000a; Griffin, 1990; Makhsous et al., 2005; Seigler and Ahmadian, 2003; Verver and van Hoof, 2004). In the current work, vibration was not measured because the relationship between vibration dose and health risks has already been established in the form of standards, and its application is closely related to material and mechanical design. Like other standards, however, revisions of the relevant standards are continuously needed to reflect recent findings and it should also be noted that vibration has been used only with respect to discomfort.

3.6.3. Interface pressure (guidelines)

Some guidelines available in the literature regarding interface pressure are summarized below.

- Minimum areas of high pressure and uniformly distributed pressure over the entire contact area (Motavalli and Ahmad, 1993)
- Total pressure beneath the ischial bones should be reduced (Ebe and Griffin, 2001).
- 1 to 3 N cm^{-2} beneath the tuberosities; 0.8 to 1.5 N cm^{-2} in the area around the tuberosities; 0.2 to 0.8 N cm^{-2} in other areas (Diebschlag et al., 1988)
- Sufficient contact area to reduce overall pressure; highest pressure only below the ischial points (1-3 N/cm^2), smoothly descending pressure around the ischial support area (0.8-1.5N/cm^2) and towards the boundary of the contact area (0.2-0.8 N/cm^2) (Weichenrieder and Haldenwagner, 1985)
- For tissue health, pressure exposure above 60 mmHg should be limited (Seigler and Ahmadian, 2003).
- Tissue ischemia is likely to occur at a threshold pressure of 60 mmHg after 1 hour of exposure (Bar, 1989).

- Seated interface pressure was inversely correlated with the time to develop tissue damage (Goonetilleke, 1998).
- “The pressure under the distal half of the thigh (e.g. from 200 mm forward of the H-point to the front of the seat) should be minimal” (Reed et al., 1994, p. 14).
- Minimum lumbar pressure peaks of about 18.75mmHg (2.5 kPa) (Kamijo et al., 1982)
- “No local maxima should be found in the pressure distribution outside the tuberosity and lumbar areas.” (Reed et al., 1994, p. 15)
- “The pressure under the distal half of the thigh should be minimal.” (Kolich and Taboun, 2004, p. 842)

Pressure distribution can be described either by Seat Pressure Distribution (SPD%) or Area Pressure Change (aP_{crms}).

- Seat pressure distribution (SPD%)

  SPD% measures a seat cushion’s ability to distribute interface pressure uniformly (Seigler and Ahmadian, 2003), and is defined as:

$$SPD\% = \frac{\sum_{i=1}^{n}(P_i - P_m)^2}{4nP_m^2} \times 100 \qquad (1)$$

- Area Pressure Change (aPcrms) (Seigler and Ahmadian, 2003)

$$aP_{crms} = \sum_{i=1}^{N} A(r_i)P_{crms}(r_i)W(r_i), \text{ where } W(r_i) \text{ is defined in Table 3} \qquad (2)$$

$$P_{crms} = \left\{ \frac{1}{T}\int_0^T \left(\frac{dP(t)}{dt}\right)^2 dt \right\}^{1/2} \qquad (3)$$

Table 3. Pressure ranges and weighting factors used in calculating aPcrms. (from Seigler and Ahmadian, 2003)

Pressure range, r_i	Weighting factor, $W(r_i)$
r_1: 40 ≤ P_m(n) < 60 mmHg	$W(r_1) = 1$
r_2: 60 ≤ P_m(n) < 80 mmHg	$W(r_2) = 2$
r_3: 80 ≤ P_m(n) < 100 mmHg	$W(r_3) = 3$
r_4: P_m(n) > 100 mmHg	$W(r_4) = 4$

3.6.4. Joint angles (guidelines)

Detailed data are shown in Tables 31-33 of Chapter 7.

3.6.5. Seat design and configuration (guidelines)

Some guidelines available in the literature regarding seat design and configuration are summarized below and in Tables 4 and 5. Variability in recommended ranges also supports that people have different preferences in terms of seat configuration. Hence, controlling seat configuration might prevent them from being in more comfortable seated postures.

- The driver's seat configuration to minimize myoelectric activity and intervertebral pressure is 120° of backrest inclination, 5 cm of lumbar support prominence, and 14° of seat pan inclination, lumbar support height at L3 (Andersson et al., 1974).
- 110° or more of backrest angle, 6° of seat inclination, and lumbar support at L3 level are recommended to reduce the postural stress, and the stresses arising from road shock and vibration (Troup, 1978).

Table 4. Recommended guidelines for seat back design (Tabulated from Lee et al., 1990; Reed et al., 1994)

Authors	Seatback (°, cm)			Lumbar Support (cm)	Effect and Other Recommendations
	angle	height	width	prominence/height	
Keegan (1964)				- / L5 (19.5)	
Andersson et al. (1974)	120			5 / L3	- Based on minimal EMG and intradiscal pressure
Hosea et al. (1986)	120			3 or 5 / -	- Based on minimal EMG
Troup (1978)	≥110			- / L3	- Reduced postural stress and stresses arising from road shock and vibration - Firm backrest
Andersson et al. (1979)				≥4 / L1-L5 (25)	- Simultaneous inclination of the seat and backrest
Grandjean (1980)	90-120	50	48	- / 10-14*	- Based on subjective ratings - Side supports for back to improve body position * from depressed auditorium seat surface
Maertens (1993)		54.5-59.5			
Oliver (1970)	114-120	51-53			
Schneider et al. (1985)			36.1**		** At 31.5 (22) cm above from the depressed seat cushion (H-point)
Reed et al. (1994)		50.5-64.5	45.6+		+ At 31.8 cm above from H-point - Any side bolster should not extend more than 28.8 cm above the H-point
Chaffin and Andersson (1991)			36-40++		++ For office chairs
Kamijo et al. (1982)				- / 23.5-27.5	- Based on subjective ratings
Porter and Norris (1987)				2 / 21.5	- Based on subjective ratings
Robins (1986)				1.5-2.5 / 25	

Table 5. Recommended guidelines for seat cushion design (Tabulated from Lee et al., 1990; Reed et al., 1994)

Authors	Seat Pan (°, cm)			Effect and Other Recommendations
	angle	depth	width	
Andersson et al. (1974)	14			- Minimal myoelectric activity and intervertebral pressure
Troup (1978)	6			- Reduced postural stress and stresses arising from road shock and vibration - Firm seat cushion
Keegan (1964)		43.2		
Chaffin and Andersson (1991)		40-48*		* For office chairs
Maertens (1993)		≤52.8 (38**)		** From H-Point
Grandjean (1980)		44-55		- Minimum 15cm seat travel - Side supports for cushion to improve body position
Oliver (1970)		48-51		
Gordon et al. (1989)		44***	≥43.2	***: 5th percentile female - Front width: 50cm for leg splay (Reed et al., 1994)

3.7. Conceptual frameworks for the current work

Ergonomics and hedonomics

As opposed to technology-centered design, the current work adopts both ergonomic and hedonomic approaches under the concept of user-centered design. Comfort and discomfort both are addressed, to determine the best subjective rating scheme and type of objective measures, and to obtain standard driving postures. The ultimate goal is to improve driver workspace and interface design (Figure 8), by making them more usable for diverse groups of people. The traditional ergonomic approach is focused mainly on the prevention of pain through minimizing perceived discomfort, whereas the hedonomic approach focuses on the promotion of pleasure by maximizing perceived comfort (Hancock and Pepe, 2005).

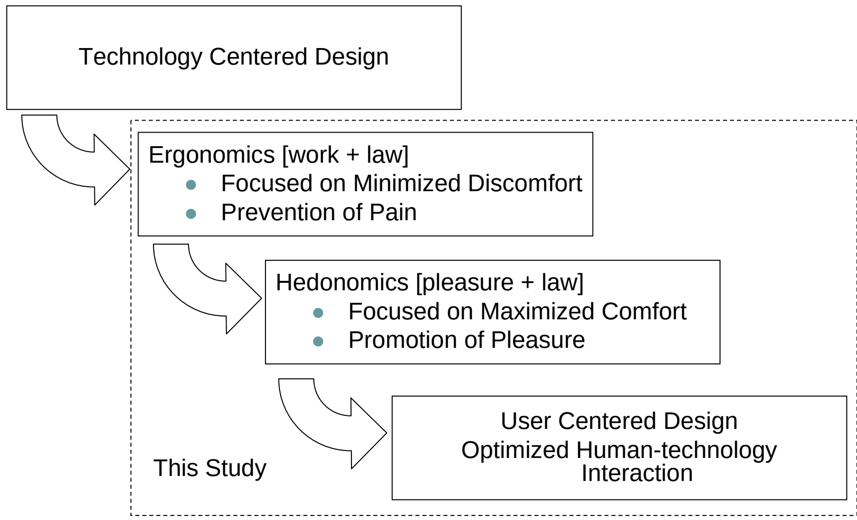


Figure 8. Framework of this study (ergonomics and hedonomics)

Maslow's hierarchy of needs

From the perspective of Maslow's hierarchy of needs (1943), comfort, relevant to aesthetic needs, is positioned at a higher level of needs than is discomfort as shown in Figure 9 (Zhang et al., 1996). Therefore, if basic needs such as prevention of discomfort are fulfilled, then more advanced needs, such as promotion of comfort, are of more relevance. Wilson and Kolcaba (2004) showed that comfort is related to the top-level need (transcendence).

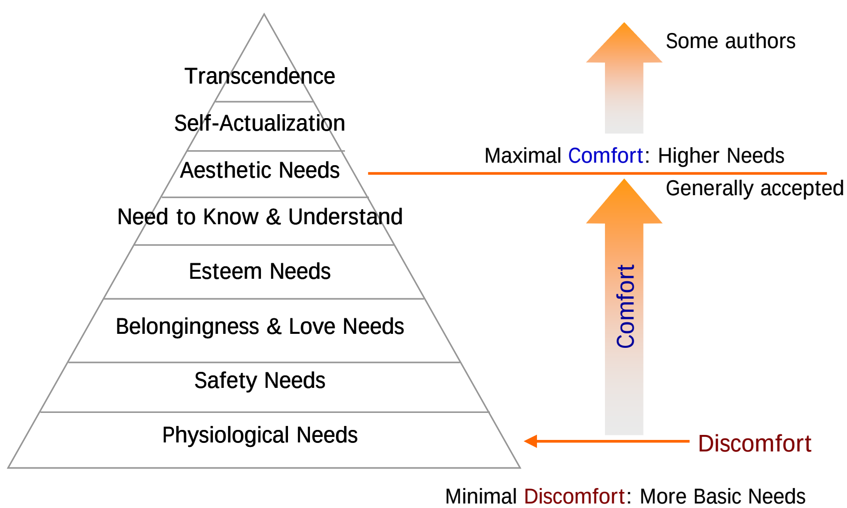


Figure 9. Hierarchy of needs and comfort/discomfort (from Maslow, 1943)

MCMD (maximal comfort and minimal discomfort) method

The vehicle packaging task is interconnected with other tasks that deal with vehicle function, aesthetics and salability. Comfort/discomfort can be regarded as a core value encompassing several automotive areas as well as packaging tasks in particular (Figure 10). Therefore, comfort/discomfort is included as a criterion for evaluating driver workspace and interface design and determining standard driving postures. In the current study, comfort was targeted to be maximized, and discomfort to be minimized. The overall method to determine the standard driving postures was termed the MCMD (Maximal Comfort and Minimal Discomfort) method, which involves a filtering process to ensure desire levels of comfort and discomfort to be associated with the standard driving postures.

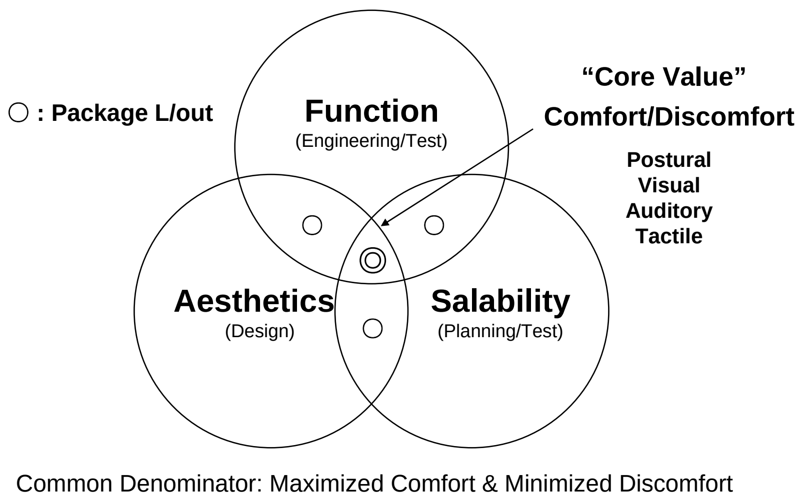


Figure 10. Comfort/Discomfort as a core value

4. Experimental methods

4.1. Assumptions and conditions

The following assumptions and conditions have been made to clarify the application scope and potential limitations of the results from the current study.

- People have the ability to find preferred postures for themselves in a given confined space or under physical constraints, and are eager to take that posture. Alternatively, if this is not possible, the most similar posture will be taken to minimize total cost in terms of tissue stress, metabolic energy consumption, torque, fatigue, vision, comfort, and discomfort (Keegan, 1953; Yang et al., 2007)
- Light clothes were worn for locating landmarks
- Participants were instructed to wear the shoes they normally wear while driving
- The same shoes were worn between lab and field sessions
- Percentiles used in this study are defined in terms of standing height
- No consideration of the clutch pedal was made
- Only two vehicle classes were considered: Sedan, and Sport Utility Vehicle (SUV)
- The steering wheel and gas pedal for one of experimental sedans (S1) were used in the lab studies for both sedan and SUV package configurations, but with different angle and position
- Participants were instructed to assume a driving posture in the following manner
  1. Two hands on the steering wheel (but, no position specified on the wheel)
  2. Right foot on the gas pedal
  3. Left foot on the foot rest (if they wanted and felt comfortable with the foot on it)
- All the joint angles were calculated in 2-dimensions side view (sagittal plane)
- A lap belt was used in lab experiment to avoid the forward sliding of the human body and to minimize the seat belt effect on the postural comfort evaluation (No shoulder belt was used)
- ‘Driving experience’ was used throughout this work to express comfort and discomfort that drivers perceive while interacting with a vehicle.
- Psychosocial factors were assumed to have no association with drivers’ behaviors that were quantified by objective measures (i.e., interface pressure, and joint angles)

4.2. Overview of experiments and participants

The experiment involved a number of driving sessions (a total of 270), in which a variety of subjective comfort and discomfort responses and/or two objective measures (i.e., joint angles, and interface pressure data) were obtained. Of particular interest were how these subjective responses were influenced by stature, age, gender, culture, vehicle segment, specific seat, and whether driving was real (on-road) or simulated (lab-based), all of which were independent variables. In addition to the subjective responses, the two objective measures were obtained as additional dependent variables to determine their relationships with, and to predict, subjective responses.

Forty nine volunteers were recruited from the local student body and general community. Criteria for inclusion were: possession of a valid driving license for a minimum of two years, normal or corrected-to-normal eye vision in both eyes, no current musculoskeletal disorders (only for younger participants), and age between 20 and 37 or ≥ 60. In addition, efforts were made to obtain a group of individuals consisting of a wide range of statures, and participants were divided into three stature groups (Table 6). Participants completed an informed consent procedure approved by the local IRB, and were compensated for their time.

Table 6. Participant descriptions and anthropometry

Cultural group	Stature group	Age group	# of people (male, female)	Mean (SD) stature (cm)	Mean (SD) BMI+ (kg/m^2)	BMI category++
North Americans	Short	Y*	9 (0, 9)	158.4 (4.4)	22.9 (2.9)	Normal
		O**	5 (1, 4)	158.4 (6.7)	23.2 (5.8)	Normal
	Middle	Y	9 (4, 5)	169.9 (3.9)	25.3 (3.6)	Overweight
		O	3 (2, 1)	170.2 (2.0)	27.4 (2.6)	Overweight
	Tall	Y	9 (8, 1)	183.9 (6.4)	22.6 (2.5)	Normal
		O	3 (3, 0)	182.5 (6.2)	27.4 (5.9)	Overweight
	Total	Y	27 (12, 15)	170.7 (11.7)	23.6 (3.2)	Normal
		O	11 (6, 5)	168.2 (11.7)	25.5 (5.2)	Overweight
	Grand Total	-	38 (18, 20)	170.0 (11.6)	24.1 (3.9)	Normal
Koreans	-	Y	11 (11, 0)	171.9 (6.2)	23.7 (3.1)	Normal

*: Younger (≥ 20 and ≤ 37), **: Older (≥ 60)
+: Body Mass Index
++: from the Centers for Disease Control and Prevention (2007)

4.3. General experimental procedures

An overview of the experiment procedure is shown in Figure 11. Laboratory-based sessions were conducted in an isolated room, using a custom-constructed driving rig (that allowed for more extended adjustments of the seat and steering wheel), and with a driving scene projected in front of the participant. Field sessions were conducted over a predetermined path on local roads. The first session began with an orientation and calibration. In the orientation part, participants went through an informed consent procedure and learned about the methods and purpose of the experiment and what was expected of them. In addition, several basic measures (stature, weight, distance between eyes, shoe size, etc) were obtained. In the calibration part, the participants learned how to locate their pubic symphysis (PS) and anterior superior iliac spines (ASIS), which were used later to estimate the hip joint center, as these were difficult to obtain by the experimenter alone. After sitting on a car seat covered with pressure mats, the participants adjusted the seat and steering wheel to take their most comfortable postures, and then drove for at least 20 minutes. During driving, they could adjust the two parts again if desired and interface pressure was continuously recorded for a later analysis. After each driving session, a set of questionnaires was completed that consisted of whole body and local body part comfort and discomfort ratings, overall rating and alertness level rating. Next, the postural sensitivity study and posture measurement followed. The field sessions followed the same procedure as the lab session, except that the postural sensitivity study was omitted due to the mechanical limitation of the experimental seats.

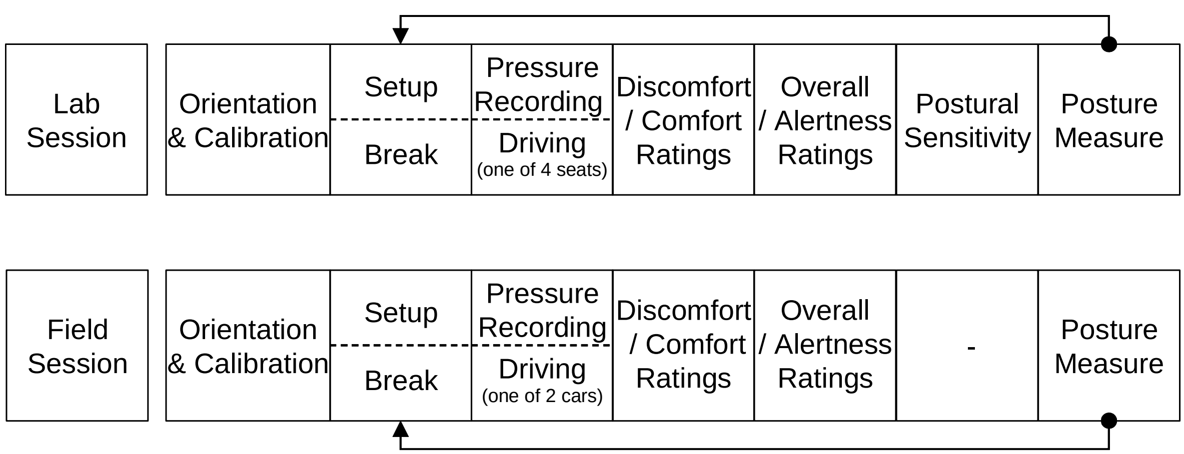


Figure 11. Experimental procedures

Seat/vehicle selection procedures, definitions and measuring methods for pressure variables and joint angles, and the method used in the postural sensitivity study are explained in the following relevant chapters. As the subsequent chapters focus on different topics, and hence analyze a different subset of data, each chapter starts with describing and explaining variables and analysis methods that are relevant.

4.4. Questionnaire structure and rating scales

A set of questionnaires consisting of 8 sections (Figure 12 and Appendix C) was developed to measure subjective responses to the driving experience. The specific presentation order was: whole body discomfort, local body part discomfort, whole body comfort, local body part comfort, overall posture rating, alertness level, posture sensitivity, and seat design preference.

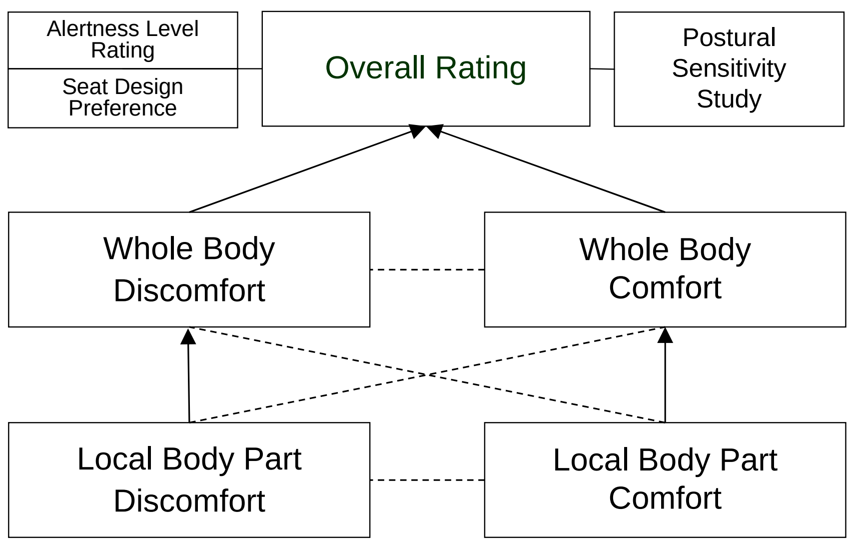


Figure 12. Questionnaire hierarchy

Though some authors have claimed that very similar feelings are perceived between the left and right sides of the body in driving postures, both sides are included in the current study in order to quantify such differences. The participants rated discomfort and comfort separately, for their whole body and each of 23 local body parts (Figure 13). Ratings were obtained using a revised version (Figure 14) of the Bishop-Corlett Scale (Corlett and Bishop, 1976) and the Borg CR 10 Scale (Borg, 1990). The discomfort scale ranged from -10 to 0, and the comfort scale from 0 to 10. Overall rating is a composite measure of comfort and discomfort ranging from maximal discomfort to maximal comfort on a continuum. Alertness level was rated by the participant to take into account the importance of safety involved in the driving posture. For this purpose, the Karolinska Sleepiness Scale (KSS) by Horne and Reyner (1995) was used (see Appendix C).

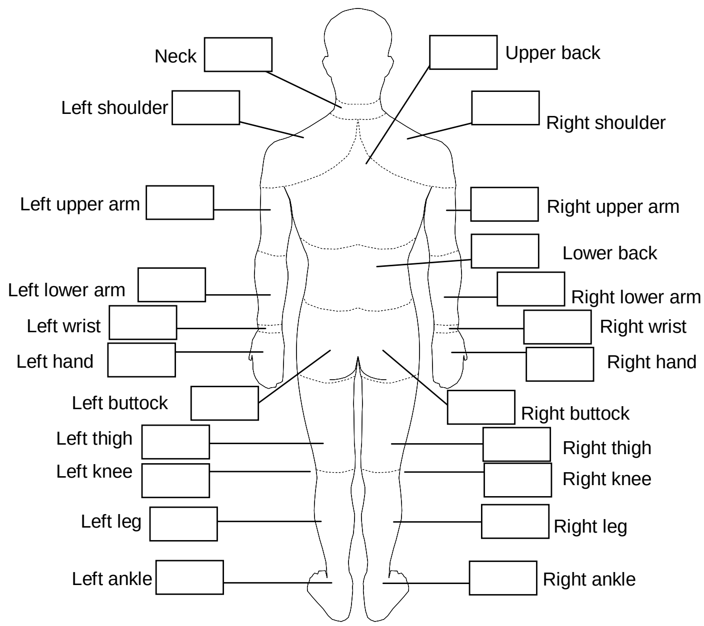


Figure 13. The 23 local body parts (adapted from Corlett and Bishop, 1976)

Discomfort	Comfort
0 : No discomfort	0 : No comfort
-0.5: Extremely weak (Just noticeable)	0.5: Extremely weak (Just noticeable)
-1 : Very weak	1 : Very weak
-2 : Weak	2 : Weak
-3 : Moderate	3 : Moderate
-4 : Somewhat strong	4 : Somewhat strong
-5 : Strong	5 : Strong
-6 :	6 :
-7 : Very strong	7 : Very strong
-8 :	8 :
-9 :	9 :
-10 : Extremely strong discomfort	10 : Extremely strong comfort

Figure 14. Revised Borg CR 10 Scale (1990) for discomfort and comfort assessment

4.5. Variables

All variables that have been used in the current work are summarized in Table 7. Detailed analysis methods are explained in the relevant chapters. Two vehicle classes (sedan, S; SUV, U), two seats (S1 and S2, and U1 and U2 from higher (1) and lower (2) rated vehicles in a given vehicle class, respectively), and two driving venues (lab-based, -L; field, -F) were involved.

Table 7. Independent and dependent variables

Type		Name and Description	
Independent Variables		Seat Condition: 6 levels (S1-L, S1-F, S2-L, U1-L, U1-F, U2-L)	
		Stature: 3 levels (Short, Middle, Tall)	
		Age: 2 levels (Younger, Older)	
		Gender: 2 levels (Male, Female)	
		Culture: 2 levels (North American, Korean)	
Dependent Variables	Subjective	Overall rating	Whole body
		Comfort rating	Whole body and 23 local body parts including - Left/right thighs (THL/THR) - Left/right buttocks (BTL/BTR) - Upper/lower back (UB/LB)
		Discomfort rating	
		Alertness rating	Alertness after driving
		Design Preference	Seat Aesthetics
	Objective	Overall pressure	Sum of six local body part pressures
		Local pressure	Each local body part
		Joint angle	13 joint angles

Data for the older group were analyzed separately and were not be included in factorial analyses where stature effect was investigated. Instead, data from the younger group that were most closely matched by stature was selected and compared with those of the older group. The same is true for the Korean group (Tables 6-7).

4.6. Minimizing effects of confounding factors

Firstly, to minimize aesthetic effects on the participants' perceived feelings, as Oliver (1970) observed, seats selected for this study shared the following features: manual adjustments of the seat track and seat cushion and back angles, no seat armrest, and neutral-color seat covering. Indeed, lumbar supports were available from two SUV seats (U1 and U2), but they were initially set to the middle range and were not used in order to minimize the difference between seats. In this way, at least two features (power seat, lumbar support) were excluded which were shown to affect user's feelings positively in Schneider et al. (1989)'s study. Further, to try to minimize any effect of seat color, the seat cushion was always covered with a pressure mat so participants could see only the seat back. The seat back was not covered with a pressure mat during initial adjustment period, as it was observed in pilot work that the mats hampered participants' free access to the seatback recliner, and that many wrinkles on, and the misalignment of, mats occurred if both mats were placed simultaneously. Hence, the second mat for the seat back was placed and the first mat for the seat cushion was realigned (if necessary) after initial adjustment and before the beginning of driving.

Secondly, to minimize thermal effects on the subjective ratings, room or vehicle temperature was set to the participant's preference before the driving session started. Ambient factors are usually set to predefined levels, yet the potential for confounding may still exist. For example, Karjalainen (2007) observed significant differences in thermal comfort and temperature preference between gender groups. Therefore, a preferred method is to allow participants to select the levels of any controllable ambient factors according to their preferences.

Despite the controls described above, aesthetic effects (e.g., the appearance of the individual seats) were thought to have the potential to act as confounders (e.g., seat backs were exposed to participants). As a partial assessment of this, participants were asked to provide expected comfort level of each seat, based solely on the seat's appearance. At least one week after completing all the driving sessions, digital images were sent to participants, via email, and the participants rated each seat's expected comfort level.

Chapter 2: Driver sitting comfort and discomfort - Use of subjective ratings in discriminating car seats and correspondence among ratings

Abstract

Several subjective rating schemes were investigated, to determine which might be the most effective for use in designing and evaluating car seats, and what relationships exist among these schemes. Participants (n=27) completed short-term driving sessions, in six combinations of seats (from vehicles ranked high and low on overall comfort), vehicle class (sedan and SUV), and driving venue (lab-based and field). Overall ratings were obtained, as well as separate measures of comfort and discomfort of the whole-body and local body parts. No association was found between subjective ratings and a publicly available overall vehicle comfort score (J. D. Power & Associates' Comfort Score), implying that other factors besides sitting comfort / discomfort (and car seats) account for overall vehicle comfort. Other major results were that contemporary car seats appeared to best accommodate those of middle stature, that packages/seats of sedans were preferred over those of SUVs, that separate processes appeared to be involved in determining whole body comfort and discomfort, and that ratings of comfort were most effective at differentiating among the car seats. Alertness was found to be strongly correlated with comfort, whereas seat aesthetic effects on perceptual responses were minimal. Finally, a scheme for the use of subjective ratings was suggested: discomfort ratings for ensuring basic seat requirements (pain prevention-oriented) and comfort ratings for promoting advanced seat requirements (pleasure promotion-oriented).

Relevance

Evidence regarding the advantages and disadvantages of different subjective rating schemes can facilitate future design and evaluation of automotive seats.

Keywords: comfort; discomfort; sitting; driving posture; packaging

1. Introduction

Seated postures have been regarded as potentially unhealthy, and considered as one of the major contributing factors for several musculoskeletal disorders such as pain in the lower back (Ebe and Griffin, 2001), neck (Schneider and Ricci, 1989), and shoulder (Magnusson and Pope, 1998). Due to increased exposures to seated postures (Grieco, 1986), especially in the car (Rajput and Abboud, 2007), sitting comfort has become an important issue that demands adequate ergonomic interventions (Dunk and Callaghan, 2005).

A driver's sitting comfort, however, needs to be distinguished from sitting comfort in home or office chairs, or in the non-vehicular workplace (Andreoni et al., 2002). The former involves more restrictions to posture in a more limited space, several controlling tasks, and vibration from the road that can lead to a higher risk of musculoskeletal disorders. Indeed, an epidemiological study by Gyi (1996) showed that people exposed to over four hours of driving per day were more than twice as likely to suffer from low back pain compared to those with over four hours of sedentary work per day. Annett (2002) defined a generalized relationship between ergonomics constructs (in our case, sitting comfort) and challenge factors (i.e., task, object, environment), and regarded a construct as a complex (i.e., behavioral, verbal, or physiological) response to a challenge. This author's view also supports that in-vehicle sitting comfort needs to be distinguished, as it is under different challenge factors (e.g., different levels of confined space, vibration, and visuomotor demands). Despite this, relatively less attention has been paid to sitting comfort in a car (Harrison et al., 2000).

In addition, sitting comfort needs to be divided into sitting comfort and discomfort. Several studies have suggested that comfort and discomfort be treated as complementary but independent entities (Sauter et al., 2005; Zhang et al., 1996). Similarly, using Maslow's hierarchy of needs (1943), Hancock and Pepe (2005) showed that discomfort and comfort are at different stages of needs, the latter being placed at a higher stage than the former. Most studies that have quantified subjective responses in seated postures, however, have included only a discomfort scale (e.g., Hsu and Wang, 2003; Jung and Choe, 1996; LeBlanc et al., 2003; Straker et al., 1997), largely due to their primary focus on pain prevention (Hancock and Pepe, 2005). Other studies have used one scale to measure mixed feelings by placing comfort and discomfort on opposite end of a continuum (e.g., Genaidy et al., 1995; Genaidy and Karwowski, 1993; Kee and Karwowski, 2001, 2003, 2004). In other studies comfort was not measured, and only a discomfort scale was used with supplemental objective measures such as electromyography (EMG), center of pressure

(COP), or interface pressure (e.g., Fenety et al., 2000). In their review of literature on sitting comfort and discomfort, de Looze et al. (2003) observed that in none of the reviewed studies had comfort and discomfort been simultaneously but separately rated using two different scales.

Driving postures are related to both comfort and discomfort. In a study by Hanson et al. (2006), participants described their preferred driving posture using adjectives. A total of 119 descriptions were collected and classified into four groups: mental (comfortable, relaxing, restful, nice, peaceful and calm), environment (adjustable, adaptable, flexible supportive, spacious and good field of vision), generally positive (good, perfect, fantastic and wonderful), and generally negative (troublesome and less good). Compared to the descriptors given in Zhang et al. (1996)'s study on sitting comfort and discomfort (Figure 15), their findings suggest that the driving posture indeed is related to both comfort and discomfort. From this, it can again be argued that subjective responses to driving postures should be rated in terms of comfort and discomfort, using two separate scales.

Zhang et al. (1996) denoted that comfort and discomfort are not merely opposing constructs, and identified well-being as one component of comfort. According to Warr (1999), well-being should also be treated as an independent construct. He showed that well-being can be measured on the three axes of comfort-anxiety, pleasure-displeasure, and enthusiasm-depression. A good state of well-being is partially related to comfort (e.g., at ease, relaxed), but not inclusively (e.g., enthusiastic and pleased are not part of comfort). Likely, a bad state of well-being is partially related to discomfort (e.g., uneasy, fatigued), but again not inclusively (e.g., anxious and depressed). A model combining the views of Zhang et al. and Warr (Figure 15) indicates that some components of comfort and discomfort indeed have opposite meanings (e.g., supported, at ease vs. unsupported, uneasy), or are common (e.g., sleepy, drowsy), and that well-being is related to both comfort and discomfort, but is not merely part of comfort or discomfort.

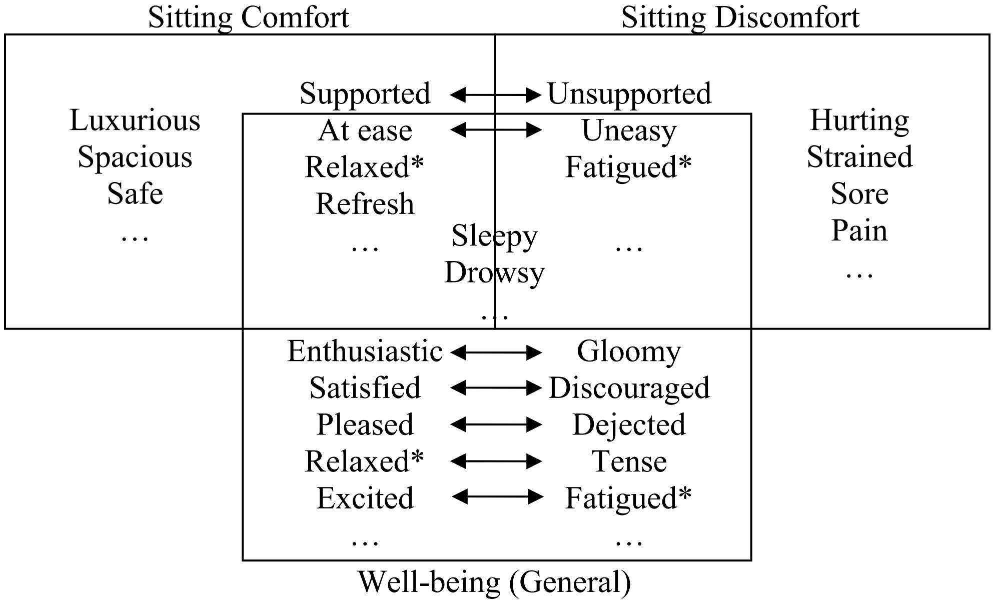


Figure 15. A combined model of sitting comfort and discomfort (Zhang et al., 1996) and well-being (Warr, 1999) (*: Opposite feeling found only in the construct of well-being)

Hanson et al. (2006) showed that preferred driving postures are not bilaterally symmetric, or that different comfort / discomfort ratings may be obtained for paired body parts. However, previous studies have tended to assume a symmetrical driving posture between the two sides (e.g., Porter and Gyi, 1998; Reed et al., 2002). In addition, most previous studies on sitting comfort / discomfort have made restrictions on seat configurations (e.g., seat back/cushion reclining angle) and/or sitting postures (e.g., torso/knee angle), which may have prohibited participants from being in the most comfortable (preferred) postures possible according to their sitting strategy (Andreoni et al., 2002), and interrupting necessary adjustments of the seat and steering wheel.

The primary objective of this study was to compare among several subjective ratings and to suggest their appropriate usage in the assessment of subjective responses in driving posture. As addressed above, designing a car seat is a challenging task that must meet multiple requirements; within a confined space where vibration is generally present, the car seat is required to accommodate diverse groups of people by firmly supporting and physically fitting their preferred postures as well as by allowing freedom to change postures. In order to support some of these requirements, this study investigated which, among several, subjective rating schemes might be the most effective for use in designing and evaluating car seats, and what relationships exist among these schemes. In addition, the association between sitting comfort / discomfort in the car seat and a publicly available overall vehicle comfort score was examined.

2. Methods

2.1. Overview of experiment and participants

The experiment involved a number of driving sessions, in which a variety of subjective comfort and discomfort responses were obtained. Of particular interest were how these responses were influenced by stature, vehicle segment, specific seat, and whether driving was real (on-road) or simulated (lab-based), each of which were independent variables. In addition to the subjective responses, other measures were obtained (posture and pressure) but are not presented here.

Twenty seven volunteers were recruited from the local student body and general community. Criteria for inclusion were: possession of a valid driving license for a minimum of two years, normal or corrected-to-normal eye vision in both eyes, no current musculoskeletal disorders, and age between 20 and 35. In addition, efforts were made to obtain a group of individuals with a wide range of statures, and participants were divided into three stature groups as shown in Table 8. Participants completed an informed consent procedure approved by the local IRB, and were compensated for their time.

Table 8. Participant characteristics

Stature group	# of participants (male, female)	Mean (SD) stature (cm)	Mean (SD) mass (kg)
Short (<165 cm*)	9 (0, 9)	158.4 (4.4)	57.4 (7.4)
Middle	9 (4, 5)	169.9 (3.9)	73.0 (12.2)
Tall (>175 cm+)	9 (8, 1)	183.9 (6.4)	76.7 (11.0)
Total	27 (12, 15)	170.7 (11.7)	69.1 (13.1)

* 18th or lower percentiles of gender-mixed population; + 90th or higher percentiles of gender-mixed population (Source: NHANES III, 1994)

2.2. Seat Conditions (seats, vehicle classes, and driving venues)

One objective was to determine how well overall vehicle comfort / discomfort are accounted for by car seat comfort / discomfort. The former was obtained from the J. D. Power and Associates'

Comfort Score (a publicly available source of vehicle overall comfort scores). This score is based upon customers' opinions regarding their car's "comfort and convenience features and seats" (J. D. Power and Associates, 2005). It is specifically defined as follows; "Taken from the most recent Automotive Performance, Execution and Layout Study (APEAL) study, which looks at the features that consumers like and dislike about their vehicles, this score is based on how consumers rated comfort and convenience features and seats" (J. D. Power and Associates, 2005). This score seems to be related to features-oriented general comfort, and not necessarily confined to the sitting comfort. Nonetheless, it was used as the vehicle and seat selection criteria to investigate to what extent sitting comfort / discomfort accounted for the general comfort (and discomfort) felt in a car. Comfort Scores are published annually, and sometimes different scores are found for the same car model between two consecutive years (possibly due to minor or major model changes). Therefore, to ensure consistency in terms of comfort, only cars that were rated equally for three years were used in this study, and the corresponding model-year vehicles and seats were accordingly obtained.

Specific seats were selected that were substantially different based on these scores. This selection was intended to facilitate identifying the relative importance of sitting comfort / discomfort in the determination of a vehicle's overall comfort / discomfort. Also, use of these scores was thought to be less biased than use of 'in-house' ratings. This issue arose from a remark by Helander et al. (1987, p. 1316) that "unless there are no obvious violations of biomechanics design rules, chair users will not complain about discomfort", which seems to be the typical case for contemporary automotive seats. Thus, instead of selecting seats by their foam thickness, size, material, etc., a different approach was taken; two vehicles (and their seats) from the same class were selected, that were rated high or low. Two vehicle classes (sedan and SUV) were also included (four vehicles total, two from each class).

To minimize aesthetic effects on the participants' subjective responses, selected seats shared the following features: manual adjustments of the seat track, seat back and cushion angles, no seat armrest, and neutral-color cloth coverings. Adjustable lumbar supports were available with two of the seats, but were set to the middle of their respective ranges. In this way, at least two features (power seat, lumbar support) were excluded that have been shown to affect user's feeling positively (Schneider and Ricci, 1989).

Two driving venues were included. These were real driving, over a predetermined course on local streets, and simulated driving, in a lab-based driving rig. These are described in more detail below. Of the eight combinations of seat, vehicle class, and driving venue, a subset of six Seat Conditions were included (seats from low-rated vehicles were only tested in the lab). In the lab-based simulations, the initial package configuration was set to that of the higher-rated vehicle of the respective class. A summary of the conditions and codings are provided in Table 9.

Table 9. Overview of testing conditions and codings (seats, vehicle classes, and driving venues)

Vehicle class	Sedan		SUV	
Code name	S1	S2	U1	U2
J. D. Power Comfort Score* (rating years)	High (4) (2003~2005)	Low (2) (2003~2005)	High (4) (2003~2005)	Low (2) (2001~2003)
Model year of car and seat used	2005	2003	2004	2001
Venue: Lab/Field	Y/Y	Y/N	Y/Y	Y/N
Comparison (Code)	Lab vs. Field (S1-L vs. S1-F)	S1 vs. S2 (S1-L vs. S2-L)	Lab vs. Field (U1-L vs. U1-F)	U1 vs. U2 (U1-L vs. U2-L)
Driving package used in the rig	S1	S1	U1	U1

*: 5 (= among the best), 4 (= better than most), 3 (= about average), 2 (= the rest)

2.3. Data collection procedures and processing

In order to minimize possible order and fatigue effects, presentation order of the six Seat Conditions was randomized. Each experimental session, both in the field and lab, lasted approximately 20 minutes (5 minutes of initial adjustments and 15 minutes of driving). The driving duration was specified to account for a driver settling into the seat (Reed et al., 1999), and about 82% of trip durations (Reed et al., 1994). In the field driving sessions, participants could adjust the seat and steering wheel as needed, though this was obviously limited to the adjustment rages of the actual vehicle. Lab sessions were conducted in an adjustable driving rig that provided more flexible and extended adjustment ranges in both the seat and steering wheel. During the lab-based session, a digital video was projected in front of participants. The video displayed a through-the-windshield view of the predetermined field driving course.

Before each driving session, participants adjusted the positions of the seat and steering wheel using a modified method of fitting trials (Jones, 1969). The original method of fitting trials set all parts to their initial positions except one part being adjusted, whereas the modified method makes a sequential adjustment with the previous parts being set to the selected positions. Participants adjusted each part's position, with assistance, according to a predefined sequence: seat fore/aft position, seat back angle, seat cushion angle, steering wheel angle, steering wheel fore/aft position, and then final micro-adjustments of any part. If a participant felt uncomfortable with this sequence, they were free to change it. In this way, except for the gas pedal (which was set to the original S1 or U1's position and angle), the seat and steering wheel were adjusted and readjusted by participants as much as they desired in order to yield their most preferred driving postures. At any time during 15 minutes of driving the participants could adjust their postures and the seat and steering wheel positions. In addition, after 8 minutes and at the end of the sessions, they were asked if they wanted to adjust either the seat or steering wheel.

2.4. Subjective ratings

Several scales were used by participants, at the end of each driving session, to assess perceived comfort and discomfort. Two scales (comfort and discomfort, Figure 16) were used for the whole body and six local body parts (bilateral thighs and buttocks, and lower and upper back). These scales were derived as combinations of versions developed by Borg (1990) and Corlett-Bishop (1976). In addition, a visual analogue scale (VAS, Figure 16) was used to obtain overall ratings of comfort and discomfort for the whole body. To minimize confusion, ratings were obtained in a consistent order: whole body discomfort, local body part discomforts, whole body comfort, local body part comforts, and overall rating. Each rating was provided on a separate sheet, and participants were reminded each time which score was the best/worst (e.g., for discomfort, zero is the best). In the lab sessions, the rating sheet was projected on the screen that displayed the driving scene, while in the field study (after the vehicle was parked) the rating sheet was placed in front of the participant so that they maintained their driving postures while providing ratings.

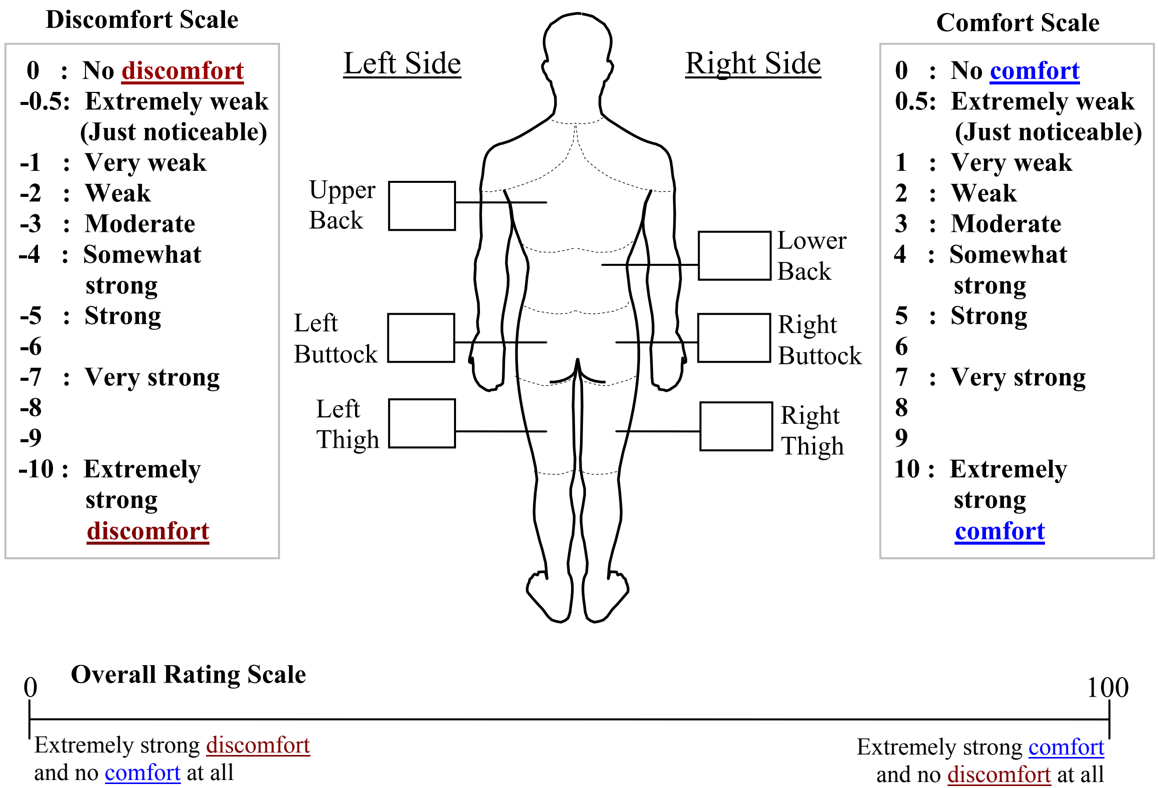


Figure 16. Comfort and discomfort rating scales (top, modified from Borg, 1990 and Corlett and Bishop, 1976) and overall rating scale (bottom)

Despite controls described above, aesthetic effects (e.g. the appearance of the individual seats) were thought to have the potential to act as confounders. As a partial assessment of this, participants were asked to provide expected comfort level of each seat, based solely on their appearance. At least one week after completing all the driving sessions, digital images were sent to participants, via email, and they rated the seats' expected comfort levels using the same scale as the J. D. Power Comfort Score (range of 2 to 5).

2.5. Data analysis

A mixed-factor analysis of variance (ANOVA) was used to determine the effects of Stature (3 levels, between-subjects) and Seat Condition (6 levels, within-subject) on subjective ratings, with the Tukey's Honestly Significantly Different (HSD) test for post-hoc pairwise comparisons. Effects were considered 'significant' or 'marginal' when $p \leq 0.05$ and $0.05 < p \leq 0.1$, respectively. Specific pairwise comparisons were done to determine if there were driving venue (lab vs. field) effects (S1-L vs. S1-F, U1-L vs. U1-F) and/or seat effects within vehicle class (S1-L vs. S2-L, U1-L vs. U2-L). In addition, two linear contrasts were tested: 1) if there was a main effect of stature (or, its effect was marginal), a linear contrast of stature groups (Middle vs. Short + Tall) was done to examine if the seats accommodated extremes in the population similar to the middle; and 2) if a main effect of Seat Condition was found (or, its effect was marginal), a linear contrast of vehicle classes (S1-L + S2-L + S1-F vs. U1-L + U2-L + U1-F), to compare preferences between the two classes. Ratings between bilateral body parts (thighs, buttocks) were examined using matched pairs comparisons. Bivariate coefficients of correlation (ρ) were obtained among the several subjective ratings. Possible aesthetic effects of four seats on comfort rating were examined using a univariate repeated-measures ANOVA. One female participant finished only the lab sessions, and this data was included for analysis.

3. Results

3.1. Whole body ratings (overall, comfort and discomfort)

<u>Whole body overall rating</u>

There was a significant ($p=0.0056$) interaction effect of Stature x Seat Condition on whole body overall ratings. Stature was not a significant main effect, while the effect of Seat Condition was marginal ($p=0.058$). Overall ratings tended to be higher in the seats of lower-rated vehicles (S2 and U2, Figure 17). A significant difference between vehicle classes was found ($p=0.018$), wherein sedan conditions were rated higher than SUVs (Figure 17), with means (SD) of 84.1 (13.3) and 80.7 (15.1), respectively.

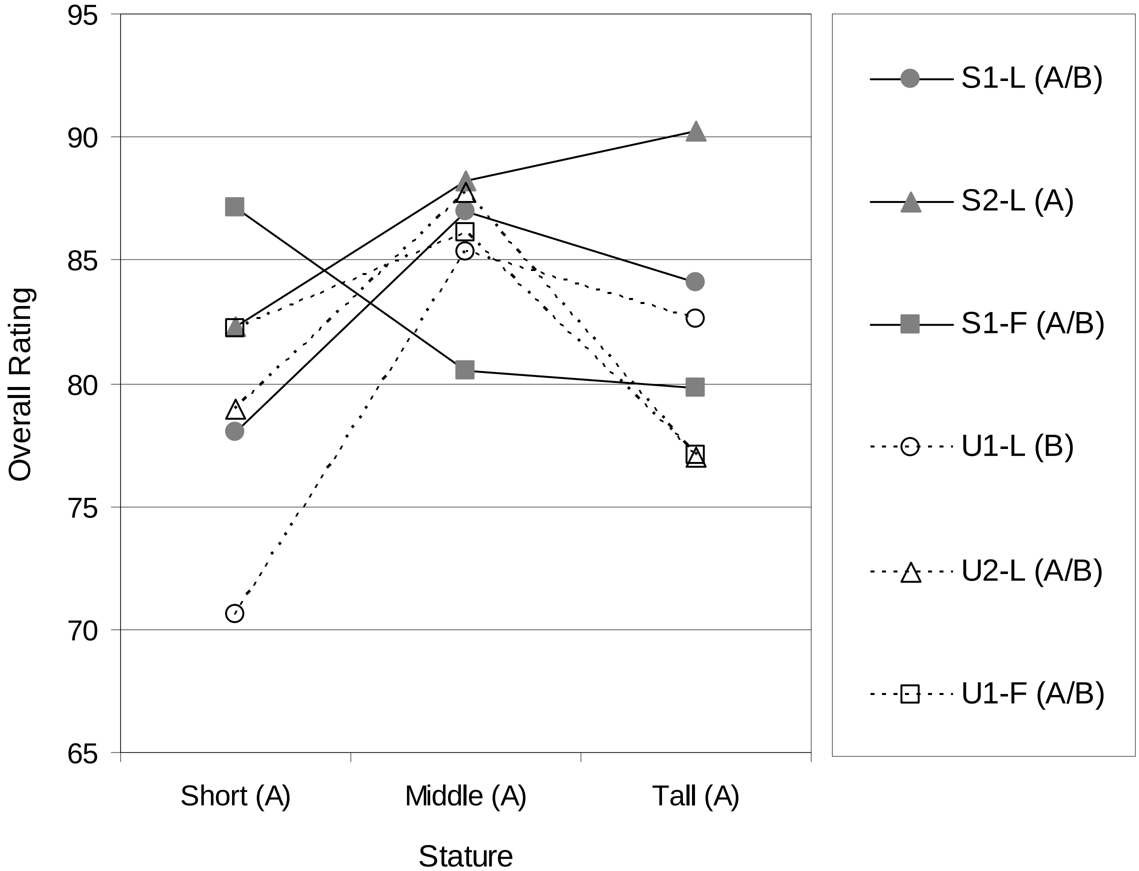


Figure 17. Effects of Stature and Seat Condition on overall ratings (Tukey's HSD grouping in parentheses; Solid symbols for sedans; Circle and square for seats of highly-rated cars according to J. D. Power and Associates' Comfort Score; Standard deviations not shown for clarity, range = 5.4~22.5)

Whole body comfort rating

There was a significant (p=0.0022) effect of Seat Condition on whole body comfort ratings. One of the selected pairwise comparisons of seats (S1-L vs. S2-L) was significant, with the seat from a lower-rated sedan (S2) being rated higher. The effect of stature was marginal (p=0.070), with higher ratings obtained from the middle group. A significant contrast between vehicle classes was found (p=0.014), with sedans conditions rated higher than SUVs (Figure 18). Respective means (SD) were 7.1 (2.5) and 6.5 (2.9).

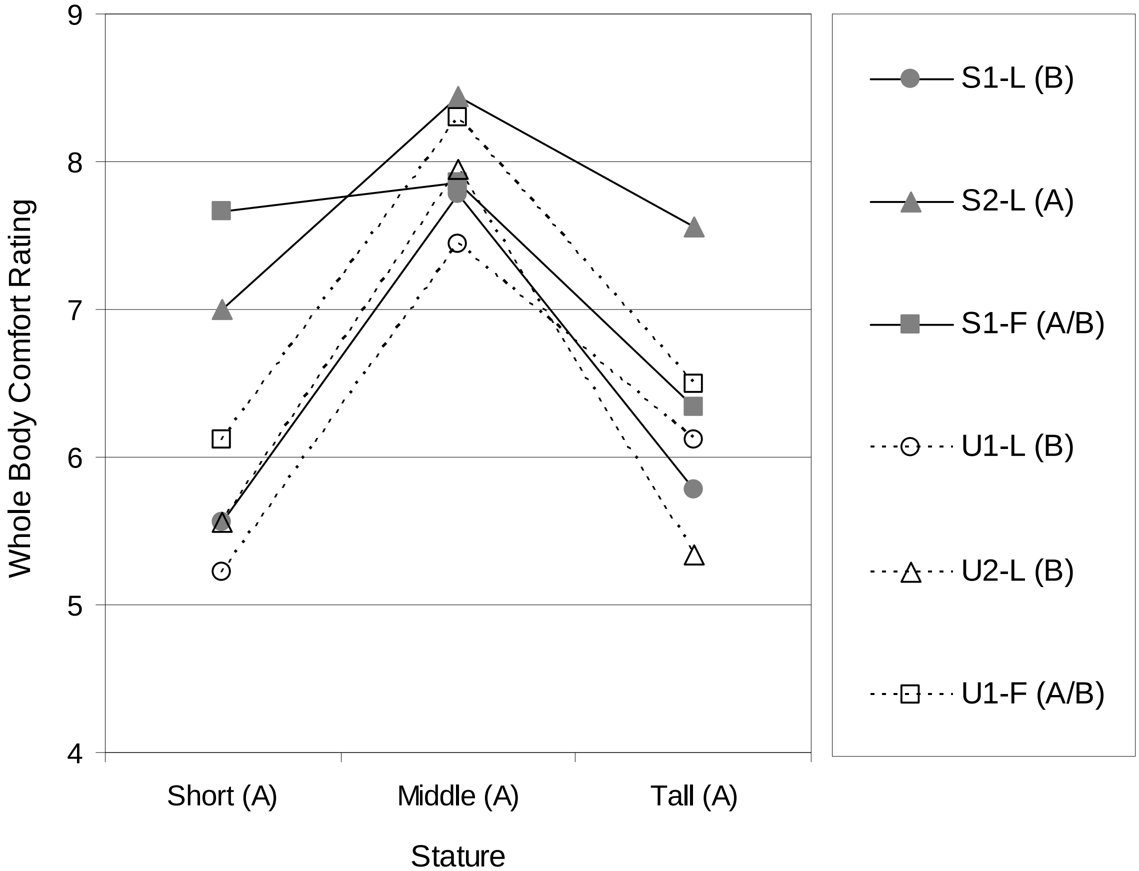


Figure 18. Effects of Stature and Seat Condition on whole body comfort rating (Tukey's HSD grouping in parentheses; Standard deviations not shown for clarity, range = 1.5~3.4)

Whole body discomfort rating

For whole body discomfort ratings, the Stature effect was marginal (p=0.098), while Seat Condition effect was not significant (p=0.41). Comparisons between driving venues or seats were not significant. The contrast of stature groups was significant (p=0.036), with higher ratings from the middle group (i.e., lower levels of discomfort). The contrast of vehicle classes was marginal (p=0.090), with sedans conditions rated higher than SUVs (Figure 19). Mean (SD) ratings were -0.8 (0.9) and -1.1 (1.3), respectively.

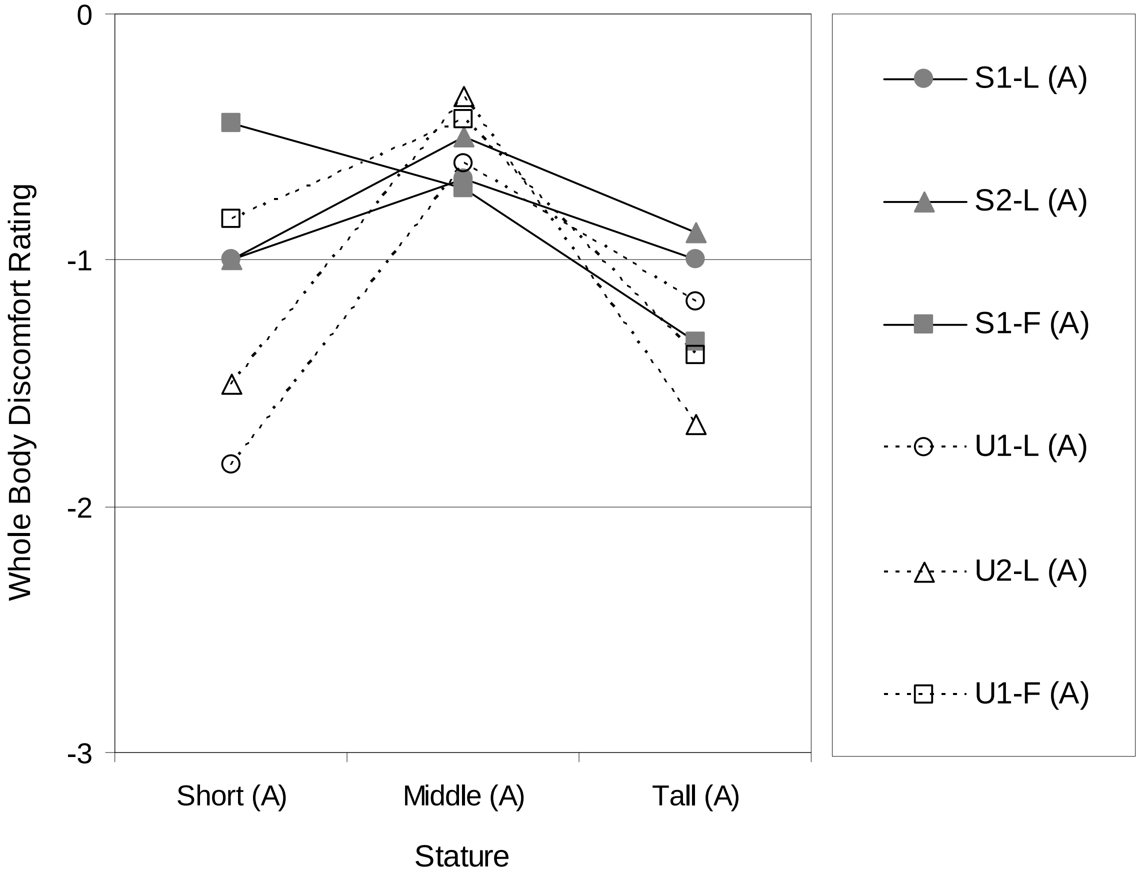


Figure 19. Effects of Stature and Seat Condition on whole body discomfort rating (Tukey's HSD grouping in parentheses; Standard deviations not shown for clarity, range = 0.4~2.0)

3.2. Local body part ratings (comfort and discomfort)

Mean ratings for the left thigh (THL) were higher than those for the right thigh (THR) in terms of comfort ($p=0.040$) and discomfort ($p=0.067$). For the buttocks, though not significant ($0.1<p<0.16$), mean right buttock (BTR) ratings were higher than mean left buttock (BTL) ratings for both comfort and discomfort. Both paired parts, however, were included in further analysis, in consideration of the asymmetry of driving posture (Hanson et al., 2006) and possible averaging processes in rating (Humphreys, 2005).

Local body part comfort ratings

Interaction effects of Stature x Seat Condition on BTL and BTR comfort were marginal (p=0.085, 0.095), whereas the interaction effect on lower back (LB) comfort was significant (p=0.043). The effect of Stature on LB comfort was also marginal (p=0.096, Figure 20). Seat Condition effects on THR, BTL, and BTR comfort were marginal (p=0.051, 0.083, 0.094), whereas its effect on upper back (UB) comfort was significant (p=0.0028, Figure 21). The contrast of stature groups on LB and UB comfort was significant (p=0.035, 0.047), with higher ratings among the middle group. Except for UB, the contrast of vehicle classes either was marginal (THL, THR, BTL, and BTR at p=0.072, 0.052, 0.083, and 0.077) or was significant (LB at p=0.039), with sedan conditions rated higher than SUVs in all five cases.

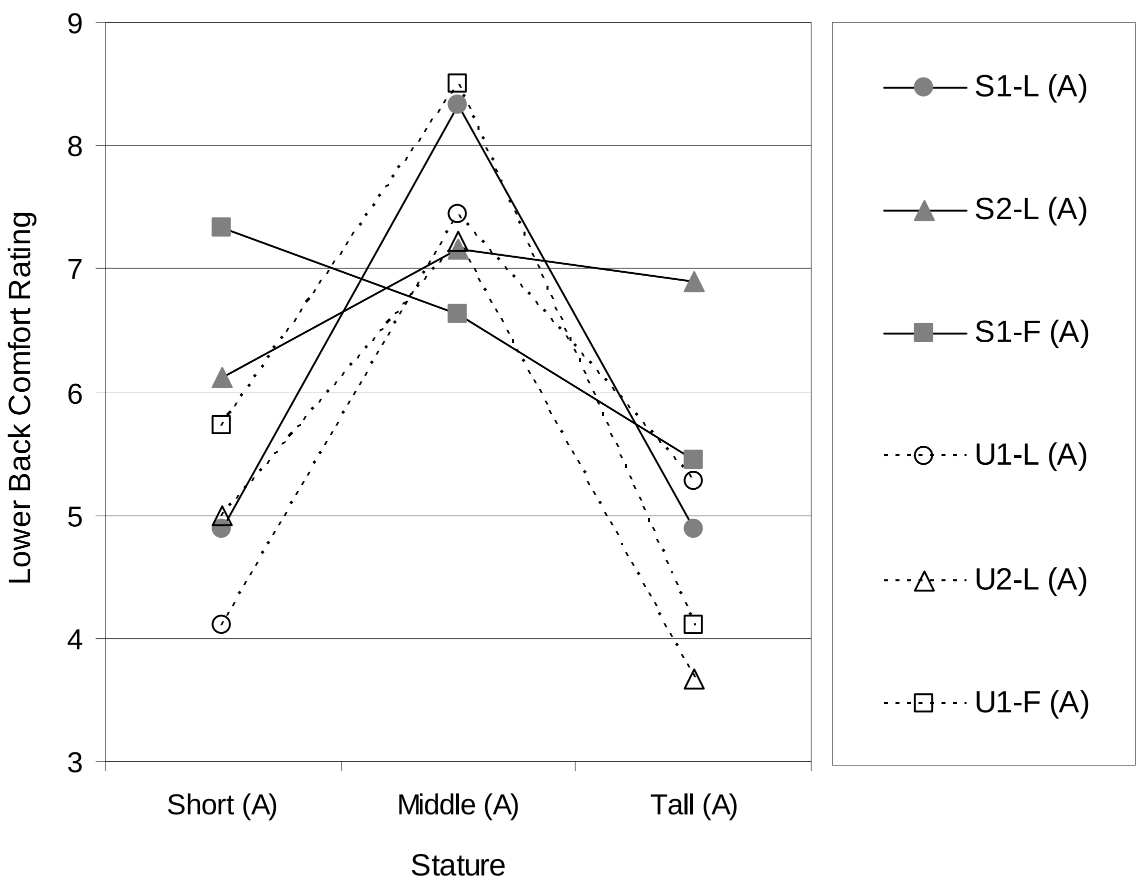


Figure 20. Effects of Stature and Seat Condition on lower back (LB) comfort rating (Tukey's HSD grouping in parentheses; Standard deviations not shown for clarity, range = 1.8~3.9)

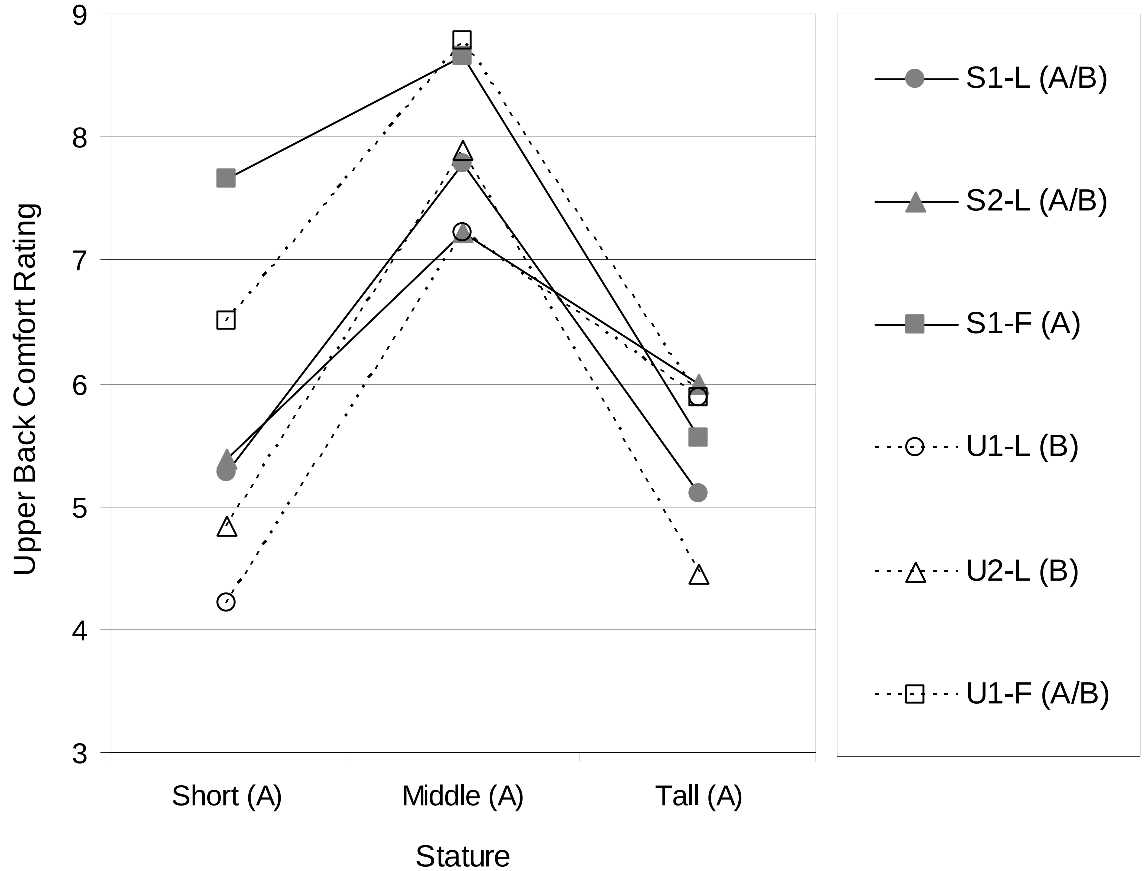


Figure 21. Effects of Stature and Seat Condition on upper back (UB) comfort rating (Tukey's HSD grouping in parentheses; Standard deviations not shown for clarity, range = 1.4~3.8)

<u>Local body part discomfort ratings</u>

Stature effects on UB discomfort were marginal (p=0.076), whereas the Seat Condition effect on UB discomfort was significant (p=0.018, Figure 22). No effects were found for other body parts (thighs, buttocks). The contrast of the stature groups on LB was significant (p=0.038), with the middle group providing higher rating (i.e. less discomfort). The contrast of vehicle classes on BTL was marginal (p=0.088), whereas the contrast of vehicle classes on LB and UB was significant (p=0.033, 0.025), with sedan conditions rated higher than SUVs in both cases.

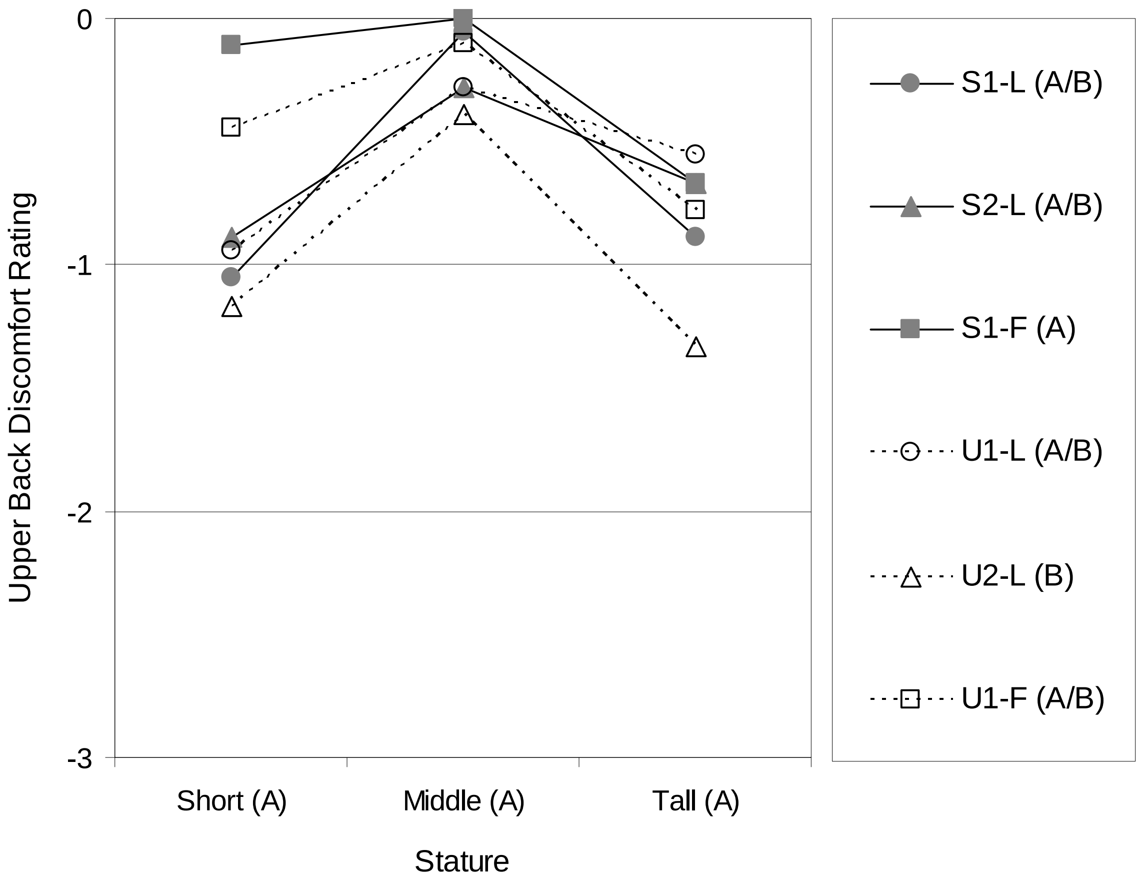


Figure 22. Effects of Stature and Seat Condition on upper back (UB) discomfort rating (Tukey's HSD grouping in parentheses; Standard deviations not shown for clarity, range = 0.0~1.6)

3.3. Correlations among subjective rating schemes

<u>Correlations among whole body ratings</u>

All bivariate correlations among the three whole body subjective ratings were significant ($p<0.0001$). Overall ratings had a higher correlation with whole body comfort ($\rho = 0.76$) vs. discomfort ($\rho = 0.53$) ratings, while the correlation between comfort and discomfort ratings was $\rho = 0.55$.

Correlations among ratings of whole body and local body parts

All local body part comfort ratings were moderately-highly correlated with each other ($\rho>0.70$) and with whole body comfort ($\rho>0.77$). Right and left paired body parts (i.e., thighs, and buttocks) were highly correlated ($\rho=0.96$, 0.99) in terms of comfort. Discomfort ratings between paired parts were also highly correlated ($\rho=0.93$, 0.96 for thighs and buttocks). Among the body parts, LB and UB discomfort had the highest correlations with whole body discomfort ($\rho=0.75$, 0.67). In addition, LB discomfort was highly correlated with whole body discomfort regardless of stature (short: $\rho=0.79$, middle: $\rho=0.71$, tall: $\rho=0.68$).

3.4. Aesthetic effect of seat

The effect of seat appearance on the expected level of seat comfort was not significant ($p=0.83$). Means values for the four seats ranged from 3.3 to 3.6 (between 'about average' and 'better than most').

3.5. Subjective ratings vs. alertness

Among the three subjective ratings, comfort ratings showed the strongest relationship with alertness level with $\rho = -0.53$, indicating a higher comfort level (closer to 10) is related to a higher alertness level (closer to 1). Discomfort and overall ratings showed weaker relationship with $\rho = -0.29$ and -0.49, respectively.

4. Discussion

Three rating schemes were used to quantify subjective responses to driving postures. Of primary interests were their inter-relationships and their relative effectiveness in distinguishing car seats, with a longer-term goal of determining suitable methods for obtaining such subjective responses. Toward these aims, several factors were included (seats, driving venues, vehicle classes, and stature groups), and a variety of analyses were employed. Effects of each factor are described and interpreted below, with implications and/or suggestions relevant to these aims.

Though important, sitting comfort / discomfort appeared to be only part of overall vehicle comfort. For whole body comfort ratings, S2-L was rated higher than S1-L, indicating the S2 seat (from a vehicle with a lower J. D. Power Comfort Score) was perceived as a better seat. It is possible that the S2 is a high-quality seat, yet other factors in the vehicle were relatively poor. These factors include, for example, other aspects of the vehicle package (note, the package of S1 was used in the experiment for S2-L), and/or on-road dynamic performance. Indeed, the Comfort Score is not limited to sitting comfort / discomfort, but instead is related to general in-vehicle comfort and convenience features as well as seats. Though sitting comfort / discomfort (and the seat) are still important factors for overall comfort in a car, these results support that other factors such as package (Rebiffé, 1969), aesthetics of seats (Zhang et al., 1996) and other car parts, seat/vehicle dynamic performance (Donati, 2002; Griffin, 1990), and thermal comfort (Cengiz and Babalik, 2007), can also substantially affect a vehicle's overall comfort.

Similar to the findings given in Shackel et al. (1969)'s study on office chairs, it also appears that car seats are in one of three categories: a few poor seats, a few quality seats, and a majority of similar (good) seats that are hard to distinguish. Convenience and aesthetic factors (e.g., power seat, heated seat, leather covering, etc.) may distinguish a seat from others, but surprisingly the same general Comfort Scores were found between high and low trim levels of the same car.

No driving venue effect was found for any of the three ratings. The merit of extended package geometry (hence, more comfortable postures possible) available in the lab setting (S1-L and U1-L) was likely compensated by the actual (field) driving experience, despite the relatively confined field settings (S1-F and U1-F). The latter conditions, for example, might be more engaging, enjoyable, and provide more interaction with environment. In addition, a possible positive effect of vibration can account for this result, as low-frequency vibration facilitates muscle blood flow (Makhsous et al., 2005).

There were package differences between S1 and U1 (in this case, due to the vehicle class difference). A sedan package (as in S1) typically has a lower seat height and a more reclined seat back angle than an SUV package (as in U1). Between the S1 and U1 packages, there was a 35mm difference in seat height and a 3^{o} difference in seat back angle at initial settings. For both overall and comfort ratings, the S1 package was rated higher than the U1 package, indicating that the participants preferred lower and more reclined seat positions (and driving postures). The package factor can even generate physiological changes. A case study by Rajput and Abboud (2007) reported that a package difference in an SUV caused abnormal callus development in a patient's right foot, by inducing the right lower limb to be more abducted.

Seats used in this study seemed to be optimized for the middle-stature group. Better ratings were found in this group, in terms of whole body discomfort and comfort, discomfort in their LB, and comfort in their UB. This implies that current seats do not accommodate all stature groups equally, and that more adjustability in the seat (especially in the seat back) may be required, consistent with suggestions by Branton (1984) and Harrison et al. (2000).

Despite that driving sessions were relatively short, and done in preferred postures, relatively wide ranges were found in comfort and discomfort ratings (comfort: 0~10, discomfort: -5~0). Though mean discomfort levels (~-1.0) were close to the 'no discomfort' extreme, it would appear that automotive seats still have room for improvement in terms of discomfort. In particular, LB and UB discomforts had higher correlations (ρ=0.75, 0.67, $p<0.0001$) with whole body discomfort than any other local body part discomfort. Thus, improvement to seatbacks may be most effective at achieving further reductions in discomfort. Better ratings were found in sedan conditions for LB and UB discomforts, and for BTL discomfort. Although these results are from short-term exposures to different combinations of seats and packages, they are in accordance with evidence from long-term exposures. A survey study by Schneider and Ricci (1989), on a sample of 252 drivers (most of who drove more than one hour), showed that the back and buttocks were most frequently reported as uncomfortable.

There appear to be different processes used in determining whole body comfort and discomfort levels. In the case of comfort, all local body part comfort ratings had a similar level of correlation with each other ($\rho>0.70$) and with whole body comfort ($\rho>0.77$). Hence, an averaging process, across local body comfort levels, seems to have been used to determine whole body comfort level. In the case of discomfort, a different pattern was observed. First, an inverse relationship was found among the correlation between ratings of two body parts and the proximity of those parts (e.g., higher correlations were found between two body parts if they were closer in proximity). This suggests either that two body parts in close proximity affect each other's discomfort levels, or that there is less ability to discriminate discomfort between the two. The latter would seem more likely. Second, discomfort ratings in some body parts (LB and UB) were more highly correlated with whole body discomfort ratings, suggesting that whole body discomfort level might be predominantly determined by local maximal discomfort. Regardless of comfort and discomfort ratings, however, paired body parts (thighs, buttocks) were always highly correlated each other (ρ>0.93). These similar responses between paired body parts can partly be accounted for by the bilateral symmetry of the seat design (therefore, similar conditions). However, THR was rated lower (less comfort and more discomfort) than THL, which might be related to pedal operations.

Among the rating schemes, comfort rating was more effective at distinguishing the car seats. Seats from higher- and lower-rated vehicles (S1 and S2) were rated differently in terms of whole body comfort, whereas no difference between seats was found for whole body discomfort ratings. Though having a fairly high correlation with comfort ratings, overall ratings also failed to distinguish between seats, possibly due to discomfort effects. These results support a hypothesis that current car seats meet basic biomechanical requirements, so that differences between them, if any, can be most effectively detected in terms of comfort rather than discomfort. Accordance also exists with Helander's (2003) findings on office chairs. If seats with "no obvious violations of biomechanics design rules" (Helander et al., 1987, p. 1316) are used in a study of sitting comfort / discomfort (such as the seats in this study, and perhaps the majority of contemporary car seats), using a discomfort rating scale alone is likely to be ineffective in distinguishing subtle differences between seats (Helander, 2003). Similarly, using overall ratings, with a main aim of preventing pain, will also be ineffective in that the level of discomfort can be changed by simultaneous consideration of comfort on a continuum. On the other hand, if comfort and discomfort are treated and rated independently, then better ergonomic intervention / evaluation seems possible; discomfort ratings can be used to ensure that basic requirements are met, whereas comfort ratings can be used to compare the quality of seats in more subtle ways.

There were several potential limitations in this study. First, genders were confounded with the stature groups; the short group consisted of only females, and the tall group consisted of eight males and one female, whereas the middle group was gender-balanced. Though the gender confounding effect was minimized using an appropriate contrast of 'middle vs. (short+tall)/2', exclusion of short males and tall females may limit generalizing the results. Second, appearances of car parts could be a confounding factor. Though an aesthetic effect of seats on subjective ratings was not found, the measures obtained were somewhat crude. In addition, there may be aesthetic effects of other car parts, which could not be controlled, especially in field settings. Third, historical driving experience with specific vehicle classes could affect subjective responses. Two participants drove a truck and three drove an SUV as their primary car (driven most often). Among the remaining 22 participants, 16 drove a sedan and six drove a coupe. In general, trucks or SUVs have a higher seat (hence, higher hip) position than coupes or sedans. Thus, the higher ratings obtained for the sedan package and/or sedan seats found here could have resulted from familiarity with or habituation to lower-hip driving postures, rather than inherently better comfort in sedan seats or package. Lastly, while several effects were significant, substantial variability remained in the subjective ratings. Such variability indicates that there are other important factors affecting the subjective responses that are yet to be determined. None of these limitations, however, would seem to affect the primary results regarding the several rating scales.

5. Conclusions

Three different rating scales (overall, comfort, and discomfort ratings) were employed to obtain subjective responses to car seats from vehicles that were rated differently in terms of overall vehicle comfort (J. D. Power and Associates' Comfort Score). No significant associations were found between the Comfort Score and the three ratings. Additional factors (e.g., package, dynamic factor, and aesthetics of other parts in the vehicle) are thus likely being used in determining a vehicle's overall comfort. Based upon the subjective ratings, contemporary car seats appear to best accommodate those of middle stature. Comfort ratings were found to be the most effective at differentiating among the car seats. An approach for subjective ratings in this or a similar context is recommended: 1) use discomfort ratings to measure the basic qualities of seats (ensuring no violation of basic seat requirements or design rules), with a "prevention of pain" objective; 2) use comfort ratings to measure more subtle qualities of seats (promoting advanced seat requirements), with a hedonomic ("promotion of pleasure", Hancock and Pepe,

2005) objective. Use of an overall rating, while convenient, is not recommended, as it measures a mixed level of comfort and discomfort, and is inferior to an independent rating when used for either of the two objectives given above.

Chapter 3: Driver sitting comfort and discomfort - Relationships with and prediction from interface pressure

Abstract

Pressure at the driver-seat interface has been used as an objective method to assess seat design, yet existing evidence regarding its efficacy is mixed. The current study examined associations between three subjective ratings (overall, comfort, and discomfort) and 36 measures describing driver-seat interface pressure, and identified pressure level, contact area, and ratio (local to global) variables that could be effectively used to improve subjective responses. Each of 27 participants was involved in six separate driving sessions which included combinations of two seats (from vehicles ranked high and low on overall comfort), two vehicle classes (sedan and SUV), and two driving venues (lab-based and field). Several pressure variables were identified as more effective for assessing sitting comfort and discomfort across a range of individual statures. Based on the results, specific approaches are recommended to improve the sitting experience: 1) lower pressure ratios at the buttocks and higher pressure ratios at the upper and lower back; and 2) balanced pressure between the bilateral buttocks, and between the lower and upper body. Finally, separate analyses supported that human-seat interface pressure was more strongly related with overall and comfort ratings than with discomfort ratings.

Relevance

Several interface pressure variables were identified that showed associations with subjective responses during sitting. Use of these measures is suggested to improve the quality of car seats.

Keywords: interface pressure; sitting comfort; driving posture; packaging

1. Introduction

A comfortable seat plays an important (though not exclusive) role in the perception of a vehicle's overall quality. As a way of meeting customers' increased need for and expectation of vehicle comfort, car makers have been seeking more effective ways to improve car seats. It is hoped that improving seat comfort will distinguish their product from others in the competitive automotive market. Subjective ratings and objective measures (e.g., joint angles, pressure, electromyography) have been used to determine how to enhance sitting comfort and discomfort (de Looze et al., 2003). Among other factors, a driver's sitting comfort and discomfort have been shown to be influenced by whether there is adequate support for preferred driving postures (Reed et al., 1994), even distribution of contact pressure (Helander et al., 1987; Sanders and McCormick, 1987), and mitigated vibration (Johnson and Neve, 2001). Each of these should be provided by the driver's seat and can be described in terms of driver-seat interface pressure.

Such pressure data was regarded by de Looze et al. (2003) as an objective measure having a clear association with subjective ratings. Previous studies have shown that preferred pressure levels are different between body parts as well as between anthropometric groups (Dunk and Callaghan, 2005; Kamijo et al., 1982; Kolich, 2004; Oudenhuijzen et al., 2003), and that there are associations between interface pressure and sitting discomfort. On the other hand, some studies have failed to find this association. For example, Gyi (1996) indicated that sole use of interface pressure was not successful in predicting car seat discomfort. Therefore, use of different types of pressure data, and quantifying comfort instead of discomfort (as in Chapter 2), may be more successful at identifying associations between pressure and human responses. If so, such associations would facilitate determining seat design and evaluation criteria for diverse groups of people in terms of pressure levels.

As psychological constructs, similar to 'fatigue' or 'effort', comfort and discomfort have been suggested to require treatment as different and complementary entities in ergonomic evaluations and interventions (Sauter et al., 2005). Zhang et al. (1996) found that comfort and discomfort are orthogonal, and therefore should be treated independently. Consistent with the orthogonality between comfort and discomfort, the present study incorporated a separate scale for each of these, and aimed at finding their relationships with objective measures (i.e., interface pressure). The longer-term goal was obtaining effective methods, using pressure variables, for ergonomic intervention and evaluation of sitting comfort and discomfort in driving workspaces.

Precise quantification of in-vehicle sitting comfort / discomfort requires that seat and package geometries, driving postures and visual demands are set close to actual driving situations. Troup (1978) showed that the car seat is one major factor affecting a driver's comfort, and can play a positive role in prevention of back pain by alleviating vibration and road-shock. Rebiffé (1969), on the other hand, indicated that ergonomic vehicle packaging, specifically harmonic layout of relevant parts, is more important for overall comfort than the seat itself. Anshel (2005) indicated that visual information in human-machine systems was so dominant that its deficiency could often result in awkward body postures. Driving involves high visual demands (Wierwille and Tijerina, 1996), which can thus change the driving posture and result in postural discomfort (Pheasant, 1992). Seat and package geometries and driving postures, in turn, likely influence interface pressure distributions.

Besides ensuring realistic conditions, in terms of seat, posture, task, and environment, which are necessary (especially in a lab-based study) for their contextual effect on the human response (Annett, 2002), a safety belt should also be incorporated for the same reason. During the past five years (2000~2004), safety belt usage rates in the U.S have risen from 72% to 81% (BTS, 2006). Thus, to better represent driving conditions, a safety belt should be worn during an experiment. Further, without a proper restraining system, participants are more likely to slip forward and to be in (more) slouched postures, which can result in pressure changes.

In general, people have more limited freedom to change their postures in car seats than in traditional chairs. For reasons of musculoskeletal health, however, postural movement is essential. Akerbloom (1948) noted that a comfortable seat should accommodate postural changes. Jenny et al. (2001) stated that facilitation of nutrition and relief of muscle fatigue come from postural movement. Likewise, Dhingra et al. (2003) suggested that changes in body position should be allowed to relieve pressure on muscle groups and to relax them. Such postural change for comfort will also be reflected in pressure data.

Different pressure levels between bilateral lower body parts in a driving posture are expected due to the different task and postural requirements placed on each lower extremity. For example, the right foot, used to control pedals, is required to take more restricted postures with less consistent support, while the left foot, unless a clutch pedal is considered, is relatively free and consistently supported by the car floor or the foot rest. Due to this, the left foot (and the left lower limb) might be involved more dominantly in postural balance, which would result in a bilaterally asymmetric posture and pressure. Indeed, the preferred driving posture has been shown to be asymmetric (Hanson et al., 2006).

Short-term and long-term sitting comfort / discomfort need to be distinguished. Sitting discomfort increases over time while sitting comfort tends to remain constant (Helander and Zhang, 1997). Increased discomfort seems largely associated with fatigue, which can result from one hour of driving (Uenishi et al., 2002). Some authors have suggested long-term test durations for the assessment of seat discomfort. For example, Gyi and Porter (1999) stated that at least two hours of testing was required to clearly assess discomfort, which seems mainly focused on measuring fatigue in seated postures. Fatigue in sitting, however, could be simply due to "the passage of time" (Helander and Zhang, 1997), and not necessarily due to the seat design. Further, fatigue in vehicles has been shown to be affected by multiple other sources such as temperature, air quality, noise (Gameiro da Silva, 2002), and circadian factors (Brown, 1994; Moore-Ede et al., 2003; Van Dongen and Dinges, 2000). Use of interface pressure does not account for these factors, but rather accounts for the seat's support and pressure distribution characteristics and postural changes. Therefore, in using pressure data for assessment of sitting comfort / discomfort, a method is required that can determine their levels within a relatively short period of time. Moreover, a compiled version of the 1990 Nationwide Personal Transportation Survey (NPTS) data by Reed and Massie (1996) showed that about 82 percent of trips taken in the U.S. were ≤ 20 minutes. Hence, short-term driving is also more representative of actual driving patterns than long-term driving.

In contrast, more extended durations have been generally used when investigating sitting discomfort (largely due to fatigue). For example, Uenish et al. (2002) investigated driver fatigue in a lab-based environment and observed its occurrence in one hour. Gyi and Porter (1999) recommended at least two hours of testing to clearly assess discomfort (fatigue). As already noted, fatigue in seated postures has diverse contributing factors, and can actually result from other sources than the seat. Even when the seat is a major factor, other aspects, rather than the seat's function in providing support and distribution of body pressure, could be the major sources of any unpleasant feeling in sitting. These other aspects include the seat's aesthetics (color, texture, leather cover) and functionality (easy-to-use controls, lumbar support, power seat, massage seat, and evaporation characteristics).

Interface pressure is commonly used as an objective measure in the study of seat discomfort, but evidence suggests that more careful consideration is needed for proper use given its limitations. Several problems can occur when using pressure mats for extended periods. The first is creep, defined as a measurement drift under a constant load, and the second is hysteresis, which is apparent as a different force-displacement pattern between loading and unloading. In fact, Fay and Brienza (2000) suggested that creep and hysteresis could have been confounding variables in the work of Gyi et al. (1999), leading to their failure to identify “a clear, simple and consistent relationship between interface pressure and driving discomfort” (Fay and Brienza, 2000, p. 2255). In addition, a seat’s sweat evaporation characteristic can be substantially altered, particularly if pressure mats are used (as they should) during the entire period of driving. Thus, with increasing sitting time, individuals are more likely to feel uncomfortable in terms of “stickiness caused by un-evaporated sweat” (Parsons, 2000), which in turn adversely affects their discomfort ratings. Comfort ratings may also be affected, as sitting comfort is significantly correlated with sitting discomfort (see Chapter 2).

In addition, ambient factors (e.g., noise, light, and air temperature) not accounted for by interface pressure can affect subjective responses. Such factors are usually set to predefined levels, yet the potential for confounding may still exist. For example, Karjalainen (2007) observed significant differences in thermal comfort and temperature preference between gender groups. Therefore, a preferred method is to allow participants to select the levels of any controllable ambient factors according to their preferences.

Aside from such technical issues, the means by which pressure data are integrated into subjective responses remains unclear. Different weightings of pressure data at local body parts may be used by individuals in determining global levels of comfort and discomfort. From a macro view, Humphreys (2005) investigated combined comfort indices of the indoor environment, consisting of warmth, lighting, humidity and air quality. Results showed that the importance of each component was different during the “subjective averaging process” (Humphreys, 2005, p. 319) used in determining an overall satisfaction level, and also that there existed different averaging processes between cultural groups. Similarly, it was postulated by the current authors that, from a micro view, while all body parts contacting the seat play a role in determining whole body comfort and discomfort, each local body part and the associated interface pressure are weighted differently in the integration/decision process. Therefore, it was investigated here whether there were more dominant body parts (and corresponding pressure variables) in this process, and whether there was an ideal ratio in terms of pressure distribution among thighs, buttocks and back that could yield improved sitting comfort and discomfort.

In summary, the primary objective of this study was to investigate the associations between interface pressure and subjective ratings of short-term sitting comfort / discomfort, in order to determine the types and derivatives of pressure data that could be substituted for, and hence predict, comfort and/or discomfort. In addition, comparisons were made between two groups of people that had different levels of reported sitting comfort and discomfort. Specific objectives were: 1) to determine the effectiveness of a comprehensive set of 36 interface pressure variables (pressure levels, contact areas, and ratios of local to global pressure). This effectiveness was determined for assessing, predicting and improving the sitting experience in terms of comfort, discomfort and/or overall ratings across a range of individual statures; 2) to identify specific pressure variables most related to a better sitting experience; and 3) to investigate effects of stature, vehicle class (sedan and SUV), seat, and venue (laboratory and field settings) on the set of variables.

2. Methods

2.1. Overview of experiment and participants

Data were obtained from a study of perceived comfort / discomfort involving both lab-based (simulated) and actual (field) driving venues. Details on the criteria for selection of participants and experimental vehicles/seats, the subjective rating scales, and the experimental design have been provided in Chapter 2, with only a summary given here. After providing informed consent, using procedures approved by the local IRB, each of 27 participants (aged 20 - 35, 12 males and 15 females, mean (SD) mass = 69.1 (13.1) kg, mean (SD) stature = 170.7 (11.7) cm) completed six short-term (15-20 minute) driving sessions. Each used, in a random order, a different combination of seat, vehicle class, and driving venue (specific combination = Seat Condition). For selection of vehicles and seats, the J. D. Power and Associates' Comfort Score (J. D. Power and Associates, 2005) was used; higher-rated and lower-rated vehicles and their seats were selected (Chapter 2). Measures of subjective responses, pressure, and posture were obtained. Additional objective measures (joint angles) were collected at the end of each session (after all subjective ratings were obtained), but are not presented here. An analysis of pressure data, and its association with subjective responses, is the focus of this report.

2.2. Variables

Independent variables

Two independent variables were included. Seat Condition had six levels, obtained as a subset of the combinations of two vehicle classes (sedan, S; SUV, U), two seats (S1 and S2, and U1 and U2 from higher (1) and lower (2) rated vehicles in a given vehicle class), and driving venue (lab-based, -L; field, -F). Lab-based sessions were conducted in an isolated room, using a custom-constructed driving rig (that allowed for extended adjustments of the seat and steering wheel), and with a driving scene projected in front of the participant. Field sessions were conducted over a predetermined path on local roads. The specific Seat Conditions were S1-L, S1-F, S2-L, U1-L, U1-F, and U2-L. The second independent variable was Stature, representing three groups of participants (short, middle, and tall) with respective stature ranges (percentiles of gender-mixed population; NHANES III, 1994) of 152-164 ($\leq 18^{th}$), 165-174, and 175-193 cm ($\geq 90^{th}$).

Dependent variables

Both subjective ratings and objective measures were obtained. Three subjective rating schemes were used, consisting of overall ratings for the whole body, and comfort and discomfort ratings for the whole body and six local body parts (Table 10). Methods used to obtain these ratings are provided in detail in Chapter 2. Briefly, overall ratings were based on a visual analogue scale, with comfort and discomfort at the extremes, thereby measuring a mixture of comfort and discomfort. The separate comfort / discomfort scales measured only one feeling independently, using scales derived as combinations of versions developed by Borg (1990) and Corlett-Bishop (1976). These scales range from 0 to 10, and from 0 to -10, for comfort and discomfort, respectively. Separate measures of comfort and discomfort were obtained to reflect existing evidence of the orthogonality of comfort and discomfort (Sauter et al., 2005; Zhang et al., 1996) or a study which has regarded these two feelings as different entities (Hancock and Pepe, 2005). Objective measures were obtained from pressure measured at the driver-seat interface, and consisted of two groups: overall and local pressures (Table 10).

Table 10. Dependent variables

Type	Name	Area to measure
Subjective	Overall rating	Whole body
	Comfort rating	Whole body and six local body parts - Left/right thighs (THL/THR) - Left/right buttocks (BTL/BTR) - Upper/lower back (UB/LB)
	Discomfort rating	
Objective	Overall pressure	Sum of six local body part pressures
	Local pressure	Each local body part

2.3. Experimental protocols

During initial seat and posture adjustments (duration ≤ 5 minutes), a pressure mat was placed on only the seat cushion and secured with masking tape (to facilitate seat adjustments). The participant was instructed to sit carefully to minimize wrinkles on the pressure mat, and then placed their right foot on the gas pedal (required) and their left foot on the foot rest (optional). Adjustments of the seat and steering wheel were made until the participant's preferred posture was found. After the participant arose from the seat, the second pressure mat was secured to the seat back. The participant sat on the seat again, wore a lap belt, and made micro-adjustments as desired. Room or vehicle temperature was set to the participant's preference before the driving session.

2.4. Data collection and processing

Subjective ratings were obtained after each session, in a consistent order to minimize confusion (discomfort, comfort, and then overall ratings). Pressure data was collected continuously during the driving sessions, using two Tekscan (South Boston, MA, USA) pressure mats (5330 CONFORMat^{TM}). Each pressure mat was comprised of 1024 (32 x 32) thin (1.78mm) resistive sensors that could easily conform to the contour of the seat, and measure up to 250 mmHg (5

PSI). Each mat had an active area of 471.4 mm x 471.4 mm, and sensor pitch was 14.73 mm (0.5 sensor / cm^2). Pressures were recorded at 0.5 Hz, the maximum possible due to hardware limitations. This sampling rate, however, was considered sufficient, as the frequency of postural changes and resultant pressure changes were not observed to occur within an order of magnitude of the sampling rate.

Pressure data from the two mats were divided into six groups (Figure 23). Bolsters on the sides of the car seat play a role in supporting thighs, hips, and back (especially when turning), and can affect sitting comfort and discomfort (Andreoni et al., 2002). To account for this, pressure data corresponding to bolstered areas were also included in the data analysis. Contact area and contact pressure were calculated by including only data from sensors that were pressed (i.e. a positive value) at least once, and average (arithmetic mean) values were determined for the last five minutes of driving. Earlier data were excluded here, as they were 'transient' due to settling into the seat (Reed et al., 1999). Contact area and pressure values were obtained from the Movie Contact Averaging function available in the CONFORMat Research software (version 5.80c).

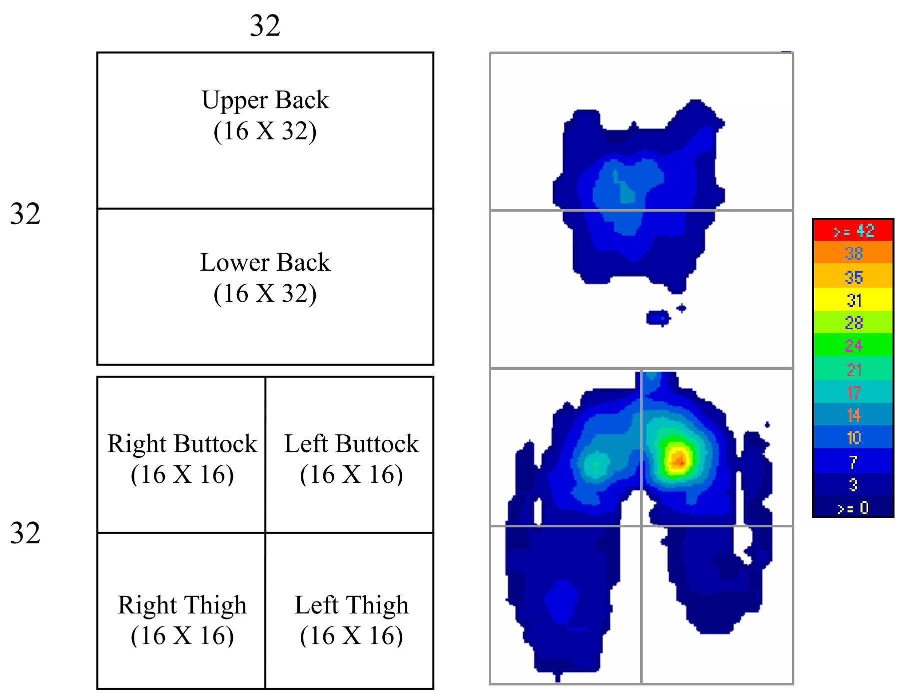


Figure 23. Division of two pressure mats for six local body parts (left, number of sensors in parentheses; row by column) and exemplar pressure distribution (right, a higher peak pressure on left buttock)

2.5. Data analysis

A total of 39 pressure variables were derived (Table 11): 1) the first 13 variables were related to average contact areas and ratios; 2) the second 13 variables described average contact pressures and ratios; and 3) the last 13 variables indicated average peak contact pressures and ratios. Three overall pressure variables (aSUM, avgSUM, and pkSUM) were only used to derive 18 ratio variables, and were not further analyzed.

To preserve the significance level for the 36 pressure variables as a whole, a Multivariate Analysis of Variance (MANOVA) was conducted initially. Then, the same analysis methods (using different dependent variables) as in Chapter 2 were used. Specifically, separate two-factor repeated-measures analysis of variance (ANOVA) for each of the 36 pressure variables to determine if there were main or interactive effects of Stature and Seat Condition, with the Tukey's Honestly Significantly Different (HSD) test for post-hoc pairwise comparisons. Specific pairwise comparisons and contrasts were of interest as before: driving venue (lab vs. field) effects (S1-L vs. S1-F, U1-L vs. U1-F), seat effects within vehicle class (S1-L vs. S2-L, U1-L vs. U2-L), and linear contrasts of stature groups (middle vs. short + tall) and vehicle classes (S1-L + S2-L + S1-F vs. U1-L + U2-L + U1-F). These contrasts were selected, as it was anticipated in advance that anthropometric extremes would be less taken into account in seat design, compared to those of middle stature, and that there would be differences in preferences between vehicle classes. Among these post-hoc analyses, the comparison between sedan seats (S1-L vs. S2-L), and the contrast between vehicle classes (sedans vs. SUVs) were of particular interest, as only these two were found previously to be differentiated based on subjective ratings (Chapter 2). Though not significant previously, driving venue effects were also of interest, as only one driving venue (field) involved exposure to road/vehicle vibration, which was expected to affect the pressure variables. Comparisons between bilateral body parts (thigh and buttock) were made using matched-pairs t-tests.

Table 11. Pressure variables and groups

Group	Variable Name and Description	
Average contact area (cm^2)	aTHL (aTHR)	: Left (right) thigh
	aBTL (aBTR)	: Left (right) buttock
	aLB (aUB)	: Lower (upper) back
	aSUM	: aTHL+aTHR+aBTL+aBTR+aLB+aUB
Average contact area ratio	aTHL/aSUM , aTHR/aSUM , aBTL/aSUM, aBTR/aSUM, aLB/aSUM, aUB/aSUM	
Average contact pressure (mmHg)	avgTHL (avgTHR)	: Left (right) thigh
	avgBTL (avgBTR)	: Left (right) buttock
	avgLB (avgUB)	: Lower (upper) back
	avgSUM	: avgTHL+avgTHR+avgBTL+avgBTR+avgLB+avgUB
Average contact pressure ratio	avgTHL/avgSUM, avgTHR/avgSUM, avgBTL/avgSUM, avgBTR/avgSUM, avgLB/avgSUM, avgUB/avgSUM	
Average peak contact pressure (mmHg)	pkTHL (pkTHR)	: Left (right) thigh
	pkBTL (pkBTR)	: Left (right) buttock
	pkLB (pkUB)	: Lower (upper) back
	pkSUM	: pkTHL+pkTHR+pkBTL+pkBTR+pkLB+pkUB
Average peak contact pressure ratio	pkTHL/pkSUM, pkTHR/pkSUM, pkBTL/pkSUM, pkBTR/pkSUM, pkLB/pkSUM, pkUB/pkSUM	

Additionally, bivariate coefficients of correlation (ρ) were obtained between each of the three subjective ratings and each of the 36 pressure variables. The presence of three statistical results were interpreted as supporting the general use of a pressure variable in seat design and evaluation, regardless of participant stature: 1) an association between a given pressure variable and any of the subjective ratings (comfort rating in particular, as it was the only subjective response able to distinguish among the Seat Conditions); 2) a significant Seat Condition effect (S1-L vs. S2-L in particular) on the variable; and 3) a lack of a significant Stature effect on the variable.

Relationships between dependent variables (i.e., subjective ratings and pressure variables) were further investigated using two steps: 1) a principal component analysis (PCA, based on the correlation matrix) to reduce the number of independent variables used in the subsequent regression analysis; and 2) a multiple regression of each subjective rating on the factors from the PCA to determine if any subjective rating could be accounted for (based on model R^2) by a linear combination of the factors, which are in turn linear combinations of the pressure variables. The number of factors was determined by two criteria, the size of the eigenvalue (>1) and the cumulative percentage (≈90%) of variance accounted for by the selected factors (Lehman et al., 2005). The selected factors were rotated by the varimax method. Finally, to determine the pressure levels that resulted in better comfort / discomfort ratings, two groups were defined: Group P (Perfect) that reported extremely strong comfort (=10) and no discomfort (=0) in their driving postures, and Group NP (Not Perfect) that had less than extremely strong comfort (<10) and some discomfort (<0). Group P included 24 cases from eight participants (three short, four middle and one tall), and Group NP 107 cases from 24 participants (eight short, seven middle, and nine tall). As there was only one tall participant in Group P, the Stature effect was not investigated. Five participants were included in both groups, whereas three were only in Group P, and 19 only in Group NP. The MANOVA and ANOVA models used for group comparisons were accordingly reduced to two factors (Group and Seat Condition). The remaining 29 cases, having an imperfect rating for either (but not both) whole body comfort or discomfort ratings, were excluded from this comparison. Statistical results were considered 'significant' or 'marginal' when $p \le 0.05$ and $0.05<p\le0.1$, respectively. One female participant did not complete the field sessions, but the lab data from this participant was included for analysis.

3. Results

3.1. Effects of stature and seat condition on interface pressures

MANOVA showed that there were significant ($p\le0.0001$) main effects of Stature and Seat Condition on the 36 pressure variables as a group. From subsequent ANOVAs, three significant ($p\le0.032$) Stature x Seat Condition interaction effects were found, on avgTHL/avgSUM, avgBTR/avgSUM, and pkTHL/pkSUM (Note: no significant interaction effect was found in MANOVA). Significant ($p\le0.046$) Stature effects were found only on the three pressure variables that were related to average contact areas and ratio (aBTR, aUB, and aUB/aSUM). For all three variables, the same post-hoc groupings were obtained, B/AB/A for short/middle/tall. The tall group had larger contact areas at the right thigh and upper back, and larger contact area ratios at the upper back.

Significant ($p<0.038$) Seat Condition effects were found on 31 pressure variables. Exceptions (pkLB, pkUB, pkTHR/pkSUM, pkBTR/pkSUM, pkUB/pkSUM) were all related to peak contact pressures or ratios. Significant mean differences between S1-L and S2-L were found for 13 pressure variables, and the same significant differences between these two seats were also found for comfort ratings (Chapter 2), indicating that these two seats can be differentiated both objectively (using 13 pressure variables) and subjectively (using comfort ratings). Among these, four (i.e., aTHR/aSUM, avgLB, avgLB/avgSUM, and pkBTL/pkSUM) were higher in S1-L than in S2-L, whereas the other nine (aBTL, aBTR, aUB, avgTHL, avgTHR, avgTHL/avgSUM, avgTHR/avgSUM, pkTHL/pkSUM, and pkTHR/pkSUM) were lower in S1-L than in S2-L.

No stature group contrasts were significant ($p>0.12$), whereas the contrast of vehicle classes (sedans vs. SUVs) was significant ($p\leq0.048$) for 13 pressure variables. Among the latter, the means of nine variables were higher in the sedan class (aBTL, aLB/aSUM, avgTHR, avgBTL, avgBTR, avgUB, avgBTL/avgSUM, avgBTR/avgSUM, and pkBTL/pkSUM). The means of the remaining four variables (aTHL, avgTHL/avgSUM, pkTHL/pkSUM, and pkBTL/pkSUM) were lower in the sedan class. Among the pressure variables, 21 showed significant differences between lab and field settings in either of two vehicle classes (i.e., S1-L vs. S1-F or U1-L vs. U1-F). The differences between venues were substantial (Range: -56.1% ~ 87.5%, Table 12).

Table 12. Percent differences in mean contact area/pressure variables between lab and field settings by vehicle class (only significant differences are shown)

Variable group	Thigh		Buttock		Back	
	Left	Right	Left	Right	Lower	Upper
Area	-32.6^{+}		-29.3 (-17.3)$^{++}$	-33.6 (-21.9)	-56.1 (-38.5)	-21.3 (87.3)
Area ratio	(19.3)	16.7 (18.0)			-17.0 (-17.5)	
Pressure	(16.9)	(13.6)	18.3		11.8	8.8
Pressure ratio	-10.7 (10.4)	- 9.5 (8.5)	10.2	(-17.2)		
Peak pressure	-14.5					
Peak pressure ratio	(14.1)	14.1	-15.4			

$^{+}$: Sedan, (S1-L–S1-F)/S1-L*100, $^{++}$: SUV, (U1-L–U1-F)/U1-L*100

Significantly ($p<0.0001$) larger contact areas and higher contact ratios were found at the right vs. left thigh (i.e., 2.3% more of the total contact area). In terms of average and peak contact pressure and ratio, the left buttock had significantly ($p \leq 0.0011$) higher levels than the right buttock (i.e., 2% more of the total average contact pressure and 3.4% more of the total average peak contact pressure).

3.2. Correlations between subjective ratings and pressure variables

There were 20 pressure variables significantly correlated either with overall or whole body comfort ratings ($-0.41 \leq \rho \leq 0.28$, Table 13). None, however, was significantly correlated with whole body discomfort ratings. Most (17) of the variables with significant correlations indicated pressures and ratios, and the remaining three were related to pressure areas. The largest correlation ($\rho = -0.41$) was found between pkBTL and overall ratings. Among the 20 variables, 14 variables (Table 4) met the three conditions noted earlier (i.e. an association with any of the subjective ratings, a Seat Condition effect, and a lack of a Stature effect). Three variables (Table 13) met stricter conditions of an association with comfort ratings and a distinction between sedan seats (S1-L vs. S2-L).

Table 13. Coefficients of correlation (ρ) between subjective ratings and pressure variables (only significant correlations given)

Pressure variable	Overall rating	Whole body comfort rating	Three conditions* met?	Strict condition** met?
aTHL		-0.20	Y	
aTHL/aSUM		-0.20	Y	
aTHR/aSUM	0.16		Y	
avgTHL		-0.18	Y	Y
avgTHR		-0.25	Y	Y
avgBTL	-0.30	-0.20	Y	
avgBTR	-0.28	-0.21	Y	
avgUB		-0.19	Y	
avgBTL/avgSUM	-0.23		Y	
avgBTR/avgSUM	-0.22		Y	
avgLB/avgSUM	0.16	0.28	Y	Y
avgUB/avgSUM	0.18			
pkTHR	-0.18	-0.16		
pkBTL	-0.41	-0.24	Y	
pkBTR	-0.29	-0.17		
pkUB	-0.28	-0.25		
pkTHL/pkSUM	0.19		Y	
pkBTL/pkSUM	-0.19		Y	
pkBTR/pkSUM	-0.16			
pkLB/pkSUM		0.160		

* : An association between a given pressure variable and any of the subjective ratings, a Seat Condition effect on the variable, and lack of a Stature effect

**: Three condition above and association with comfort rating and distinction of the sedan seats (S1-L vs. S2-L)

3.3. PCA and regression analysis using pressure variables

Nine factors with an eigenvalue > 1 accounted for 87.8 % of the total variance (Table 14). Based upon the smallest communality of 0.778 (found on pkUB/pkSUM), the variance of each pressure variable was well (at least 77.8% of it) accounted for by the selected factors. Each Factor, based on review of the coefficients, appeared to have a more general interpretation (as indicated in Table 14). A subset of (3-4) pressure variables were found in each Factor that predominantly determined the respective Factor level, as evidenced by large coefficients (>0.6). Further, these subsets of variables were mutually exclusive, and distinguishable in terms of relevant body part, or type of pressure, and Factors were termed according to this (Table 14). For Factors 1 and 9 that were related to contact area ratios, coefficients with opposite signs were found between the thigh and buttock average contact area ratios (i.e., aTH(L or R)/aSUM vs. aBT(L or R)/aSUM), and between the lower and upper back contact area ratios (i.e., aLB/aSUM vs. aUB/aSUM), respectively. In other words, there were negative associations between the thigh and buttock and between the lower and upper back in terms of contact area ratio. For Factor 5, coefficients relating to contact areas of the bilateral buttocks and low back were all positive (hence, positive associations between the buttocks and low back in terms of contact area).

Regression analyses showed that overall and comfort ratings could be somewhat better accounted for (R^2 = 0.24 and 0.12, respectively) by the nine Factors than could discomfort rating (R^2 = 0.098). Fitted models for overall and comfort ratings were significant ($p \leq 0.023$), while the model for discomfort ratings was marginal ($p=0.071$). Based on the size of the standard beta weights, which represent the relative effects of each Factor on their dependent variable (Freund et al., 2003), increasing Factor 5 and decreasing Factor 3 would be effective at improving overall and whole body comfort ratings, as these had larger beta weights (Table 15). The largest and positive beta weights, for Factor 5 (13.7 and 8.5, respectively for overall and comfort ratings), indicated that increasing contact areas at the buttocks and lower back (specifically, aBTL, aBTR, and aLB) would be the most effective method for improving overall and whole body comfort ratings. Similarly, the second largest but negative beta weights, for Factor 3 (-10.7 and -6.8, respectively), suggest that decreasing average (peak) contact pressures and ratios relevant to the left buttock (specifically, avgBTL, avgBTL/avgSUM, pkBTL, pkBTL/pkSUM) would be the second most effective way of improving the two subjective ratings. Factor 4 had the third largest weights (10.1 and 7.2, respectively), suggesting a third strategy of increasing pressure levels and ratios at the right thigh.

Table 14. Nine principal components after varimax rotation (underlined values are > 0.6 and maximal across Factors in their absolute values)

Pressure variable	Factor 1 thigh vs. buttock (area)	Factor 2 right buttock (pressure)	Factor 3 left buttock (pressure)	Factor 4 right thigh (pressure)	Factor 5 buttock & lower back (area)	Factor 6 lower back (pressure)	Factor 7 left thigh (pressure)	Factor 8 upper back (pressure)	Factor 9 lower vs. upper back (area)
aTHL	0.822	-0.010	-0.126	0.147	0.164	-0.019	0.320	0.214	0.043
aTHR	0.823	-0.303	-0.084	0.241	0.067	-0.009	0.055	0.044	0.052
aBTL	-0.107	0.004	-0.059	-0.031	0.928	0.018	-0.089	-0.010	0.056
aBTR	-0.147	-0.056	-0.038	-0.112	0.915	0.040	0.072	0.017	0.080
aLB	0.198	-0.050	-0.161	0.033	0.799	0.169	0.007	-0.304	-0.329
aUB	0.322	0.100	0.040	0.219	0.388	0.043	0.178	-0.032	0.784
aTHL/aSUM	0.715	0.017	-0.097	0.074	-0.300	-0.087	0.270	0.342	-0.078
aTHR/aSUM	0.636	-0.348	-0.015	0.139	-0.493	-0.067	-0.086	0.151	-0.092
aBTL/aSUM	-0.778	0.082	0.057	-0.240	0.063	-0.075	-0.279	0.097	-0.261
aBTR/aSUM	-0.796	-0.004	0.075	-0.320	0.134	-0.048	-0.068	0.118	-0.208
aLB/aSUM	-0.126	-0.032	-0.155	-0.057	0.507	0.164	-0.108	-0.394	-0.632
aUB/aSUM	0.063	0.189	0.150	0.190	-0.106	-0.008	0.155	-0.016	0.914
avgTHL	0.322	0.222	0.010	0.518	0.001	0.123	0.634	0.059	0.208
avgTHR	0.421	0.192	0.070	0.808	-0.037	0.016	0.183	0.100	0.143
avgBTL	0.018	0.490	0.688	0.357	-0.144	0.142	0.116	0.066	0.248
avgBTR	-0.019	0.782	0.387	0.338	-0.006	0.131	0.075	0.103	0.211
avgLB	-0.094	0.063	0.143	0.237	-0.036	0.826	0.174	0.149	-0.031
avgUB	0.143	0.280	0.241	0.333	-0.120	0.205	0.025	0.692	0.224
avgTHL/avgSUM	0.281	-0.276	-0.447	0.104	0.079	-0.165	0.657	-0.109	0.045
avgTHR/avgSUM	0.491	-0.243	-0.335	0.621	0.020	-0.272	0.030	-0.010	-0.011
avgBTL/avgSUM	-0.188	0.242	0.819	-0.118	-0.149	-0.096	-0.141	-0.176	0.172
avgBTR/avgSUM	-0.213	0.832	0.212	-0.096	0.120	-0.092	-0.187	-0.086	0.119
avgLB/avgSUM	-0.245	-0.407	-0.210	-0.233	-0.002	0.650	-0.050	-0.015	-0.272
avgUB/avgSUM	-0.031	-0.383	-0.249	-0.320	-0.092	-0.152	-0.308	0.630	-0.072
pkTHL	0.281	0.095	0.099	0.263	-0.051	0.105	0.797	0.075	0.215
pkTHR	0.264	0.218	0.157	0.786	-0.113	0.030	0.205	0.140	0.178
pkBTL	-0.013	0.353	0.881	0.086	-0.069	0.053	0.015	0.098	0.098
pkBTR	-0.040	0.880	0.245	0.132	-0.089	0.054	0.075	0.074	0.089
pkLB	0.124	0.109	0.023	-0.076	0.129	0.852	-0.047	0.046	0.103
pkUB	0.167	0.265	0.210	0.276	-0.074	0.291	0.155	0.707	0.072
pkTHL/pkSUM	0.177	-0.383	-0.322	-0.001	-0.022	-0.198	0.739	-0.130	0.086
pkTHR/pkSUM	0.295	-0.158	-0.237	0.788	-0.072	-0.222	0.097	-0.012	0.133
pkBTL/pkSUM	-0.205	-0.087	0.824	-0.234	0.002	-0.279	-0.251	-0.122	-0.064
pkBTR/pkSUM	-0.189	0.881	-0.034	-0.092	-0.049	-0.186	-0.133	-0.134	-0.038
pkLB/pkSUM	0.019	-0.203	-0.266	-0.244	0.156	0.810	-0.180	-0.088	-0.029
pkUB/pkSUM	0.045	-0.260	-0.279	-0.036	-0.072	-0.046	-0.059	0.785	-0.054
Eigenvalue	9.120	7.547	3.853	3.198	1.919	1.782	1.751	1.260	1.172
Cum Percent	25.33	46.30	57.00	65.88	71.21	76.16	81.03	84.53	87.79

Table 15. Regression coefficients and standard beta weights for regression models relating PCA Factors to overall and whole body comfort ratings

Term	Overall rating		Whole body comfort rating	
	Estimate	Standard Beta Weight	Estimate	Standard Beta Weight
Intercept	82.35	0	6.77	0
Factor1	-0.12	-4.10	-0.01	-2.08
Factor2	0.91	5.74	0.13	4.35
Factor3	-2.06	-10.69	-0.25	-6.83
Factor4	1.36	10.14	0.18	7.24
Factor5	0.49	13.78	0.06	8.55
Factor6	-0.06	-0.46	-0.02	-0.77
Factor7	-0.88	-5.30	-0.10	-3.23
Factor8	-0.04	-0.53	-0.01	-0.98
Factor9	0.001	0.04	-0.006	-0.94

3.4. Comparisons between groups P and NP

MANOVA showed that there were main effects of Group P/NP and Seat Condition on the 36 variables as a group ($p \leq 0.006$). ANOVAs showed that among the 36 variables, Group P/NP effects were significant ($p \leq 0.043$) for seven variables, whereas these effects were marginal ($p \leq 0.096$) for another four variables. Of interest was that Group P, versus NP, had lower pressure ratios at their left buttock, with 1.9 % and 2.7% less of the total body pressure in terms of avgBTL/avgSUM ($p=0.0008$) and pkBTL/pkSUM ($p=0.027$), respectively (Figure 24). Group P also had higher pressure ratios at their lower back with 1.3% more of the total body pressure in terms of avgLB/avgSUM ($p=0.043$), and at their upper back with 1.2% more of the total body pressure in terms of pkUB/pkSUM ($p=0.096$, Figure 24). Group P had balanced bilateral (peak) pressures and ratios at their buttocks ($0.21<p<0.79$ for avgBTL(/aSUM) vs. avgBTR(/aSUM) and pkBTL(/pkSUM) vs. pkBTR/(pkSUM)). In contrast, Group NP had higher pressures and ratios at their left buttock ($0<p<0.019$). For Group NP, an additional 2% of the total body pressure was found at their left buttock (0.22 vs. 0.20 for avgBTL/avgSUM, and 0.23 vs. 0.21 for pkBTL/pkSUM).

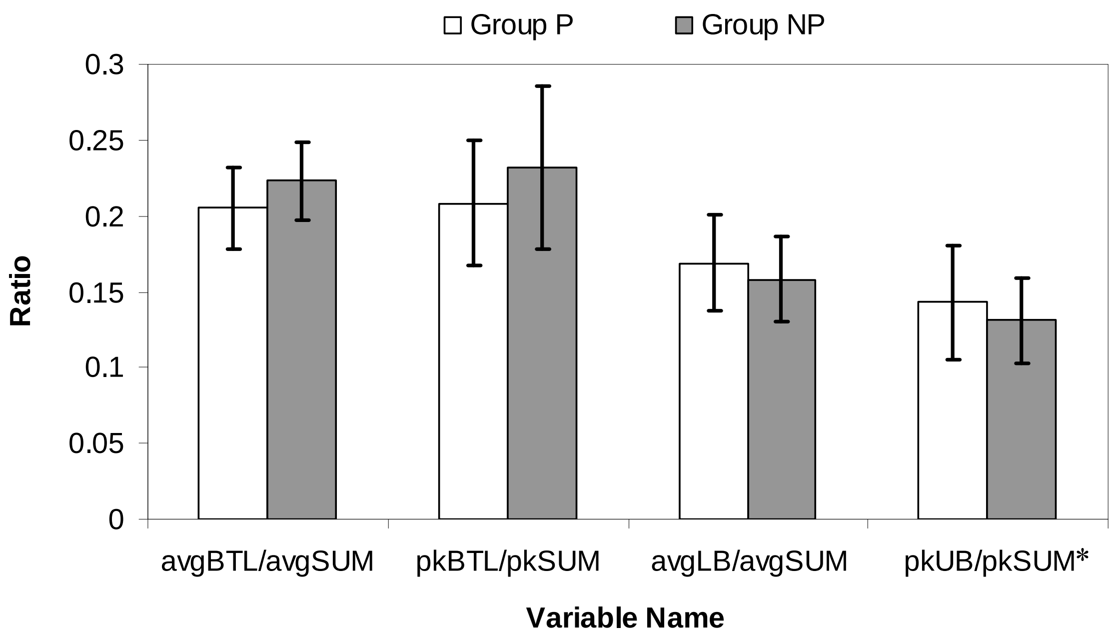


Figure 24. Pressure ratios having significant Group (P vs. NP) effects (*: marginal effect, p = 0.096)

4. Discussion

This study focused on sitting comfort and discomfort during short-term driving, and used interface pressure data as objective measures with particular interest in the relationship between pressures and subjective responses. In the following, the specific driving duration used and the separation of comfort and discomfort are discussed. In addition, the experimental results are interpreted and recommendations are given for use of interface pressure in seat design and evaluation.

There is still debate on the proper experimental duration for studies related to human responses in seated postures. Shackel et al. (1969)'s study using office chairs showed that 5 minutes of sitting was sufficient to identify comfortable seats. Wachsler and Learner (1960) found no differences in sitting comfort ratings obtained during short-term (5 minutes) and longer-term (10, 15, 30 minutes, 4 hours) trials. Reed et al. (1999) showed that 15 minutes was sufficient for posture 'settlement' in car seats, whereas Hanson et al. (2006) observed no difference in driving postures between 5 and 20 minutes of driving. In addition, judgments on long-term comfort were regarded as "very unstable and unreliable" (Branton, 1969). The present study used a 20 minute duration (5-minute initial adjustments and 15-minute driving), primarily to account for posture settlement.

Most mean pressure variables considered in this study showed a venue effect, or a difference between lab and field settings. Primary factors contributing to this discrepancy seem to be road/vehicle vibration, and more active operation of controls (pedals and steering wheel) involved in field studies. Therefore, lab studies without simulated vibration, though easier to conduct, may only be valid for measures of static comfort/discomfort, whereas on-road field studies, though done in a more realistic environment, will likely be limited to measures of dynamic comfort/discomfort. As a consequence, recommended pressure levels for sitting comfort / discomfort should be classified according to the underlying driving venue.

As opposed to the general consensus in the literature (i.e., that interface pressure is association with discomfort), this study found that pressure data were more strongly associated with comfort. None of 36 pressure variables was significantly correlated with whole body discomfort, whereas 20 pressure variables were significantly correlated with either overall or whole body comfort ratings. This is also opposite to the expectation provided by de Looze et al. (2003), that objective physical measures such as interface pressure will be more directly associated with discomfort. In addition, only two regression models were significant, which related overall and whole body comfort ratings to composites of pressure variables. This offers an additional reason for the lack of a relationship between interface pressure and subjective ratings found by Gyi et al. (1999), in that they only focused on discomfort and did not investigate comfort.

There is still no consensus as to what type of scale is best for relating comfort / discomfort to pressure. Shen and Parsons (1997) investigated the reliability and validity of six scales with respect to rating seated discomfort in the mid-thigh in response to four discrete levels of pressure stimuli (i.e., 60, 85, 120, and 165 mmHg). Among the six scales were the CP-50, the Borg CR-10 scale and Corlett discomfort scale. The other three were an 8-point ordinal scale, a modified intensity and discomfort scale, and a 21-point ratio scale. CP-50, a category partitioning scale, consisted of 'no discomfort (0)', five categories (1-50, 10 points for each) of 'very slight',

'slight', 'medium', 'high', and 'very high discomfort', and finally 'maximal (>51)'. Reliability of each scale was determined by test-retest correlation, relative rating change, and coefficient of variation, whereas its validity was determined by "absoluteness of rating and functional consistency" (Shen and Parsons, 1997, p. 441). The authors concluded that the CP-50 was the best in terms of both reliability and validity.

While appropriate for the pressure range and body part involved, there are potential problems in directly using the CP-50 scale in a seat study involving both interface pressure and subjective ratings. First, an assumption used in the CP-50 scale descriptors (lower pressure = less discomfort) may not have internal / external validity if applied to other body parts. Results in the present study showed that for an individual to be more comfortable, the lower and upper back needed higher pressure levels than the experimental seats provided (higher levels of average lower/upper back contact pressure ratios were found in Group P), consistent with the work of Milivojevich et al. (2000). In addition, the validity of CP-50 is unknown when used at other, especially lower, pressure levels. Note that maximum pressure levels found here were 48.3 mmHg at the thigh and 69.1 mmHg at the lower back. Finally, it is also unknown whether the CP-50 can be used for comfort or overall ratings, with the same level of validity and reliability that were earlier demonstrated for discomfort.

The three stature groups in the present study had different values of average contact area in their upper back, and average contact pressure ratios in their lower and upper back. This stature effect indicates that different pressure requirements are needed for the seatback, as criteria in seat design and evaluation criteria. Previous studies have also shown the need for more adjustability in the seat back (Branton, 1984; Harrison et al., 2000).

From a PCA, contrasting associations were found between local body parts in terms of contact area ratio: negative associations between the thighs and buttocks, and between the lower and upper back, and positive associations between the buttocks and low back. These associations imply that, as might be expected, if some body parts (e.g., the buttocks and lower back) have large contact areas (hence, are supported more), then the other parts (e.g., the thighs and upper back) tend to have smaller contact areas (hence, are supported less). From these, two possible sitting strategies appeared. One is described by sitting deep toward the seat biting line (where the seat cushion and back meet each other), corresponding to the case of having large contact areas for the buttocks and lower back. The other involved being slipped forward on the cushion and leaving a large space between the pelvis and the biting line, corresponding to the case of having large contact areas for the thighs and upper back.

People prefer to decrease the number of degrees of freedom in their seated postures to increase sitting stability (Dempster, 1955), and which can be attained by external and/or internal support (Hendriks et al., 2006). In driving, external support can come, for example, from the arm rest, steering wheel, head rest, foot rest, floor, and door and crash pad trims, or by getting sufficient contact area from these car parts. Internal support can be gained by supporting the head with the left or right hand or by putting a hand on the thigh. As less firm and inconsistent support is expected for the right foot (due to pedal operations), drivers can lean slightly to the left side to increase stability provided from the seat. If so, pressures at the left buttock should be higher than the right. Indeed, higher average and peak contact pressures and ratios were found at the left buttock in the bilateral comparisons using the pooled data, and more importantly this same result was found only in Group NP.

Asymmetric pressure distributions between the bilateral buttocks can be considered undesirable as they appear to lead to lower subjective ratings. As indicated earlier, Group NP (those reporting imperfect comfort and discomfort ratings) showed unbalanced bilateral pressure distributions at their buttocks (i.e., higher pressures and ratios on the left side). In contrast, Group P (reporting perfect levels of comfort and comfort) showed a balanced pressure distribution. Therefore, an alternative approach to the design of seat cushions may be needed. Asymmetrical seat design (in terms of contour) or use of different materials (in terms of hardness) between the bilateral seat buttock areas might facilitate more even pressure distribution and result in more comfortable seats. Evenly distributed pressure may also facilitate improved physiological responses (e.g., increase of blood flow and prevention of unnecessary muscular compensation and lactic acid accumulation), reduce feelings of discomfort, and delay fatigue (Cohen, 1998). The regression results in this study also suggest that lowering pressure and ratio levels in the left buttock will effectively increase (improve) overall and whole body comfort ratings. This was evidenced by the negative coefficient (and the large negative standard beta weight) of Factor 3 in the regression models, which was, in turn, predominantly and positively influenced by four pressure variables related to the left buttock area (i.e., avgBTL, avgBTL/avgSUM, pkBTL and pkBTL/pkSUM).

Beside bilaterally balanced pressure at the buttocks, a balanced distribution of pressure between lower and upper bodies was also found to relate to an improved sitting experience. Specifically, Group P had lower levels of left buttock pressure ratios, but higher levels of upper back pressure ratios than Group NP. This suggests that any additional pressure on the left buttock should be distributed to other body parts (especially to the upper back) to facilitate more balanced support of the whole body and ultimately to improve comfort / discomfort. This offers another partial explanation for Gyi et al. (1999)'s results indicating no relationship between interface pressure and driving discomfort, as they only measured interface pressure on the right side of body.

Though the regressions of comfort (and overall) ratings on the pressure factors were significant, these models only accounted for a small portion of the total variability in subjective ratings. A shortcoming of these models, though, is that ratings for local body parts that were not in contact with the seat (e.g., neck, upper limbs, knees, and body parts below knees) were not effectively accounted for using interface pressure. Other objective measures (e.g., joint angles), that incorporate these body parts, might explain a larger portion of the variability in responses. Alternatively, using both posture and interface pressure data is expected to account for more variability than using either alone.

Inherent here are the same potential limitations described in Chapter 2. In brief, they are gender-confounded stature groups, aesthetic effects from other car parts except the seats, and participants' historical driving experiences. As these may have affected the subjective ratings (though probably not substantially), the relationships between pressure and subjective ratings reported here could have somewhat limited generality. Specific seats used in the experiments represent an additional limitation. The four experimental seats used, though carefully selected and representative of two different vehicle classes, could be distinguished from each other only in terms of comfort (Chapter 2). Given this, it may have been unlikely to find a relationship between discomfort and pressure variables. However, it is also unlikely that a group of contemporary seats could actually be found that would be clearly distinguished in terms of discomfort (Helander, 2003; Shackel et al., 1969).

5. Conclusions

Several types of pressure variables were identified that were related with subjective responses and that distinguished between two groups with different levels of comfort / discomfort. Some pressure variables, derived in terms of average contact area and average (peak) contact pressure ratio, could be used across stature groups for the assessment of sitting comfort / discomfort. An improved sitting experience is argued as requiring a balancing of pressures between the bilateral buttocks as well as between the upper and lower body. Use of pressure data is suggested as more appropriate for assessing short-term comfort / discomfort, reflecting seat support and the distribution of body load on it, but not for the assessment of long-term discomfort (fatigue), due to inherent limitations in pressure measurement, and several potentially confounding influences. Larger-scale, more comprehensive experiments are required, firstly to determine preferred pressure values and ratios required for different vehicle classes, stature groups, and driving venues, and secondly to confirm the present findings that human-seat interface pressure is more strongly associated with comfort than with discomfort.

Chapter 4: Aging effects on drivers' perceptual and behavioral responses

Abstract

Due to physiological changes with age, older individuals are likely to have different perceptual responses to and different needs for driver-vehicle interface design. To assess this, a study was conducted in which a total of 22 younger and older participants completed six short-term driving sessions. These sessions involved a subset of combinations of vehicle class (sedan and SUV), driving venue (lab-based vs. field) and seats (from vehicles ranked high and low by J.D. Power and Associates' Comfort Score). Three subjective ratings (comfort, discomfort, and overall) were obtained, along with 36 driver-seat interface pressure measures, and used to determine whether aging affects: 1) the efficacy of each rating when used for designing and evaluating driver workspace, 2) preferences for sedan and SUV settings, 3) the decision processes involved when relating whole-body and localized perceptions of comfort and discomfort, and 4) the associations between subjective ratings and pressure measures. For both age groups, localized comfort ratings were found to be more effective at distinguishing among automotive seats / packages, compared to global ratings or localized discomfort ratings. Further, two distinct processes appeared to be used in determining whole-body perceptions based on localized perceptions; specifically, whole body comfort appears determined by averaging localized comforts, whereas whole body discomfort appears determined predominantly by maximal local discomforts. Other major results were that the younger group preferred sedans over SUVs, whereas the older group preferred SUVs, and that whole body discomfort levels were largely affected by lower back discomfort in the younger group, versus upper back discomfort in the older group. In addition, older individuals appeared to be less sensitive to discomfort than younger individuals. Several pressure measures indicated different dynamic behaviors or loading patterns (due to postural differences) between the two age groups, and bilateral asymmetry of driving postures in general. These results indicate that, when designing car seats and interior geometries, different pressure requirements should be specified and used separately for each age group and for each seat side.

Relevance

Both differences and similarities between younger and older drivers, in terms of perceptions, preference, driving posture, and interface pressure distribution, should be incorporated in driver workspace design to yield more appealing and usable products.

Keywords: age; comfort; discomfort; driving experience; interface pressure; seating

1. Introduction

For most people, aging leads to several decrements including poor eyesight, slow reaction time, lack of muscular strength and dexterity, susceptibility to fatigue (Warnes et al., 1993), and loss of joint flexibility (Haywood et al., 1991), each of which has the potential to adversely affect an individual's driving experience and posture. As a specific example highlighting the importance of understanding aging effects in the context of seat design, Reynolds (1993) showed that different forms of spinal curves (i.e., "flatter and more kyphotic") were observed in the sixth decade of life. Hence, to the contrary to its intention, a contoured seat back could actually make the elderly uncomfortable. Aging effects on driving posture and postural sensitivity have been observed previously in automotive seating (see Chapters 6 and 7), with older drivers preferring to sit closer to the steering wheel. From a safety perspective, Burger et al. (1977) showed that the design of the vehicle interior contributed to at least 7.5% of all accidents. However, with respect to driver workspace and interface design, age-related differences in the efficacy of perceptual ratings have not been investigated, nor is there any evidence regarding whether a single rating scheme might be effective across a diverse age range.

Perceived (dis)comfort can affect drivers' performance, safety, and even posture. Specifically, visual (dis)comfort induced by vehicle in/exterior design is related to hazard misperception (e.g., gap, distance) as well as hazard non-perception (e.g., vision obstruction, reduced visibility), both of which are regarded as major crash contribution factors (Wierwille and Tijerina, 1996). Anshel's study (2005) on man-computer systems showed that visual information is so dominant that its deficiency was compensated by changing body posture. Most elderly individuals have slower and limited abilities in static and dynamic visual acuity (Eby and Kantowitz, 2006; Nicolle and Abascal, 2001), compared to younger individuals. Hence, the former group is more likely to adopt different driving postures due to the decrement in their vision, as well as due to the difference in their normal posture (e.g., kypothic spine). Postural or physiological differences between age groups likely lead to different behaviors (hence, different loading patterns on the seat) within a driver workspace, which necessitates age-specific requirements in terms of interface pressure between the seat and the driver.

Hanson et al. (Hanson et al., 2006) disclosed that driver sitting experience is related to both comfort and discomfort, similar to sitting experience in office or home chairs (Helander and Zhang, 1997; Zhang et al., 1996). Though not a necessary condition, nociceptors at the nerve endings are generally responsible for nociception, the perception of pain (Brooks and Tracey, 2005). Pain is a factor of discomfort along with poor biomechanics and tiredness, whereas comfort factors are well-being and plushness (Zhang et al., 1996). Less is known, however, whether there are differences between age groups in the perceptions of comfort and discomfort of sitting experience, in terms of magnitude and dominance of each perception.

The goals of this study were to investigate whether aging affects 1) the efficacy of each of three subjective ratings (i.e., comfort, discomfort, and overall) when used for designing and evaluating driver workspace, 2) preference for sedan and SUV settings, 3) the decision processes involved when relating whole-body and localized perceptions of comfort and discomfort, and 4) the associations between subjective ratings and pressure measures.

2. Experimental methods

2.1. Overview of experiment and participants

Eleven older individuals were newly recruited, whereas 11 younger individual data were selected from among 27 younger individual data (used in Chapters 2 and 3). The latter were selected in order to achieve a close match in terms of gender distribution, stature, body mass, and data size between the two age groups (Table 16). No significant differences existed in terms of stature and body mass (t-test, $p = 0.68$ and 0.23). Each participant completed six driving sessions, and subjective ratings and interface pressure measures were obtained in the same way as described in Chapters 2 and 3. Each participant completed an informed consent procedure, approved by the local Institutional Review Board, prior to the first experiment session. Brief descriptions of the experimental procedure and settings, and subjective and objective measures used in this study, are given below. For more information, readers are referred to Chapters 2 and 3.

Table 16. Participant characteristics

	Age Group	
	Younger	Older
# of Participants (M/F)*	11 (6/5)	11 (6/5)
Mean (SD) Stature (cm)	168.9 (11.2)	168.2 (11.7)
Mean (SD) Age (year)	21.8 (3.2)	71.4 (8.6)
Mean (SD) Body Mass (kg)	67.9 (11.1)	73.5 (22.0)

* Number of males and females

Six driving sessions (later called Seat Condition) combined two vehicle classes (sedan [S]; SUV [U]), two driving venues (lab-based, [-L]; field-based, [-F]), and two seats (from vehicles ranked high [1] and low [2] by J. D. Power and Associates (2005)' Comfort Score) per vehicle class. Hence, specific Seat Conditions were S1-L, S1-F, S2-L, U1-L, U1-F, and U2-L. Participants completed three sessions (two in the lab and one in the field) for each vehicle class. An adjustable driving rig was used in the lab-based sessions that involved simulated driving, and two cars were used for the field sessions that involved on-the-road driving. In both cases, driving was conducted for 20 minutes. Before and during driving, participants adjusted the seat and steering wheel to best support their preferred driving postures. As in Chapter 2, a modified method of fitting trials (Jones, 1969) was used for the initial adjustment.

After driving, and while maintaining their preferred postures, participants rated their postures in terms of comfort, discomfort, and a combination of these two (overall rating). Several scales were used by participants, at the end of each driving session, to assess drivers' perceptions. Comfort and discomfort scales were derived as combinations of versions developed by Borg (1990) and Corlett-Bishop (1976), and used for the whole body and six local body parts (bilateral thighs and buttocks, and lower and upper back). In addition, a visual analogue scale (VAS) was used to obtain overall perceptual ratings of the whole body. The Karolinska Sleepiness Scale (KSS) by Horne and Reyner (1995) was used to measure drivers' alertness level.

Two Tekscan (South Boston, MA, USA) pressure mats (5330 CONFORMat^{TM}) were used to collect a variety of pressure data over the course of each driving session. The first pressure mat was used on the seat cushion and was divided into four areas corresponding to bilateral thighs and buttocks. The second pressure mat was hung on, and tied to the seat back, and divided into two areas corresponding to the lower and upper back. Six types of variables were measured from each of six divided area: contact area, contact pressure, peak pressure, and ratio of each of these three variables (local to global). Hence, a total of 36 interface variables were used to describe the driver-seat interface.

2.2. Data analysis

Methods for data analysis are similar to those described earlier (Chapters 2 and 3), except that an Age factor was assessed rather than Stature. Specifically, a mixed-factor analysis of variance (ANOVA) was used to determine the effects of Age (2 levels, between-subjects) and Seat Condition (6 levels, within-subject) on each of the three subjective ratings. Tukey's Honestly Significantly Different (HSD) test was used, where relevant, for post-hoc pairwise comparisons. Effects were considered 'significant' when $p \leq 0.05$, with potential trends highlighted when $0.05 < p \leq 0.1$. Specific pairwise comparisons were done to determine if there were driving venue (lab vs. field) effects (S1-L vs. S1-F, U1-L vs. U1-F) and/or seat effects within vehicle class (S1-L vs. S2-L, U1-L vs. U2-L). In addition, a linear contrast of vehicle classes (S1-L + S2-L + S1-F vs. U1-L + U2-L + U1-F) was tested to compare preferences between the two classes. Ratings between bilateral body parts (thighs, buttocks) were examined using matched pairs comparisons, for each age group. Bivariate coefficients of correlation (ρ) were obtained among the several subjective ratings, at both local and global levels, for each age group. Possible aesthetic effects of four seats on comfort ratings were examined using a univariate repeated-measures ANOVA. Additional bivariate coefficients of correlation (ρ) were obtained between each of three whole-body subjective ratings and alertness level.

With respect to the 36 pressure variables, a Multivariate Analysis of Variance (MANOVA) was conducted to preserve the overall significance level, prior to an additional mixed-factor ANOVA. The later was similar to the one described above, but involved different dependent variables (i.e., 36 pressure variables). The same pairwise comparisons as described above were also used as post-hoc analysis. Among these, the comparison between sedan seats (S1-L vs. S2-L), and the contrast between vehicle classes (sedans vs. SUVs) were of particular interest, as only these two were previously found to be differentiated based on subjective ratings obtained from younger individuals (see Chapter 2). Driving venue effects were also of interest, as only one driving venue (field) involved exposure to road/vehicle vibration, and which was expected to affect the pressure variables as observed in Chapter 3. Comparisons between bilateral pressure measures (i.e. at the thighs and buttocks) were made using matched-pairs t-tests. Additionally, bivariate coefficients of correlation (ρ) were obtained between each of the three subjective ratings and each of the 36 pressure variables. The presence of the following three statistical results was interpreted as supporting the general use of a pressure variable in seat design and evaluation, regardless of drivers' age: 1) an association between a given pressure variable and any of the subjective ratings; 2) a significant Seat Condition effect on the pressure variable; and 3) a lack of a significant Age effect on the pressure variable.

As in Chapter 3, relationships between subjective ratings and pressure variables were further investigated using two steps: 1) a principal component analysis (PCA); and 2) a multiple regression of each subjective rating on the factors from the PCA. Here, the focus was to develop a method that can be applied to improve car seats and packages for both age groups. The number of factors were determined by two criteria : 1) eigenvalue > 1; and 2) the cumulative percentage of variance close to 90% (Lehman et al., 2005). The selected factors were rotated using the varimax method.

3. Results

3.1. Subjective ratings

3.1.1. Whole body ratings (overall, comfort, and discomfort)

Whole body overall rating

Main effects (Age, Seat Condition) were not significant ($p>0.43$) while the effect of Age × Seat Condition showed a trend ($p=0.08$). Younger participants tended to provide lower ratings than those in the older group, with means (SD) of 75.9 (16.0) and 80.5 (15.9), respectively. The former group also tended to prefer sedan settings while the latter tended to prefer SUV settings. Overall ratings tended to be higher in the field settings (S1-F and U1-F, Figure 25) for both groups. No significant difference between vehicle classes was found (p=0.32), though sedan conditions were rated higher than SUVs (Figure 25), with means (SD) of 78.8 (15.7) and 77.5 (16.4), respectively.

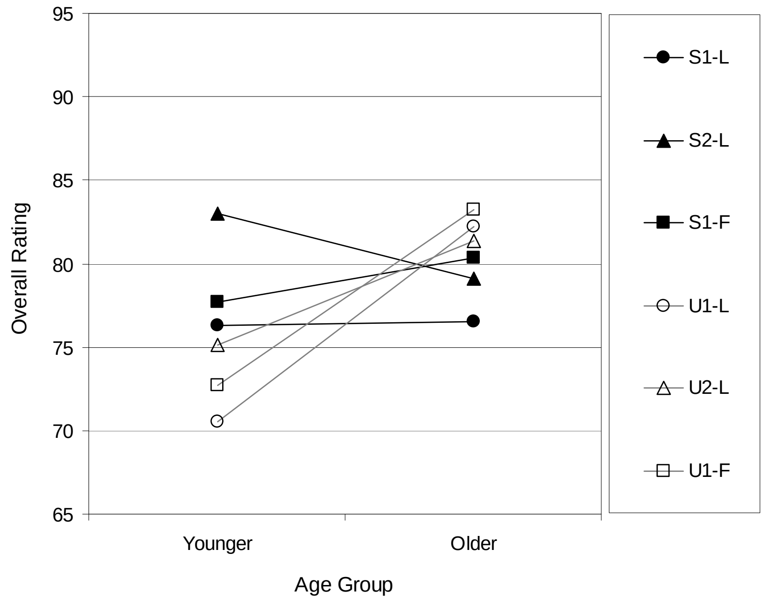


Figure 25. Mean overall ratings for the different Age Groups and Seat Conditions (SDs not shown for clarity, range = 10.6~21.1)

Whole body comfort rating

No effects (Age, Seat Condition, and Age × Seat Condition) were significant (p>0.12). The younger group tended to rate lower than the older, with means (SD) of 5.7 (2.7) and 6.9 (2.6), respectively. The former group also tended to prefer sedan settings while the latter tended to prefer SUV settings. Comfort ratings tended to be higher in the field settings (S1-F and U1-F, Figure 26) for both groups. A trend between vehicle classes was found (p=0.08), with sedan conditions rates higher than SUVs (Figure 26). Respective means (SD) were 6.6 (2.5) and 6.0 (2.9).

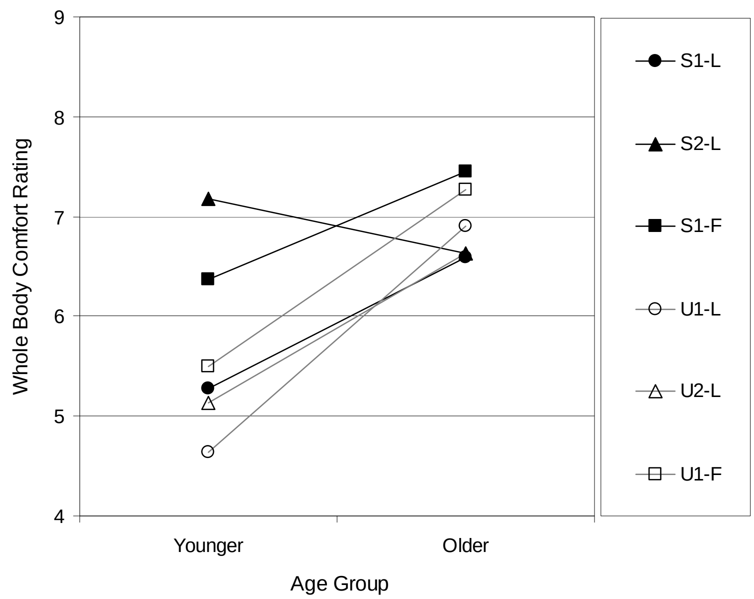


Figure 26. Mean whole-body comfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 1.7~3.2)

Whole body discomfort rating

Age and Seat Condition were not significant as main effects (p>0.75), though the Age × Seat Condition interaction was (p=0.04). Younger and older groups reported a similar level of discomfort, with means (SD) of -0.95 (1.1) and -0.97 (1.3), respectively. The former group also tended to prefer sedan settings while the latter tended to prefer SUV settings. Discomfort ratings tended to be higher (less uncomfortable) in the field settings (S1-F for the younger and U1-F for the older, Figure 27).

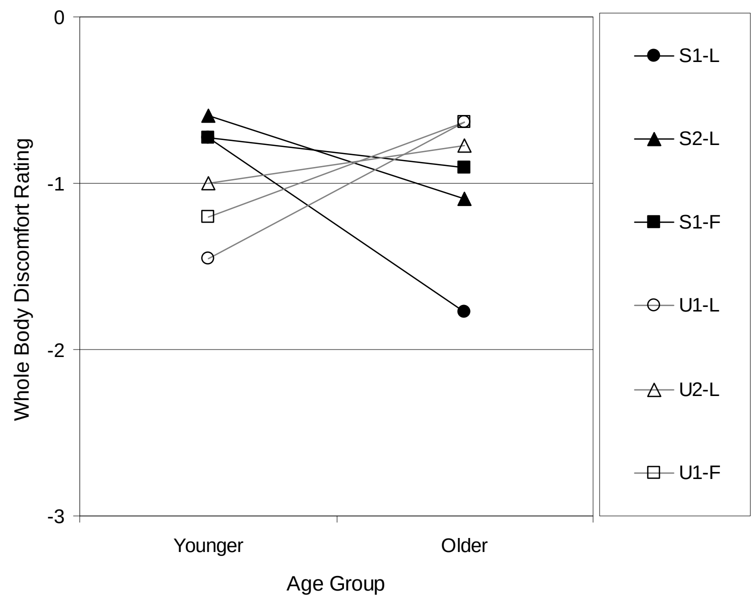


Figure 27. Mean whole-body discomfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 0.5~1.6)

3.1.2. Local body part ratings (comfort and discomfort)

Paired body parts

Comfort ratings for the left thigh (THL) were higher than those for the right thigh (THR), with respective mean differences of 0.27 (p=0.04) and 0.02 (p=0.16) in the younger and older groups. Comfort ratings for the left buttock (BTL) were higher (p=0.056) than those for the right buttock (BTR) ratings, with the mean difference of 0.27 in the older group, but the younger group rated their buttocks the same. No difference was found between these bilateral parts in terms of discomfort.

Local body part comfort ratings

Effects of Age and Age × Seat Condition on BTL showed a trend (p=0.08, 0.09; Figure 28). Comfort level at left buttock was lower for the younger vs. older group, with respective means of 5.24 (3.3) vs. 7.13 (2.8). For THL, effects of Age, Seat Condition, and Age × Seat Condition were all significant ($p<0.035$; Figure 29), while for THR only the two main effects were significant ($p\leq0.024$; Figure 30). For both cases, the younger group's ratings were lower than the older group's. Respective means were 5.8 (2.9) and 5.6 (3.1) for the younger vs. 8.1 (2.4) and 8.0 (2.4) for the older. In addition, for THL and THR, sedan settings were rated higher

($p<0.012$) than SUV settings. For UB and LB, the effect of Age was significant ($p<0.05$), and the younger group's ratings were again lower than their counterparts (Figures 31-32). Respective means were 5.2 (3.5) and 4.9 (3.3) for the younger group vs. 7.8 (2.5) and 7.2 (3.0) for the older group.

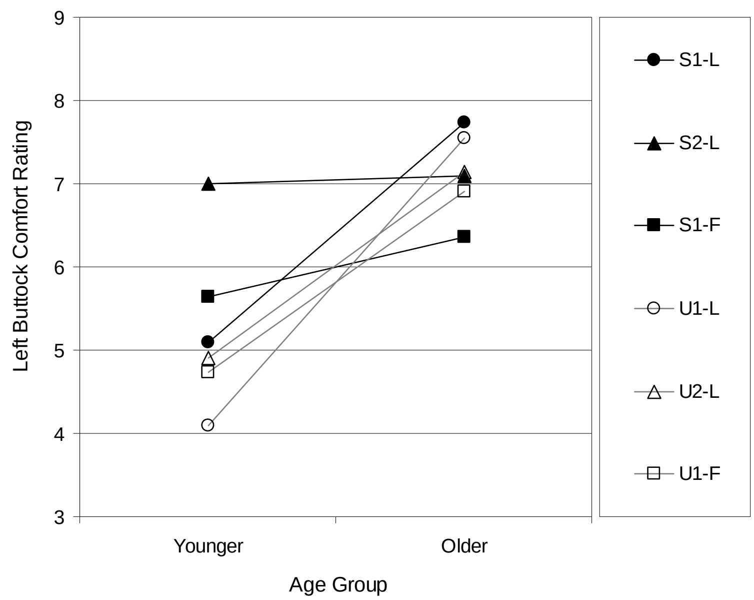


Figure 28. Mean left buttock (BTL) comfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 2.3~3.9)

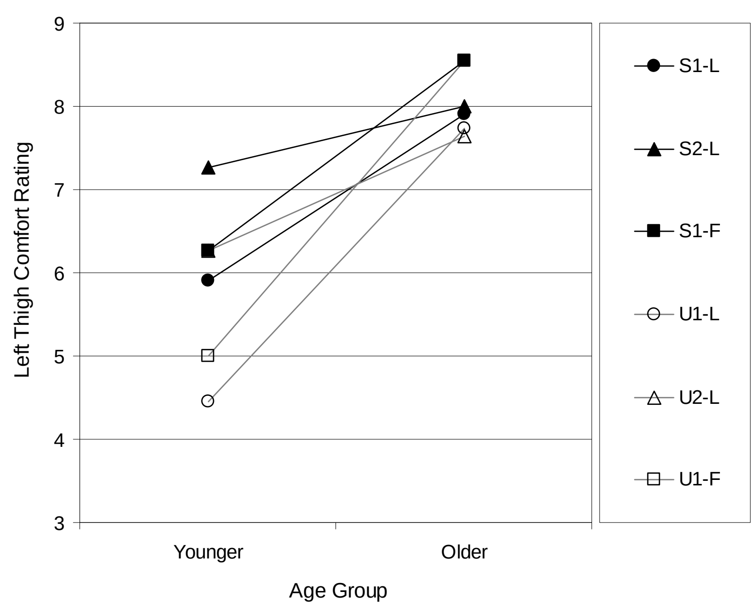


Figure 29. Mean left thigh (THL) comfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 2.0~3.3)

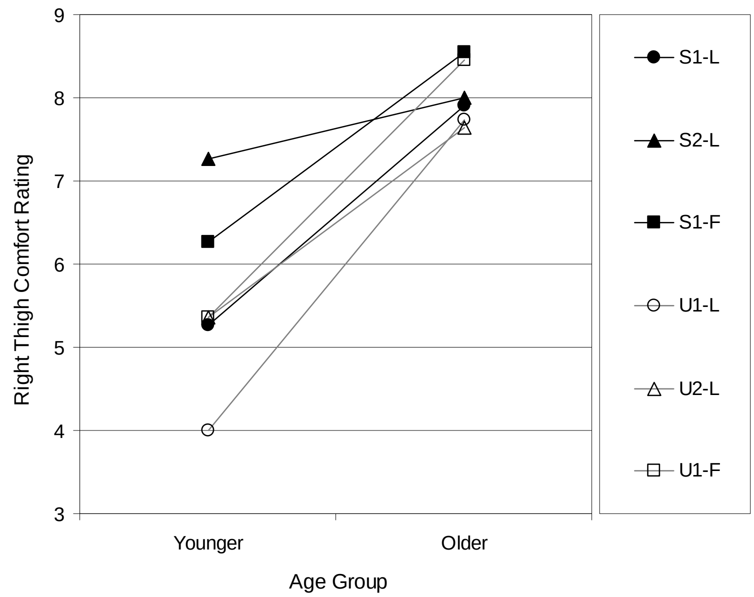


Figure 30. Mean right thigh (THR) comfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 2.0~3.5)

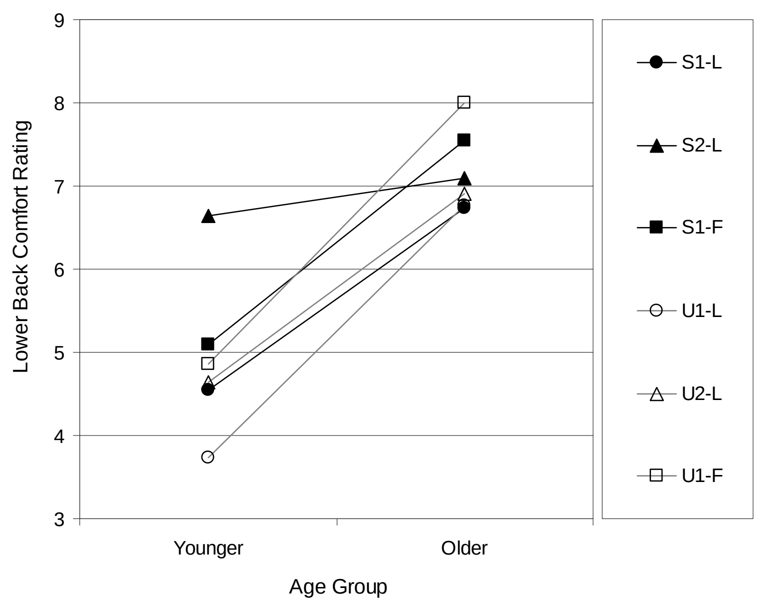


Figure 31. Mean lower back (LB) comfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 2.2~3.9)

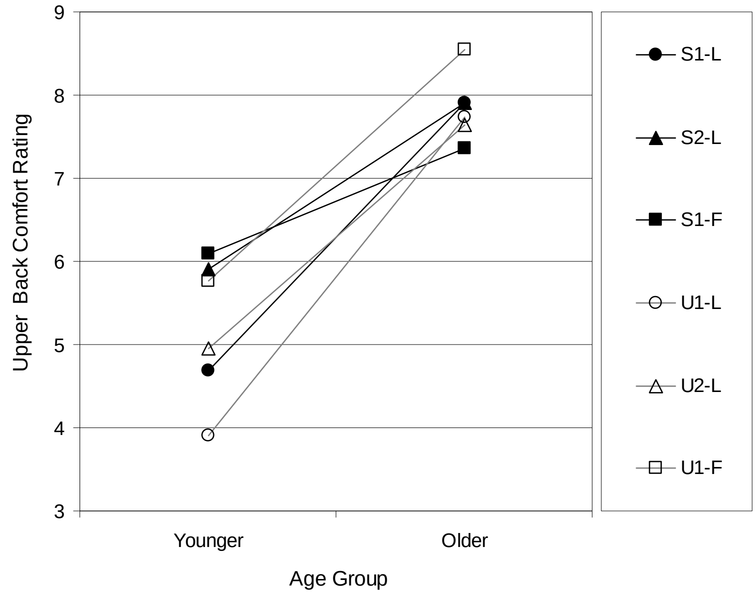


Figure 32. Mean upper back (UB) comfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 2.2~4.2)

Local body part discomfort ratings

No effects of Age and Seat Condition were found for any of the six body parts. However, the effect of Age × Seat Condition on THL, THR, and UB was significant ($p=0.006$, 0.015, 0.04; Figures 33-35); mean ranges across conditions were quite small (between 0 and -1). With respect to thigh (THL, THR) discomforts, U2-L and U1-F were perceived inversely between two age groups.

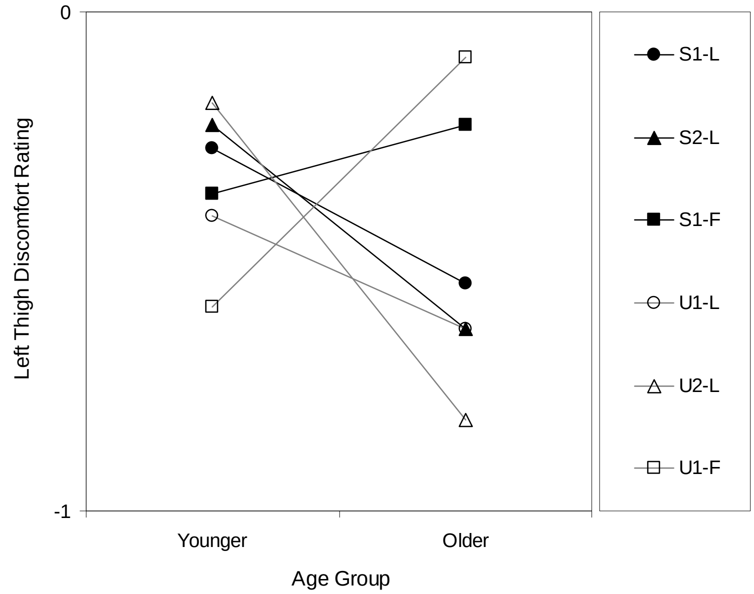


Figure 33. Mean left thigh (THL) discomfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 0.2~1.2)

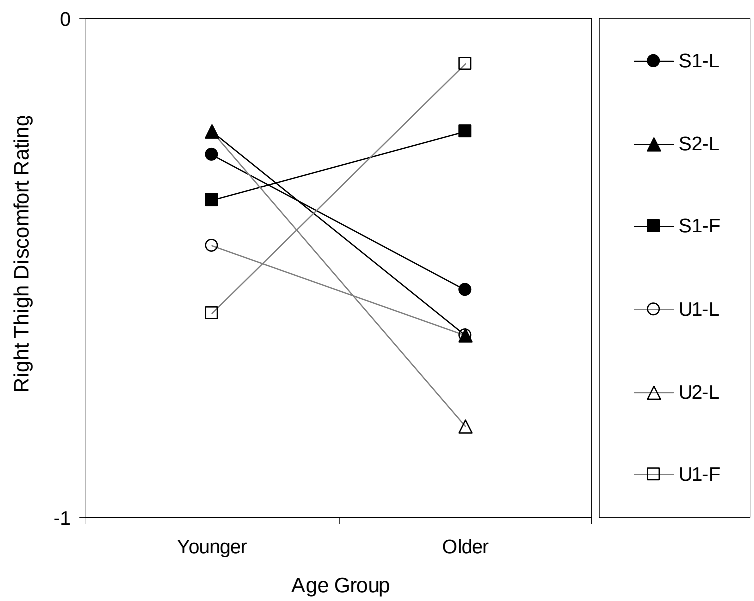


Figure 34. Mean right thigh (THR) discomfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 0.2~1.2)

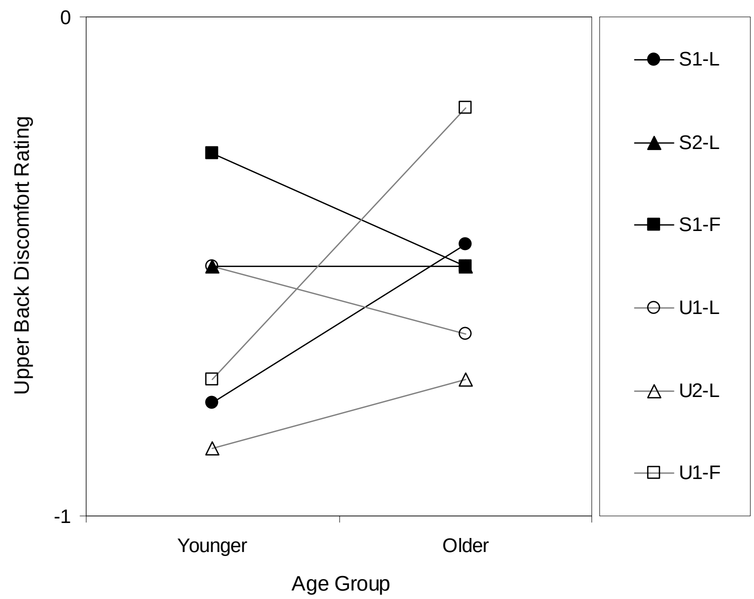


Figure 35. Mean upper back (UB) discomfort ratings for different Age Groups and Seat Conditions (SDs not shown for clarity, range = 0.3~1.4)

3.1.3. Correlations among subjective rating schemes

Correlations among whole body ratings

All bivariate correlations among the three whole body subjective ratings were significant ($p \leq 0.0009$) for both age groups. Overall ratings had a higher correlation with whole body comfort (ρ = 0.75 and 0.79 for the younger and older groups) vs. discomfort (ρ = 0.42 and 0.40) ratings, while the correlation between comfort and discomfort ratings was ρ = 0.43 and 0.41.

Correlations among ratings of whole body and local body parts

All local body part comfort ratings were moderately-highly correlated with each other ($0.61 \leq \rho \leq 1.0$ for the younger group; $0.48 \leq \rho \leq 1.0$ for the older group) and with whole body comfort ($0.72 \leq \rho \leq 0.84$; $0.5 \leq \rho \leq 0.86$). Bilateral comfort ratings (i.e., at thighs and buttocks) were highly correlated (ρ=0.91, 1.0; ρ=0.99, 0.88). Discomfort ratings between paired parts were also highly correlated for thighs and buttocks (ρ=0.96, 0.93; ρ=1.0, 0.97). Among the six body parts, LB discomfort had the highest correlation with whole body discomfort for the younger group (ρ=0.74), while UB discomfort had the highest correlation for the older group (ρ=0.54).

3.1.4. Aesthetic effect of seat

The effect of seat appearance on the expected level of seat comfort was not significant (p=0.12). Means values for the four seats ranged from 3.0 to 3.9 (between 'about average' and 'better than most').

3.1.5. Subjective ratings vs. alertness

All bivariate correlations among the three whole body subjective ratings and the alertness rating were significant ($p \leq 0.0009$) for the younger age group, but none was significant ($p \geq 0.67$) for the older age group. For the younger age group, comfort ratings showed the strongest relationship with perceived alertness level with $\rho = -0.70$, with a higher comfort level (closer to 10) corresponding to a higher alertness level (closer to 1), followed by overall ratings ($\rho = -0.63$). Discomfort ratings showed relatively weaker relationships with alertness level ($\rho = -0.28$). For the older group, the correlation range was $-0.05 < \rho < 0.02$.

3.2. Interface pressure

3.2.1. Effects of Age and Seat Condition on interface pressures

MANOVA showed that there were significant ($p \leq 0.0001$) main effects of Age and Seat Condition on the 36 pressure variables as a group, but there was no significant interaction effect. From subsequent ANOVAs, 13 significant ($p \leq 0.041$) Age x Seat Condition interaction effects were found. Significant ($p \leq 0.042$) Age effects were found on four pressure variables that were related to average contact areas (ratios), average contact pressure and peak contact pressure ratios (aBTR, aTHL/aSUM, avgLB, and pkUB/pkSUM). The older group had larger contact areas at the right buttock (aBTR), lower average contact pressure at the lower back (avgLB), smaller contact area ratio at the left thigh (aTHL/aSUM), and smaller peak contact pressure ratio at the upper back (pkUB/pkSUM).

Significant ($p<0.021$) Seat Condition effects were found on 29 pressure variables, while Seat Condition showed a trend ($p<0.09$) on four pressure variables (aBTL/aSUM, pkBTR, pkLB, and pkUB). No effects were found on the remaining three variables (pkTHR/pkSUM, pkBTR/pkSUM, and pkUB/pkSUM) that were all related to peak contact pressure ratios. Significant mean differences between S1-L and S2-L were found for 10 pressure variables (aUB, aTHR/aSUM, aUB/aSUM, avgTHL, avgTHR, avgLB, avgTHL/avgSUM, avgTHR/avgSUM, avgLB/avgSUM, and avgUB/avgSUM), all of which were related to the thighs, and upper/lower back. The same significant differences between these two seats were not found in comfort ratings at either local or global level, indicating that these two seats can be differentiated only objectively (using 10 pressure variables).

The contrast of vehicle classes (sedans vs. SUVs) was significant ($p \leq 0.038$) for 14 pressure variables. Among these, the means of nine variables were higher in the sedan class (aLB, aBTR/aSUM, aLB/aSUM, avgBTL, avgBTR, avgBTL/avgSUM, pkBTL, pkBTR, and pkBTL/pkSUM). The means of the remaining 5 variables (aTHL, aTHL/aSUM, avgTHL/avgSUM, pkTHL/pkSUM, and pkUB/pkSUM) were lower in the sedan class. Among the pressure variables, 19 showed significant differences between lab and field settings. The differences between venues was substantial (Range: -54.8% ~ 22.0%, Table 17).

Significantly larger contact areas and area ratios were found at the right vs. left thigh ($p<0.0001$; 2.1% more of the total contact area), and at the right vs. left buttock ($p=0.006$; 0.4% more of the total contact area). In terms of average and peak contact pressure and ratio, the left buttock was significantly ($p \leq 0.0023$) higher than the right buttock (i.e., 1.7% more of the total average contact pressure and 2.7% more of the total average peak contact pressure).

Table 17. Percent differences in mean contact area/pressure variables between lab and field settings by vehicle class (only significant differences are shown)

Variable group	Thigh		Buttock		Back	
	Left	Right	Left	Right	Lower	Upper
Area	-29.5[+] (-17.2)[*]		-27.0 (-14.8)	-24.5 (-14.9)	-54.8 (-38.2)	-23.1 (-38.2)
Area ratio		15.4 (16.7)			-14.3 (-15.8)	
Pressure	(13.9)	(10.8)	22.0 (19.0)		8.5	13.6 (7.4)
Pressure ratio		-15.4	16.0 (8.7)	-4.8 (-15.8)		
Peak pressure	(12.8)		19.6		-45.2	17.7
Peak pressure ratio			17.2	(-14.3)	-30.8	

[+]: Sedan, (S1-L–S1-F)/S1-L*100, [*]: SUV, (U1-L–U1-F)/U1-L*100

3.3. Correlations between subjective ratings and pressure variables

There were 22 pressure variables significantly correlated with at least one of the subjective ratings ($-0.26 \leq \rho \leq 0.31$, Table 18). The highest correlation ($\rho = 0.31$) was found between avgBTR and discomfort ratings. Among the 22 variables, 15 (Table 18) met the three conditions noted earlier (i.e. an association with any of the subjective ratings, a Seat Condition effect, and a lack of an Age effect).

Table 18. Coefficients of correlation (ρ) between subjective ratings and pressure variables (only significant correlations given)

Pressure variable	Overall rating	Whole body comfort rating	Whole body discomfort rating	Three conditions* met?
aBTL			0.17	Y
aBTR		0.21		
aLB		0.26		Y
aUB			0.20	Y
aTHL/aSUM		-0.23		
aTHR/aSUM		-0.20		Y
aBTR/aSUM			-0.20	Y
aLB/aSUM	0.20	0.3		Y
avgTHL			0.27	Y
avgTHR	-0.21	-0.23	0.25	Y
avgBTL			0.26	Y
avgBTR			0.31	Y
avgLB			0.28	
avgUB		-0.22		Y
pkTHL			0.24	Y
pkTHR	-0.26	-0.23	0.19	Y
pkLB			0.18	
pkUB	-0.19	-0.24	0.19	
pkTHR/pkSUM	-0.19	-0.17		
pkBTL/pkSUM			-0.18	Y
pkLB/pkSUM	0.25	0.26		Y
pkUB/pkSUM		-0.26		

* : An association between a given pressure variable and any of the subjective ratings, a Seat Condition effect on the variable, and lack of an Age effect

3.4. PCA and regression analysis using pressure variables

Eight factors with an eigenvalue > 1 accounted for 86.5 % of the total variance (Table 19). The smallest communality of 0.77 (found on aTHL) indicated that the variance of each pressure variable was well (at least 77% of it) accounted for by the selected factors. For Factor 1, which was related to contact areas and ratios, coefficients with opposite signs were found between the thigh and buttock average contact area ratios (i.e., aTH(L or R)/aSUM vs. aBT(L or R)/aSUM), and between the lower and upper back contact area ratios (i.e., aLB/aSUM vs. aUB/aSUM), respectively. In other words, there were negative associations between the thigh and buttock and between the lower and upper back in terms of contact area ratio. For Factor 3, coefficients with opposite signs were found between the right thigh and upper back average contact pressure ratios (i.e., avgTHR/avgSUM vs. avgUB/avgSUM). For Factor 5, coefficients relating to contact areas of the bilateral buttocks and low back were all positive (hence, positive associations between the buttocks and low back in terms of contact area).

Table 19. Eight principal components after varimax rotation (underlined values > 0.5 in their absolute values)

Pressure variable	Factor 1 overall (area/ratio)	Factor 2 left buttock (pressure)	Factor 3 right thigh vs. upper back (pressure)	Factor 4 right buttock (pressure)	Factor 5 buttock & lower back (area)	Factor 6 left thigh (pressure)	Factor 7 lower back (pressure)	Factor 8 upper back (pressure)
aTHL	**0.57**	-0.24	0.38	-0.07	0.22	0.40	0.14	0.10
aTHR	**0.80**	-0.13	0.30	-0.29	0.11	0.20	0.04	-0.04
aBTL	0.12	-0.19	0.07	0.05	**0.92**	0.04	0.08	-0.07
aBTR	0.02	-0.09	-0.06	-0.04	**0.93**	0.15	0.04	-0.09
aLB	0.08	-0.41	0.15	0.06	**0.72**	-0.09	0.20	-0.34
aUB	**0.75**	0.19	0.12	0.10	0.43	0.21	-0.07	0.27
aTHL/aSUM	0.38	-0.26	0.41	-0.06	-0.18	0.41	0.13	0.15
aTHR/aSUM	**0.56**	-0.01	0.19	-0.39	-0.51	0.11	-0.03	-0.04
aBTL/aSUM	**-0.82**	0.02	-0.31	0.05	0.06	-0.25	-0.03	-0.07
aBTR/aSUM	**-0.81**	0.16	-0.42	-0.08	0.01	-0.09	-0.10	-0.06
aLB/aSUM	-0.42	-0.45	0.05	0.12	0.31	-0.28	0.20	-0.48
aUB/aSUM	**0.64**	0.44	-0.01	0.12	0.02	0.14	-0.17	0.42
avgTHL	0.40	0.25	0.44	0.08	0.03	**0.66**	0.05	0.28
avgTHR	0.49	0.16	**0.73**	0.06	0.03	0.28	0.00	0.21
avgBTL	0.13	**0.76**	0.35	0.32	-0.08	0.18	0.05	0.30
avgBTR	0.19	0.49	0.37	**0.63**	0.10	0.14	0.08	0.31
avgLB	-0.02	0.01	0.29	0.05	-0.08	0.05	**0.77**	0.31
avgUB	0.24	0.51	0.13	0.17	-0.13	0.11	0.09	**0.65**
avgTHL/avgSUM	0.25	-0.31	0.06	-0.34	0.05	**0.74**	-0.18	-0.05
avgTHR/avgSUM	0.49	-0.32	**0.60**	-0.26	0.11	0.16	-0.19	-0.13
avgBTL/avgSUM	-0.17	**0.85**	-0.08	0.12	-0.16	-0.12	-0.17	0.04
avgBTR/avgSUM	-0.01	0.21	-0.02	**0.84**	0.24	-0.23	-0.09	0.03
avgLB/avgSUM	-0.33	-0.46	-0.14	-0.22	-0.08	-0.19	**0.64**	-0.06
avgUB/avgSUM	-0.19	-0.12	**-0.64**	-0.30	-0.20	-0.30	-0.19	0.26
pkTHL	0.39	0.18	0.41	0.08	0.06	**0.71**	0.15	0.20
pkTHR	0.36	0.11	**0.81**	0.04	-0.11	0.10	-0.01	0.27
pkBTL	0.00	**0.87**	0.01	0.23	-0.17	-0.15	0.03	-0.03
pkBTR	-0.02	0.30	0.10	**0.88**	-0.08	0.01	0.13	0.02
pkLB	0.13	0.09	-0.04	0.11	0.15	0.02	**0.87**	-0.01
pkUB	0.16	0.23	0.32	0.19	-0.16	0.06	0.25	**0.74**
pkTHL/pkSUM	0.26	-0.34	0.20	-0.35	0.15	**0.72**	-0.17	0.00
pkTHR/pkSUM	0.35	-0.31	**0.70**	-0.30	0.03	0.13	-0.27	0.09
pkBTL/pkSUM	-0.21	**0.75**	-0.28	-0.10	-0.19	-0.31	-0.25	-0.14
pkBTR/pkSUM	-0.18	-0.14	-0.14	**0.90**	-0.04	-0.13	-0.13	-0.17
pkLB/pkSUM	0.00	-0.29	-0.17	-0.13	0.22	-0.05	**0.83**	-0.12
pkUB/pkSUM	0.02	-0.26	0.00	-0.27	-0.10	0.03	-0.06	**0.84**
Eigenvalue	10.86	7.27	4.25	2.95	1.91	1.57	1.26	1.08
Cum Percent	15.31	29.40	41.18	51.93	60.94	69.69	78.19	86.52

Based on the size of the standard beta weights (Table 20), which represents the degree to which an independent variable contributes to its dependent variable (Freund et al., 2003), increasing Factors 5 and Factor 7 would be effective at improving all three ratings, as these had relatively large and positive standard beta weights. For Factors 3 and 8, standard beta weights with opposite signs were found between the whole-body discomfort regression model and the other two models, resulting in conflicting design guidelines (e.g., pkTHR should be decreased for comfort ratings, but it should be increased for discomfort ratings).

Table 20. Regression coefficients and standard beta weights for regression models relating PCA Factors to three ratings

Term	Overall rating		Whole body comfort rating		Whole body discomfort rating	
	Estimate	Standard Beta Weight	Estimate	Standard Beta Weight	Estimate	Standard Beta Weight
Intercept	78.17	0.00	6.30	0.00	-0.96	0.00
Factor1	-1.29	-0.08	-0.26	-0.09	-0.02	-0.01
Factor2	-1.82	-0.11	-0.08	-0.03	0.07	0.06
Factor3	-3.32	-0.21	-0.38	-0.14	0.27	0.23
Factor4	1.32	0.08	0.25	0.09	0.14	0.12
Factor5	0.34	0.02	0.45	0.17	0.20	0.17
Factor6	1.28	0.08	0.04	0.01	0.15	0.13
Factor7	3.12	0.19	0.58	0.21	0.23	0.20
Factor8	-2.26	-0.14	-0.69	-0.25	0.16	0.14

4. Discussion

Physiological changes with age might lead to perceptually and/or behaviorally different responses in driving context. To investigate this, three rating schemes and different types of interface pressure variables were used to quantify driving experiences of two age groups. Of primary interest were the inter-relationships among values obtained using these schemes and interface variables, their relative effectiveness in distinguishing (and hence designing and improving) car seats / packages, and differences in these relationships and effectiveness between age groups. A longer-term goal of this work is to determine general methods for obtaining such subjective responses from people across a wide age range, and to identify interface pressure variables that are strongly associated with subjective responses, which can then be used to improve car seats / packages. Toward these aims, several factors were included (seats, driving venues, vehicle classes, and age groups), and a variety of analyses were employed. Effects of each factor are described and interpreted below, along with implications and/or suggestions relevant to these aims.

At the whole-body level, none of the three rating schemes was particularly effective at distinguishing car seats. In contrast to Chapter 2, a distinction between S1-L and S2-L (sedan seat conditions in the lab) was not observed among six seat conditions in terms of whole body comfort. In this study, only several trends were observed. The younger group showed lower overall and comfort ratings compared to the older group. A different preference between age groups for vehicle class (or package) was also observed. The older group preferred the SUV package (U1) over the sedan package (S1), while the younger group preferred S1. The latter preference was also shown in Chapter 2. U1 had a 35 mm higher seat height and a 3 degree less reclined seat back angle than S1 at initial settings. Hence, the older group appears to prefer higher and more upright seat positions (and driving postures). This preference may be partly due to their flatter and more kyphotic spinal curves (Milne and Lauder, 1974).

At the localized level, Age effects were identified, but, only in terms of comfort. The younger group showed lower levels of comfort for five body parts (the left buttock, thighs, and upper/lower back) compared to the older group. Local body discomforts, however, did not show any difference between two age groups. From correlation analysis, UB discomfort appeared to be the major determinant of whole-body discomfort among individuals in the older group, whereas LB discomfort was of primary importance in the younger group. Coupled with age-related differences in vehicle class preference, this difference in which local part primarily contributes to whole-body discomfort might be due to a difference in the normal driving posture between the age groups, and a lack of effective seatback support for both groups.

Several pressure measures also supported that there were different loadings (due to postural differences) between two age groups. Peak pressure ratio at UB (pkUB/pkSUM) exhibited an Age effect (but no Seat Condition effect), with the older group having 13.9% smaller values. The contrast of vehicle class was also significant, with sedans having 7.6% lower values. It can be concluded that seats in SUV settings provided more support for the upper back in terms of peak pressure ratio than those in sedan settings. The older group did not appear to have sufficient support for their upper back compared to the younger group regardless of vehicle class, but could get relatively better support for their upper back in SUV settings. Note that upper back discomfort ratings were the major determinant of whole-body discomfort for the older group and that this group preferred SUV settings, as discussed above. Hence, a more concave design for the upper back profile may be considered to improve seat back design and to reduce upper back discomfort among older drivers. In addition to the measure of pkUB/pkSUM, three pressure measures (aBTR, aTHL/aSUM, and avgLB) were affected by Age. Based on differences in these four measures, the older group seemed to adopt a driving posture that was relatively forward and rightward leaning, compared to the younger group's backward and leftward leaning postures.

From the correlation and regression analyses, average pressure at the right buttock (avgBTR) should be higher to reduce discomfort and increase comfort. Of the 36 pressure measures, the largest positive correlation ($\rho = 0.31$) was found between avgBTR and discomfort ratings. Factor 4, with positive coefficients for right buttock pressures and ratios (avgBTR(/avgSUM) and pkBTR(/pkSUM)), had positive standard beta weights for three regression models (overall, comfort, and discomfort). Hence, consistent with the findings in Chapter 3, the rear seat cushion area in contact with the buttocks should be designed asymmetrically (e.g., in terms of contour and/or hardness) in order to achieve a balanced pressure distribution and to improve the sitting experience. Further, bilateral asymmetry in lower limb postures was apparent from bilaterally unbalanced pressure distribution at the seat cushion (0.4-2.7% bilateral difference in terms of contact area/ratio and pressure/ratio).

There are additional ways of improving seat design using the pressure measures obtained in this study. The seat cushion should be made softer, especially the area contacting the buttocks. The basis for this is that Factor 5, with positive standard beta weights in three regression models, was largely determined by buttock contact areas (aBTL, aBTR) with positive coefficients. Consistent with findings in Chapter 3, higher pressure is needed at the lower back region since lower back (peak) contact pressures and ratios (avgLB(/avgSUM) and pkLB(/pkSUM)) had positive coefficients for Factor 7 with positive standard beta weights in three regression models. Lastly, from Factor 3, average pressure ratios for the right thigh and upper back (avgTHR/avgSUM and avgUB/avgSUM) appeared to be negatively associated (as confirmed by $\rho = -0.40$). In general, the front seat cushion area should be designed in a way that not only supports the underside of the right thigh, but also does not hamper pedal operations. The current results suggest that if the front seat cushion area is too thick (hence, overemphasizing its supporting function), it can even negatively affect upper back support. However, three regression models proposed conflicting design guidelines, with standard beta weights having opposing signs for Factors 3 and 8. Hence, between the right thigh and upper back, increased comfort for one leads to more discomfort for the other. Besides general seat design recommendations (e.g., well-rounded waterfall front edge design; Carter and Banister, 1994), more investigation is needed to optimize this seat area.

Age effects were evident in terms of pressure measures as well as subjective rating. The two age groups had different values of average contact area and ratio at their right buttock (aBTR, 12.9% larger for the older group) and left thigh (aTHL/aSUM, 7.3% higher for the younger group), average contact pressure at their lower back (avgLB, 30.8% higher for the younger group), and average peak pressure ratios at their upper back (pkUB/pkSUM, 13.9% higher for the younger). In terms of local comfort ratings, five local body parts except for the right buttock showed age effects (i.e., higher comfort for the older group). Though mean ranges across conditions were quite small (between 0 and -1), U1-F was rated worst by the younger group, yet rated best by the older group, in terms of discomfort at the thighs (THL and THR). A similar contrasting result was found in U2-L, which was rated best by the younger group but worst by the older group. These age effects indicate that different pressure requirements are needed for the seat, as criteria in seat design and evaluation to accommodate different ages of drivers. Previous studies have also shown the need for more adjustability in the seat back (Branton, 1984; Harrison et al., 2000; Chapter 2), however, in these cases not to account for the age effect, but rather for anthropometric variability.

LB and UB discomforts had, respectively, the highest correlations (ρ=0.74, 0.54) with whole body discomfort than any other local body part discomfort for the younger and older groups. Thus, improvement to the seatback may be most effective at achieving further reductions in discomfort. These results are in accordance with evidence from short-term exposures (e.g., Chapter 2) as well as from long-term exposures (e.g., Schneider and Ricci, 1989), though further consideration of any potential age-specific requirements is needed.

Results here are comparable with those from previous studies (e.g., Chapters 2 and 3), supporting more generalized applicability of previous findings to drivers of diverse ages. The first is that distinct processes are used in determining whole-body comfort and discomfort levels (i.e., averaging of local discomforts when determining whole-body comfort, and predominating of local maximal discomfort when determining whole-body discomfort). Second, though only at the local levels here, comfort ratings were still more effective at distinguishing better seating conditions (i.e., sedan settings were perceived more comfortable for the thighs (THL, THR), with the mean differences of 0.71 and 0.79). Third, most pressure variables (19 out of 36) showed a venue effect, or a difference between lab and field settings, indicating that recommended pressure levels for sitting comfort / discomfort should be specified for each venue type, with the difference ranging from -54.8% to 22.0%. Hence, lab-based investigation (without vibration) will be valid only for measuring a vehicle's static comfort. Fourth, from the PCA, contrasting associations were found between local body parts: negative associations between the right thigh and upper back (avgTHR/avgSUM vs. avgUB/avgSUM), and positive associations between the buttocks and low back (aBTL(R) and aLB). The latter association was also found in Chapter 3.

There were several potential limitations in this study. First, stature effects were not investigated, though this factor was significant for subjective ratings and some pressure measures in Chapters 2 and 3. Second, appearances of car parts could be a confounding factor. Aesthetic effects of other car parts except for the seats could not be effectively controlled in field settings. Third, historical driving experience with specific vehicle classes could affect subjective responses negatively or positively (the participants drove a sedan more often than any other vehicle type). Forth, though three regressions of subjective ratings on the pressure factors were significant, these models only accounted for a small portion of the total variability in subjective ratings, likely due to excluding local body parts that were not in contact with the seat (e.g., neck, upper limbs, knees, and body parts below knees). Fifth, experimentwise type I error might have been inflated, since 36 pressure measures were used and they are not uncorrelated. One of objectives of this study, however, was to identify potentially useful measures via an exploratory approach (hence, including diverse types of measures). Hence, although some significant effects may be spurious, the findings in the current study should still be useful when designing future experiments that involve pressure measures.

5. Conclusions

The current study showed that at local levels, comfort ratings are effective at evaluating driver workspace, and that age did not influence the processes used when determining whole-body perceptions based on localized perceptions. Some age-related differences were also identified; different preferences for vehicle class, different local body part predominantly determining whole-body discomfort, and several pressure measures of significantly different values. In addition, older individuals appeared to be less sensitive to discomfort than younger individuals. These similarities and differences should be carefully considered when designing the driver workspace.

Chapter 5: Cross-cultural difference between North Americans and Koreans in perceptual responses to driver workspace design

Abstract

In contrast to the general recognition of regional differences in automotive seat design requirements, less is known about potential cultural differences in perceptual responses to driver workspace design. Three subjective rating schemes were incorporated to determine whether there were cultural differences in: 1) the efficacy of each rating for use in designing and evaluating the driver workspace and interface design, 2) driving experience in sedan and SUV settings, and 3) the local-to-global perceptual decision process with respect to an individual's driving experience. Two cultural groups (North Americans and Koreans) completed four short-term simulated driving sessions that involved two vehicle classes (sedan and SUV) and two seats (from vehicles ranked high and low by J.D. Power and Associates' Comfort Score) for a given vehicle class. Three ratings were obtained for comfort, discomfort, and a combination of these two (overall rating). The first two ratings were also obtained from local body parts. For both cultural groups, comfort rating at the whole body level was the most effective at distinguishing among automotive seats/packages, and two processes were used to relate local to global perceptions (whole-body comfort determined by averaging local body part comforts, and whole-body discomfort determined predominantly by some local parts' discomforts). A difference in preference for the two vehicle classes was also found between the two cultural groups: the North American group reported better a driving experience in sedans than in SUVs, whereas the Korean group showed no difference.

Relevance

Differences and similarities between cultural groups with respect to perceptual response and preference should be incorporated into designing any products including automobiles.

Keywords: cultural effect; comfort; discomfort; decision process; driving experience

1. Introduction

According to Kolich and Taboun (2004), perceived comfort for a particular automotive seat is assumed to be distinct among consumers of different regions, or cultural groups (e.g., Western Europeans vs. North Americans). Indeed, there are different specifications being used when designing car seats. For example, low density foams, high density foams, and highly resilient foams are used respectively for car seats manufactured for North America, Europe, and Japan consumers, in order to correspond to differences in regional needs (Leenslag et al., 1997). These alternatives are based on the general recognition that North Americans prefer soft seats, Europeans prefer hard seats, and Japanese prefer resilient seats (Leenslag et al., 1997).

There has been extensive work conducted on seat comfort and comfortable driving postures, nearly all of which, however, has been conducted among North Americans and Europeans. By comparison, there is very little evidence available from studies that involved Asian populations. Exceptions are Park et al. (2000) and Matsuoka and Hanai (1988), who addressed comfortable driving postures for Koreans and Japanese, respectively. Unlike the availability of worldwide specifications for seat foams, and evidence on comfortable driving postures, there is little evidence regarding whether differences exist among cultural groups in the perceptual responses to driver workspace design or the effectiveness of alternative subjective rating schemes.

To address these needs and limitations, the goals of this study were: 1) to determine effective subjective rating schemes for two cultural groups (North Americans and Koreans), so that such schemes can be used to design and evaluate driver workspace design, 2) to investigate cultural differences in driving experience in each of two vehicle classes (i.e., sedans and SUVs), and 3) to investigate whether these two cultural groups use the same decision processes when relating local and global perceptions within driver workspaces.

2. Experimental methods

2.1. Overview of experiment and participants

Eleven Korean younger males were newly recruited, and the same number of North American males from an earlier study (Chapters 2 and 3) was selected to match the two groups in terms of gender, stature, and body mass (Table 21). No significant differences existed in terms of stature and body mass between two groups (t-test, $p = 0.08$ and 0.09), though the Korean group was significantly older ($p<0.0001$).

Table 21. Participant characteristics

	Cultural Group	
	North Americans	Koreans
# of Participants and Gender	11 males+	11 males
Mean (SD) Stature (cm)	176.9 (9.5)	171.9 (6.2)
Mean (SD) Body Mass (kg)	75.7 (9.6)	69.9 (9.6)
Mean (SD) Age (year)	22.3 (3.5)	31.2 (3.2)

+: Out of 12 younger American males, the tallest person (stature = 192.5cm) was excluded.

Earlier work by Park et al. (2000) showed that there was no substantial difference in driving postures between North Americans and Koreans (trunk-thigh angle and knee angle were suggested slightly larger for Koreans, though no statistical tests were reported). Hence, objective measures (e.g., joint angles and pressure data) were not collected in this study. Two cultural groups completed four 20-min simulated driving sessions in a lab environment using an adjustable driving rig. Two vehicle classes (sedan [S] and SUV [U]) and two seats (S1, S2; U1, U2) for each vehicle class were used for these sessions. Seats were from vehicles ranked high [1] and low [2] by J. D. Power and Associate's Comfort Scores (2005).

Each participant completed an informed consent procedure, approved by the local Institutional Review Board, prior to the first experiment session. After driving, and while maintaining their preferred postures, participants rated their postures in terms of comfort, discomfort, and a combination of these two (overall rating), in the same way as described in Chapter 2. Several scales were used by participants, at the end of each driving session, to assess drivers' perceptions. Comfort and discomfort scales were derived as combinations of versions developed by Borg (1990) and Corlett-Bishop (1976), and used for the whole body and six local body parts (bilateral thighs and buttocks, and lower and upper back). In addition, a visual analogue scale (VAS) was used to obtain overall perceptual ratings of the whole body. The Karolinska Sleepiness Scale (KSS) by Horne and Reyner (1995) was used to measure drivers' alertness level.

2.2. Data analysis

A mixed-factor analysis of variance (ANOVA) was used to determine whether there were main and interaction effects of Culture (North Americans and Koreans) and Seat Condition (S1, S2, U1, and U2) on each of three subjective ratings (overall, comfort, discomfort), with the Tukey's Honestly Significantly Different (HSD) test used for post-hoc pairwise comparisons among Seat Conditions. Effects were considered 'significant' when $p \leq 0.05$, with potential trends highlighted when $0.05<p\leq0.1$. Specific pairwise comparisons were done to determine if there were seat effects within vehicle class (sedan - S1 vs. S2; SUV - U1 vs. U2). In addition, a linear contrast of vehicle classes (S1 + S2 vs. U1 + U2) was tested, to compare preferences between the two classes. Ratings between bilateral body parts (thighs, buttocks) were examined using matched pairs comparisons, for each cultural group. Bivariate coefficients of correlation (ρ) were obtained among the several subjective ratings, at both local and global levels, for each age group. Possible aesthetic effects of four seats on comfort rating were examined using a univariate repeated-measures ANOVA. Lastly, bivariate correlation coefficients (ρ) were obtained between each of three ratings and alertness level, for each cultural group.

3. Results

3.1. Whole body ratings (overall, comfort, and discomfort)

<u>Whole body overall rating</u>

None of the effects (Culture, Seat Condition, or Culture × Seat Condition) were significant ($p>0.206$). The North American group, however, tended to rate higher than the Korean group, and overall ratings also tended to be higher in the seats of lower-rated vehicles (S2-L and U2-L; Figure 36). No significant difference between vehicle classes was found ($p=0.11$), though sedan conditions were rated higher than SUVs, with means (SD) of 79.4 (13.8) and 76.9 (14.4), respectively.

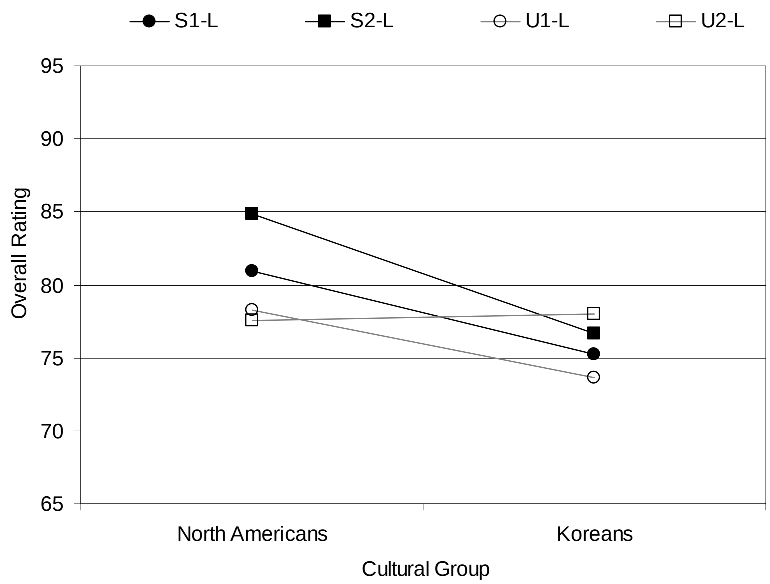


Figure 36. Mean overall ratings for different Cultural Groups and Seat Conditions (SDs not shown for clarity, range = 11.5~16.6)

Whole body comfort rating

There was a significant (p=0.0324) effect of Seat Condition on whole body comfort ratings. One of the selected pairwise comparisons of seats (S1-L vs. S2-L) was significant, with the seat from a lower-rated sedan (S2) being rated higher, consistent with Chapter 2. Effects of Culture and Seat Condition × Culture were not significant (p>0.59). In contrast to Chapter 2, the contrast between vehicle classes was not significant (p=0.275), largely due to no experiential difference between sedans and SUVs among Koreans (Figure 37). Respective means (SD) for sedans and SUVs were 6.5 (3.0) and 5.9 (3.1) for North Americans, and 5.6 (2.6) and 5.6 (3.0) for Koreans.

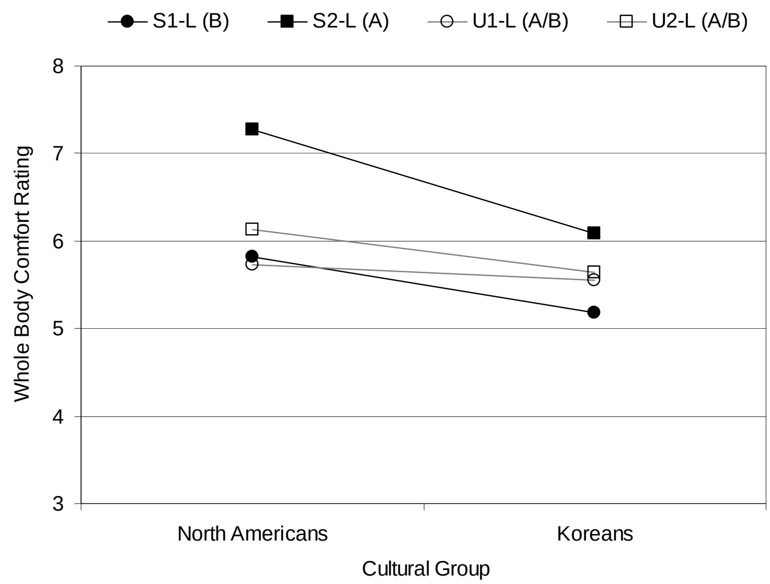


Figure 37. Mean whole-body comfort ratings for different Cultural Groups and Seat Conditions (Tukey's HSD grouping in parentheses; SDs not shown for clarity, range = 2.34~3.55)

Whole body discomfort rating

For whole body discomfort ratings, only the effect of Culture was significant (p=0.01), with better (higher) ratings from the North American group. Mean (SD) ratings were -0.8 (0.8) and -2.3 (1.8), respectively, for North Americans and Koreans. The contrast of vehicle classes was not significant (p=0.25), though sedans conditions were rated higher than SUVs (Figure 38). Mean (SD) ratings were -1.4 (1.4) and -1.7 (1.7), respectively.

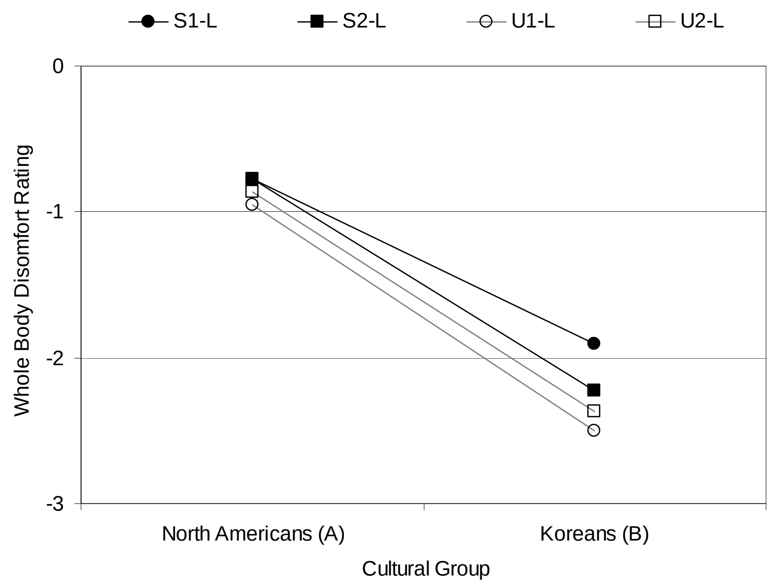


Figure 38. Mean whole-body discomfort ratings for different Cultural Groups and Seat Conditions (Tukey's HSD grouping in parentheses; SDs not shown for clarity, range = 0.7~2.4)

3.2. Local Body Part Ratings (Comfort and Discomfort)

Paired body parts

Comfort ratings for the left thigh (THL) were higher (better) than those for the right thigh (THR), in the North American group (p=0.04), but not in the Korean group (p=0.44). Respective mean differences were 0.34 and 0.02. No difference was found between bilateral thighs in terms of discomfort, in either cultural group. Similarly, no difference was found in either cultural group between bilateral buttocks (BTL and BTR) in terms of comfort or discomfort.

Local body part comfort ratings

The effect of Seat Condition on LB was significant (p=0.0029). No main or interaction effect was found for the remaining body parts (upper back, buttocks, and thighs). Of the four seats, S2-L was rated highest for LB and grouped differently (Figure 39). The contrast of vehicle classes was significant for LB (p=0.0064), with sedan conditions rated higher than SUVs.

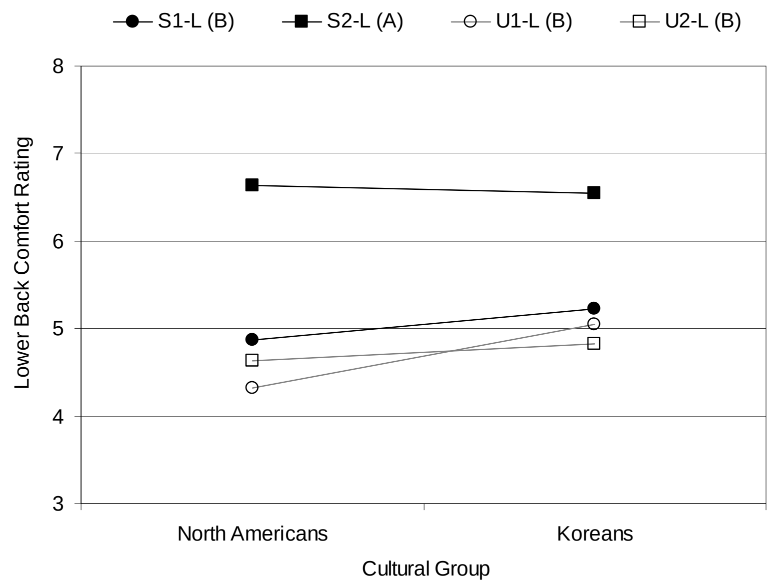


Figure 39. Mean lower back (LB) comfort ratings for different Cultural Groups and Seat Conditions (Tukey's HSD grouping in parentheses; SDs not shown for clarity, range = 2.3~3.6)

<u>Local body part discomfort ratings</u>

Culture effects on thighs (THL and THR) discomfort were significant ($p<0.049$; Figure 40; Figure 41), while effects on upper and lower backs (UB, LB) discomfort showed a trend ($0.05<p\leq0.099$). For all of these four body parts, discomfort ratings for the North American group were higher (i.e., less discomfort). A significant Seat Condition effect was found only for LB ($p=0.04$), with S2-L differently grouped from the other seats (Figure 42). However, the contrast of vehicle classes was not significant ($p=0.17$). The effect of Culture × Seat Condition showed a trend for THL ($p=0.07$).

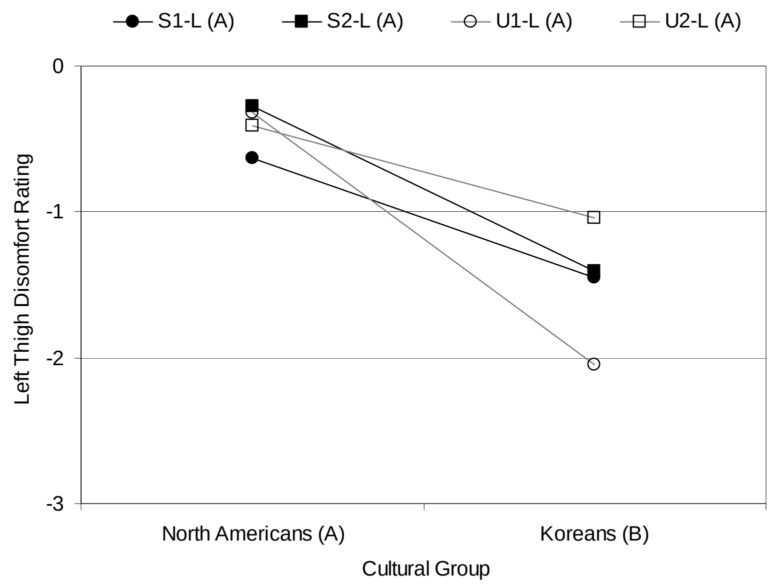


Figure 40. Mean left thigh (THL) discomfort ratings for different Cultural Groups and Seat Conditions (Tukey's HSD grouping in parentheses; SDs not shown for clarity, range = 0.5~1.8)

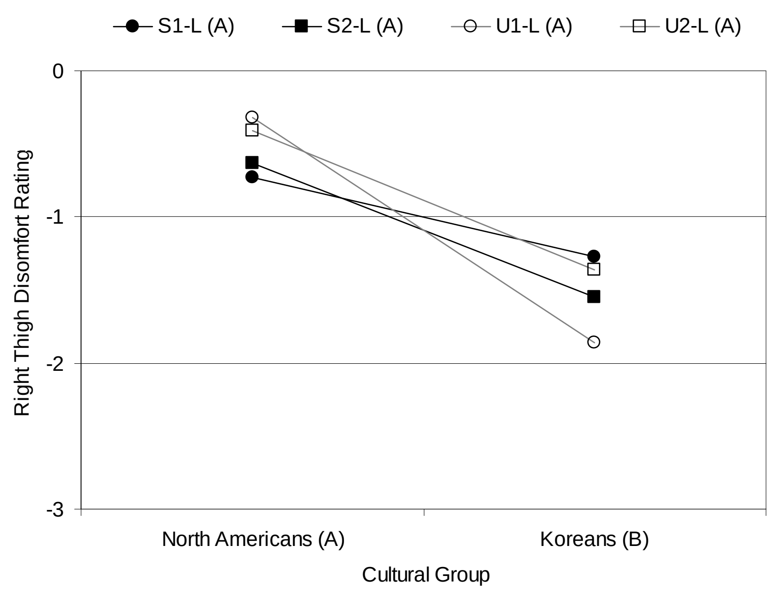


Figure 41. Mean right thigh (THR) discomfort ratings for different Cultural Groups and Seat Conditions (Tukey's HSD grouping in parentheses; SDs not shown for clarity, range = 0.5~1.8)

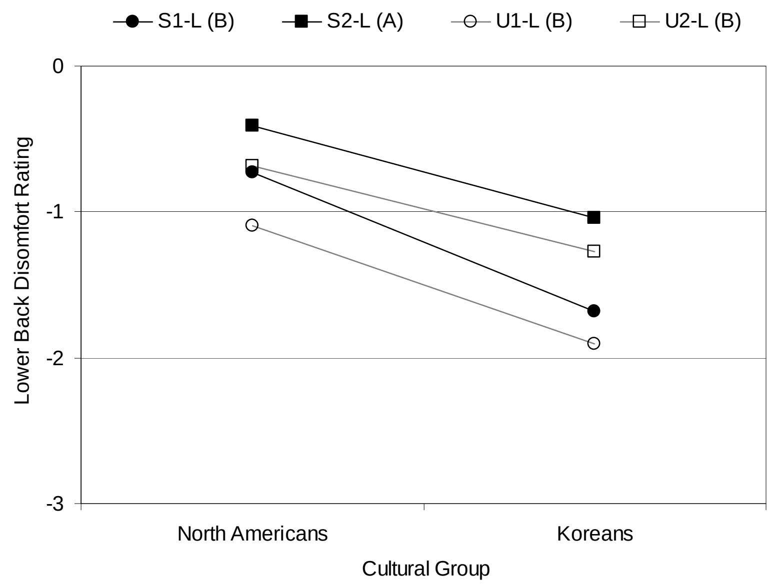


Figure 42. Mean lower back (LB) discomfort ratings for different Cultural Groups and Seat Conditions (Tukey's HSD grouping in parentheses; SDs not shown for clarity, range = 0.6~2.0)

3.3. Correlations among subjective rating schemes

Correlations among whole body ratings

All bivariate correlations among the three whole body subjective ratings were significant ($p<0.05$). For the two respective cultural groups, overall ratings had a higher correlation with whole body comfort (ρ=0.73 for the North American group, 0.74 for the Korean group) vs. discomfort (ρ=0.30, 0.62) ratings, while the correlation between comfort and discomfort ratings was relatively small (ρ = 0.41, 0.51).

Correlations among ratings of whole body and local body parts

All local body part comfort ratings were moderately-highly correlated with each other ($\rho \geq 0.73$ for the North American group, $\rho \geq 0.63$ for the Korean group) and with whole body comfort ratings ($\rho \geq 0.82$, $\rho \geq 0.81$) for the two respective cultural groups. Right and left paired body parts (i.e., thighs, and buttocks) were highly correlated ($\rho \geq 0.93$, $\rho \geq 0.94$) in terms of comfort. Discomfort ratings between paired parts were also highly correlated ($\rho \geq 0.80$, $\rho \geq 0.88$). Among the body parts, thigh (THL, THR) discomforts had the highest correlation with whole body discomfort ($\rho \geq 0.62$, $\rho \geq 0.96$) for the two respective groups.

3.4. Aesthetic effect and alertness

The effect of seat appearance on the expected level of seat comfort was not significant ($p=0.91$). Means values for the four seats ranged from 3.3 to 3.5 (between 'about average' and 'better than most'). For the North American group, comfort ratings showed the strongest relationship with the alertness level with $\rho = -0.83$, indicating a higher comfort rating (closer to 10) is related to a higher alertness level (closer to 1), followed by overall ($\rho = -0.68$) and discomfort ratings ($\rho = -0.51$). For the Korean group, overall ratings showed the strongest relationship with the alertness level with $\rho = -0.54$, followed by discomfort ($\rho = -0.31$) and comfort ratings ($\rho = -0.21$).

4. Discussion

Despite the recognition of regional differences in automotive seat design requirements, less is known about cultural differences in the perceptual response to driver workspace design. In the current study, three rating schemes were used to quantify subjective responses to simulated driving experience, and were compared each other to investigate whether previous findings (Chapter 2) can be generalized across cultural groups. Specifically, the earlier study showed: 1) comfort ratings are the most effective at distinguishing among automotive seats / packages for younger Americans, 2) sedans provide a better driving experience than SUVs, and 3) separate processes are used in determining whole body perceptions from local body perceptions. This study investigated whether or not there were cultural (North Americans vs. Koreans) effects on each of these three previous findings.

Among three subjective ratings measured at the whole-body levels, comfort rating showed the same outcome as in Chapter 2 (i.e., S2-L were rated higher than S1-L). This result supports that comfort ratings might be generally applied regardless of cultural groups. The results of discomfort rating were similar to those in the previous study; higher (better) rates were found for sedan settings. The current study also found Culture effects, with the Korean group reporting more discomfort. This was deemed to be largely due to the fact that the seats used in this study were from the cars targeted for, hence probably customized for, the American market. Though not significant, the Korean group also showed lower comfort ratings (i.e., this group reported worse ratings in terms of comfort as well).

On the contrary, the results in terms of overall rating in this study were somewhat different from those in the previous study. This study found no experiential difference between vehicle classes, due to the fact that the Korean group did not show different ratings between sedan and SUV settings. The North American group reported a better driving experience in sedan settings in both studies (Note: data for American participants used in the current study was a portion of the data collected from the previous study). More studies are, however, needed to generalize these findings as well as to address any potential cultural differences in ratings more in general, including investigation of cross-cultural “differences in judgment criteria” (Brown et al., 1990, p. 5).

Several similar results were found for local body part comfort ratings between the two studies. THL (in terms of comfort) was rated higher (better) than their counterpart, indicating that bilateral body parts were not rated equally. The contrast of vehicle classes was significant for LB in both studies, with the same result of higher ratings from sedan conditions. From this result, sedan seats seem to better support drivers’ lower back. Therefore, SUV seats can be improved by referring to sedan seats, but at the same time, the different postural requirements between age groups (as shown in Chapter 4), and between vehicle classes (e.g., more upright posture in SUV settings as shown in Chapter 8) also should be carefully taken into account.

Differences also existed between the two studies with respect to local body part discomfort. The only significant Seat Condition effect was on LB comfort in this study, yet UB comfort in the previous study. The contrast of vehicle classes was not significant for any local body part in this study, whereas it was significant for LB and UB comfort in the previous study. This discrepancy, as above, was also likely due to the specific seats used for this study (i.e. tailored for the American market), which is supported by the fact that the Korean group showed lower (worse) discomfort ratings for four local body parts (THL, THR, UB, and LB).

Correlations among whole body ratings showed a similar pattern between the two studies (hence, between two cultural groups as well): significant bivariate correlations among three ratings and overall ratings having a higher correlation with comfort ratings. Similarly, both studies showed that all local body part comfort ratings had moderately high correlations with each other and with whole-body comfort ratings, and comfort (discomfort) ratings between paired body parts also showed high correlations. One difference was that, in the current study, discomfort ratings for the thighs (THL and THR) were most highly correlated with whole-body discomfort ratings, whereas back (LB and UB) ratings were not highly correlated, both in contrast to the previous study. This difference seemed to come from significant Culture effects on thigh (THL and THR) discomfort. It can also be speculated that Koreans might be more sensitive to discomfort in their thighs compared to North Americans. In addition, the seat factor described above and anthropometric differences (i.e., relatively smaller ratio of lower to upper body for Koreans; Diffrient et al., 1990) could contribute to this discrepancy in correlations between two studies.

There were several limitations in this study. First, in order to validate the findings that Koreans are more discomfort sensitive, a further study is required that uses different seats made for other car markets including the Korean market (seats from the same vehicles, but targeted for different regions would be the best choice). Second, this study measured only participants' stature and did not collect other anthropometric data. Therefore, it could not be determined that both cultural groups participating in this study really had a different lower-to-upper body ratio. Third, age differences between two cultural groups could also have affected the results since, on average, the Korean group was 8.9 years older than the North American group. However, with age, people tend to become less sensitive to their postural discomfort (as shown in Chapter 4). Hence, the findings were more likely due to cultural rather than age differences.

5. Conclusions

This study showed two consistent results across two cultural groups: the effectiveness of comfort ratings at distinguishing among automotive seats / packages, and the existence of separate processes in determining whole body perceptions from local body feelings. The reported driving experience according to vehicle class was also different between two cultural groups: The North American group reported a better experience in sedans, whereas the Korean group showed no difference.

In future work, a field study (involving on-the-road driving) should be conducted to increase the external validity of the present findings. In addition, potential differences between older individuals within the two cultural groups as well as between younger and older Koreans, in subjective ratings and objective measures (e.g., interface pressure), need to be investigated.

Chapter 6: Sensitivity of preferred driving postures and determination of core seat track ranges

Abstract

With advances in virtual prototyping, accurate digital modeling of driving posture is regarded as a fundamental step in the design of ergonomic driver-seat-cabin systems. Extensive work on driving postures has been carried out focusing on the measurement and prediction of driving postures and the determination of comfortable joint angle ranges. However, studies on postural sensitivity are scarce. The current study investigated whether a driver-selected posture actually represents the most preferred one, by comparing the former with ratings of postures selected at 20 predefined places around the original hip joint center (HJC). An experiment was undertaken in a lab setting, using two distinctive driving package geometries: one for a sedan and the other for an SUV. The 20 postural ratings were compared with that of the initial user-selected position. Alternative HJC locations for each gender, age and stature groups were identified where a postural rating was close to, and sometimes even higher than, the initial score. Using these ratings, equal comfort contour maps with respect to HJC were drawn for each group. In addition, SAE recommended practices related to the positioning of HJC as well as eyes and ball of foot (BOF) were evaluated.

1. Introduction

A driver's sitting comfort is regarded as an important part of overall vehicle comfort. As one aspect of a driver's sitting comfort, postural comfort also plays an important role in determining vehicle comfort. In the age of virtual prototyping, the importance of accurately positioning the human model in a virtual driving workspace has increased (Hanson et al., 1999), as it is the fundamental step for subsequent ergonomic tasks (e.g., visibility, hand reach, easy operation, collision safety, etc).

A large body of work on driving posture has been reported, focusing on the measurement and prediction of driving postures and the determination of comfortable joint angle ranges (Andreoni et al., 2002; Grandjean, 1980; Porter and Gyi, 1998). Results of driving posture studies have been used to determine representative driving postures of digital human model software (e.g., Jack, RAMSIS, and Safework). However, previous driving posture studies have simply taken the measure of driver-selected postures, and treated them as optimal or most preferred in terms of comfort or discomfort, or without any reference to comfort or discomfort, and tended to overlook the potential problem of postural sensitivity. In the current study, we determined the sensitivity of driving posture to systematic changes in HJC among different gender, age and stature groups.

The objectives of this study were first to determine if and to what extent a self-selected postural rating was affected by alterations in HJC. In addition, two SAE recommended practices (i.e., J1517, J941), which mainly aim at accommodating 95% of a gender-mixed population, were reviewed against the results from this study, and any adjustments required were suggested. Finally, a method combining SAE practices and the adjustments was proposed that could be used to locate the seat track and the human body more accurately and to accommodate a wider range of people.

2. Methods

2.1. Participants

A total of 38 individuals, in two age groups (27 younger: 20~33 years old, 11 older: 60~91 years old), participated in this study. Of these, 18 were male and 20 were female. Participant statures (standing height, cm) ranged from American female (AF) 1st percentile to American male (AM) 99th percentile. Descriptive data are provided in Table 22.

Table 22. Summary of participant characteristics

Stature	Small (11)	Middle (14)	Tall (13)
Percentile	<30	30< <80	80<
Male (18)	162.5-171.5 (6)	172-182 (5)	182.5-192.5 (7)
Female (20)	147-158 (5)	158.5-167 (9)	167.5-184.5 (6)

Age (year)	Younger (27)	Older (11)
Male (18)	20-31 (12)	60-91 (6)
Female(20)	20-33 (15)	62-80 (5)

( ): number of people

2.2. Definitions

Several terms are defined in the Definition Section at the end of this paper. In order to locate HJC, Reed et al. and Seidel et al.'s recommendations (Reed et al., 1999; Seidel et al., 1995) were used.

2.3. Procedures

A simulated driving experience was conducted in a laboratory setting, in which actual vehicle seats were attached to an adjustable rig, and a driving scene was projected in front of the participant. Two driving package geometries were used as initial settings, those of a sedan (Car S) and an SUV (Car U). The rig allowed participants to select more extended positions for the seat and the steering wheel (i.e., in terms of angular rotation and horizontal and vertical translation).

Initial 'fitting' was conducted for 5 minutes, during which participants were asked to adopt their most comfortable posture. Adjustments were made in the following order: seat distance from accelerator, seat cushion and back angle, and steering wheel distance and angle from the participant. However, if any participant preferred a different order, the preferred order was used instead. Before simulated driving started, a lap belt was worn in order to prevent the driver from slipping forward on the seat as well as to minimize effects of the belt on driver's perceptions, especially in the shoulder and abdominal regions. Subsequently, 15 minutes of simulated driving was performed. This latter duration was recommended as sufficient to account for settling (sinking) into the seat (Manary et al., 1998). At any time during simulated driving, the participant could adjust their posture, the seat, and the steering wheel. In addition, at 8 minutes from the beginning, and at the end of the 15 minutes, participants were explicitly asked whether any adjustment was needed, and adjusted the seat and the steering wheel as necessary. At the end of each driving session (using Cars S and U), participants rated their sitting comfort / discomfort using a VAS (visual analogue scale) with a 0 to 100 range (Figure 43). In favor of the orthogonality between comfort and discomfort suggested by Zhang et al (1996), descriptors comprised of comfort and discomfort were used. However, in order to summarize levels of perceived comfort and discomfort into one number, inevitably descriptors were placed on a continuum. The perfect state (rating of 100) was described as when there is no discomfort but extremely strong comfort, in other words, when the driver felt maximized comfort and minimized discomfort (MCMD). The participant-selected HJC was recorded, and used in the subsequent sensitivity testing. The locations of additional landmarks and hard points (i.e., eye points, AHP, top point of right shoe, accelerator pedal center, and steering wheel center) were obtained. All locations were obtained using a 3D coordinate measuring machine (Faro Digital Template ™ 1.1).

Figure 43. Rating scale for sitting comfort / discomfort

In addition, two 15-minute on-road driving sessions were performed using two cars (S and U), on a fixed course in the local area, to compare HJC and eyes locations between lab and field sessions. Car presentation order was randomized to minimize learning and fatigue effects. Postural sensitivity, described below, was not conducted in the field due to mechanical limitations.

2.4. Posture sensitivity

After the preferred driving posture for each participant was determined and rated by the participant, an additional study was conducted in order to assess postural sensitivity. It was determined from this assessment if alternative positions provided a similar level of comfort and discomfort, which could thus be substituted with only a minimal difference in perception. For this purpose, overall postural ratings were provided by participants after being placed at 20 locations around their original hip point (Figure 44). The alternative locations had a 10mm pitch from each other, and the HJC was placed in each in a random order. Horizontal and vertical movements of the seat were realized by a modified floor jack attached under the seat base. This jack had wheels that traveled on a track. A normalization technique (Figure 45) was applied to the postural rating to aid in analyzing and summarizing the results.

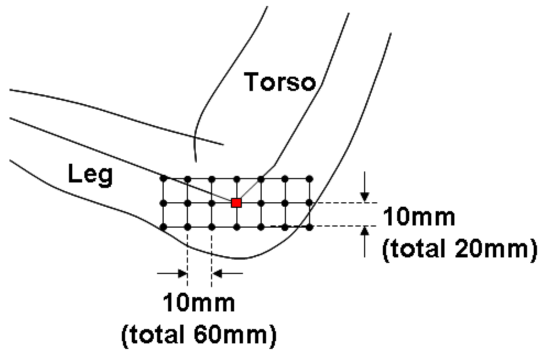


Figure 44. Posture sensitivity analysis

$$N=|(R_o-R_{max})/R_{max}|*100$$

$C=0$ if $N<2.5^*$; $C=1$ if $N<7.5$; $C=2$ if $N<12.5$; ….;
$C=5$ if $N<27.5$

where R_o: Original driving posture rating (0~100),
R_{max}: Max value among 21 ratings,
N: Normalized rating, C: Posture category.
(* '2.5' = 2.5% degraded posture compared to the best.)

Figure 45. Normalization of rating data

2.5. Analysis

Analysis of variance (ANOVA) was used to assess the effects of gender, age, and stature. A full-factorial model was not possible, however, due to limited numbers of participants in some cells. Hence, analysis was performed using three one-way ANOVAs for each car (S or U). P-values ≤0.05 were considered significant.

3. Results and discussion

3.1. Postural sensitivity

3.1.1. Case 1 - Sedan Car/Seat (S)

<u>Overall results</u>

Normalized postural ratings formed four regions over the 21 HJCs tested (Figure 46). The user-selected position (+) was rated the best among them. A 10 mm forward, backward or upward displacement resulted in a 5% degraded posture rating (from 1 to 2), whereas a 10 mm downward movement caused a 10% degradation. The lowest ratings (4th region) were clustered around the bottom and left area (marked "X"), which is close to the gas pedal.

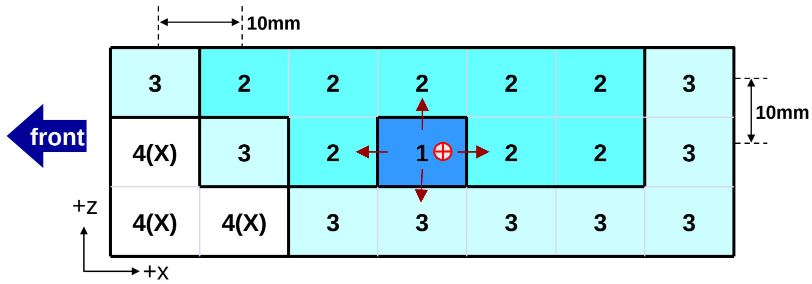


Figure 46. Overall posture sensitivity - Seat S

<u>Gender effect</u>

A gender effect was found on postural sensitivity (Figure 47). Qualitatively, females had a larger number of regions (4 vs. 3) and generally a larger number in each cell compared to the corresponding cell of males. Thus, females appeared to be more sensitive to postural changes, and this difference was also statistically significant ($p<0.001$). This gender difference is likely related to the relatively small statures of the female participants, leading to narrower ranges of motion (ROMs) for comfortable driving postures.

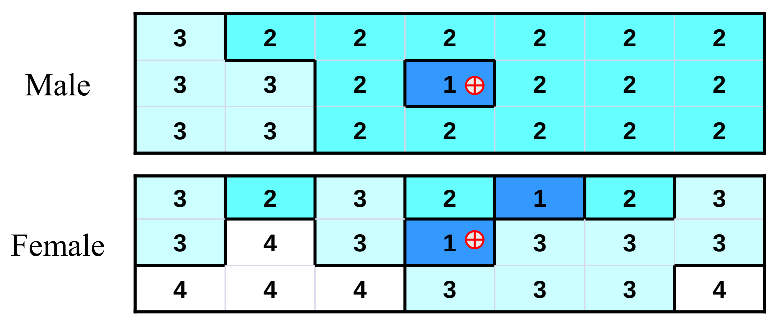


Figure 47. Gender effect on posture sensitivity - Seat S

<u>Stature effect</u>

A significant ($p<0.001$) difference among the three stature groups in posture sensitivity was found (Figure 48). The tall group had two optimal positions for their hip locations (user-selected position and a 20mm backward position). Therefore, it may be effective to consider a 20mm rearward margin when designing the seat track. For the mid-size group, it may be equally useful to provide a 20mm rearward margin or a 10mm upper and rearward margin from their-selected position. The small group showed the most sensitive responses to postural changes among the three groups, which again relates to their narrower ROMs for comfortable driving posture due to smaller stature and body segment lengths. Therefore, when designing the seat track, selected positions among smaller individuals must be included.

Tall	4	2	2	2	2	2	2
	3	2	2	1 ⊕	2	1	2
	4	3	2	2	2	2	2
Mid-Size	4	2	3	2	1	2	2
	3	3	3	1 ⊕	2	1	2
	5	4	3	3	3	2	2
Short	4	3	3	2	2	2	5
	4	5	3	1 ⊕	4	4	4
	3	5	5	4	4	4	6

Figure 48. Stature effect on posture sensitivity - Seat S

Age effect

As shown in Figure 49, there was an age effect on the postural rating ($p<0.001$), despite the two age groups having no difference in mean stature ($p>0.55$, older group: mean = 168.2 cm, SD = 11.7 cm, range = 147 ~ 187.5 cm, younger group: mean = 170.7 cm, SD = 11.66 cm, range = 152 ~ 192.5 cm). Older participants appeared more sensitive to postural changes (larger numbers in most cells).

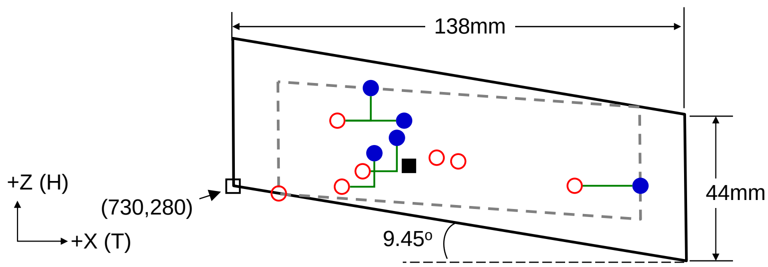
Younger	3	2	2	2	2	2	2
	3	3	2	1 ⊕	2	2	2
	4	3	3	3	3	3	2
Older	5	3	3	2	1	3	3
	3	4	3	1 ⊕	2	2	3
	4	5	4	3	4	3	4

Figure 49. Age Effect on posture sensitivity - Seat S

In summary, the user-selected HJC was always in the 1st region. However, no region with normalization value of 0 (< 2.5% degraded from the best rating) was found in either of 4 cases (i.e., overall, gender, stature, or age), which means that the best rating was not always made at the user-selected HJC or at any specific point.

Application of results to seat track design (Sedan)

The above results were applied to find a minimum seat track boundary for sedans that should be covered (Figure 50). This boundary was determined by including all group means and alternative locations suggested by the sensitivity analysis, as well as considering the difference in seated hip thickness between stature groups and gender groups (Diffrient et al., 1990). The resulting boundary has a steeper angle than found in average sedans in the current market (9.45^o vs. 5^o).



■: Overall mean
O: Mean of each group (age, gender, stature)
●: Alternatives from ratings
Origin (0,0) = (acc pedal center ‘T’, carpet floor ‘H’), initial H30 =285mm
Seat track angle: 4.1°(regression line) -> 9.45°(differences in hip sizes)
Solid line: Core boundary to be covered

Figure 50. Minimum seat track boundary for sedans

3.1.2. Case 2 - SUV Car/Seat (U)

Overall results

Overall, as was the case for S, four regions were apparent, though the pattern was slightly different (Figure 51). The user-selected position (+) was again rated the best among the 21 locations. A 10 mm backward or upward displacement resulted in a 5% degraded posture rating (from 1 to 2), whereas a 10 mm forward or downward movement produced a 10% degradation. The lowest ratings (4^{th} region) were again found around the bottom and left area, which is close to the gas pedal.

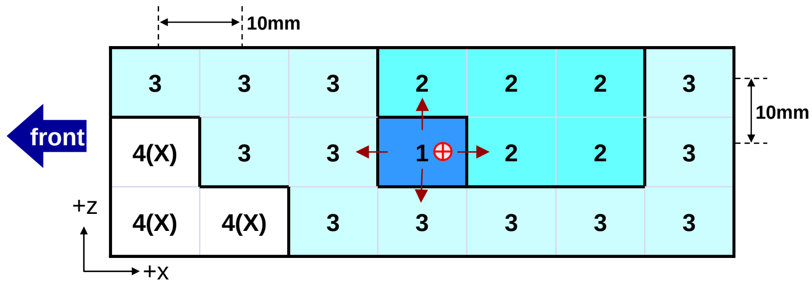


Figure 51. Overall posture sensitivity - Seat U

Gender effect

Gender differences were found in posture sensitivity (Figure 52). Generally, females appeared to be more sensitive, in that they had larger numbers in each cell and a large number of regions (5 vs. 3). Gender effect was also statistically significant ($p<0.001$). The relatively small statures of the female participants likely account for these differences.

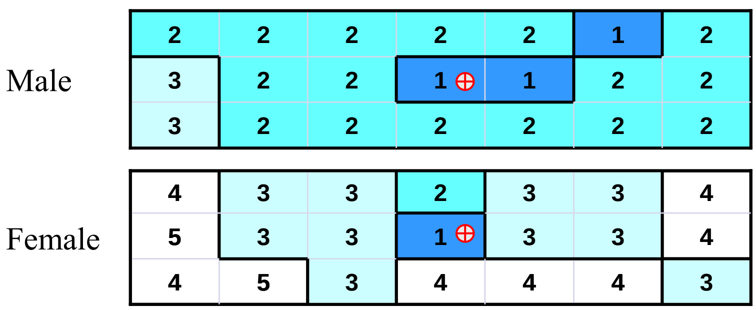


Figure 52. Gender effect on posture sensitivity - Seat U

Stature effect

A difference among the three stature groups ($p<0.001$) in posture sensitivity was found (Figure 53). The tall group had four optimal positions for their hip locations (user-selected position, a 10 or 20mm backward position, and a 20 mm backward and 10 mm upward position). Therefore, it may be effective to consider one of these margins when designing the seat track. For the mid-size group, it may be equally useful to provide a 20 or 30 mm rearward margin from a user-selected position. The small group showed the most sensitive responses in postural changes among the three groups, which again relates to their narrower ROMs for comfortable driving posture due to smaller body segment lengths. For this group, their selected positions and a 10 mm upward position should be included.

Tall	2	2	2	2	2	1	2
	3	2	2	1 ⊕	1	1	2
	3	2	2	2	2	2	2
Mid-Size	3	3	2	2	2	2	2
	4	2	3	0 ⊕	2	1	1
	4	3	2	2	3	2	2
Small	4	3	4	1	3	4	5
	5	3	3	1 ⊕	3	4	6
	4	5	4	5	4	4	5

Figure 53. Stature effect on posture sensitivity - Seat U

Age Effect

As shown in Figure 54, there was an age effect on the postural rating (p=0.006), though the two age groups had no differences in mean stature (p>0.55). Older participants had more sensitive responses to the postural changes (larger numbers in most cells).

Younger	3	2	2	2	2	2	3
	3	2	2	1 ⊕	2	2	3
	3	3	3	2	3	3	3
Older	5	4	3	3	3	2	3
	5	4	4	1 ⊕	3	2	2
	5	4	3	4	3	3	3

Figure 54. Age effect on posture sensitivity - Seat U

In summary, the user-selected HJC always belonged to the best rated region in all four cases (i.e., overall, gender, stature, or age). A region with value of 0 (less than 2.5% degraded from the best rating) was only found in the mid-size group.

Application of results to seat track design (SUV)

As for the sedan, the results were used to determine a minimal track boundary for SUVs (Figure 55). The resulting track slant angle was 5.6°, which is steeper than found in average SUVs in the current market (3°).

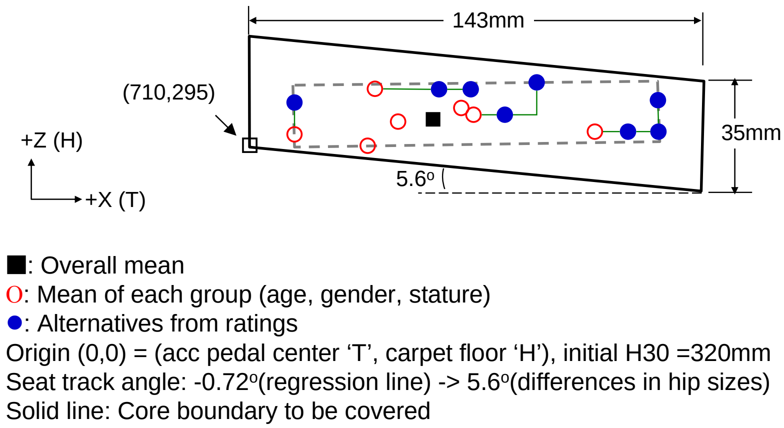


Figure 55. Minimum seat track boundary for SUVs

3.2. Ranges of hard points

Locations of five hard points (i.e., eye points, hip point, steering wheel center, AHP, and BOF), taken from participants' driving postures and adjusted parts, were analyzed with respect to participants' stature and age, session type, and vehicle segment.

Ranges of hard points - Car/Seat S

Wider ranges of the hard point locations were found in the lab session, where using a second seat track and a telescopic steering wheel allowed the participants to change the driving package into a more extended and comfortable. The ranges of each hard point are depicted in Figure 56. Results from the lab session formed a maximal adjustment range covering from AF 1st to AM 99th percentiles.

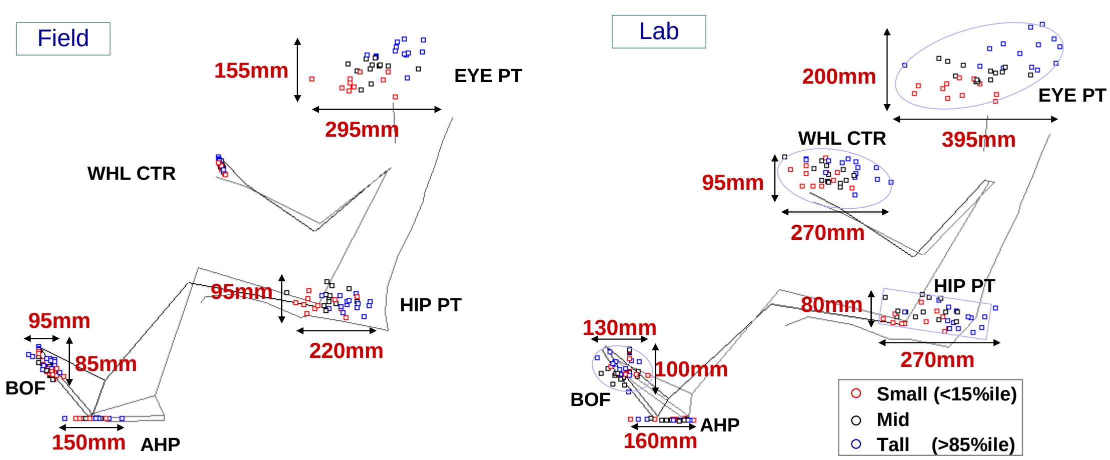


Figure 56. Ranges of hard points - Car S by Stature

Comparison between the age groups (Figure 57) showed that, in spite of having a similar stature range, the older group had narrower ranges of hard points than the younger group. In addition, hard points among the older group were closer to the steering wheel, and these formed the lower limits of the ranges.

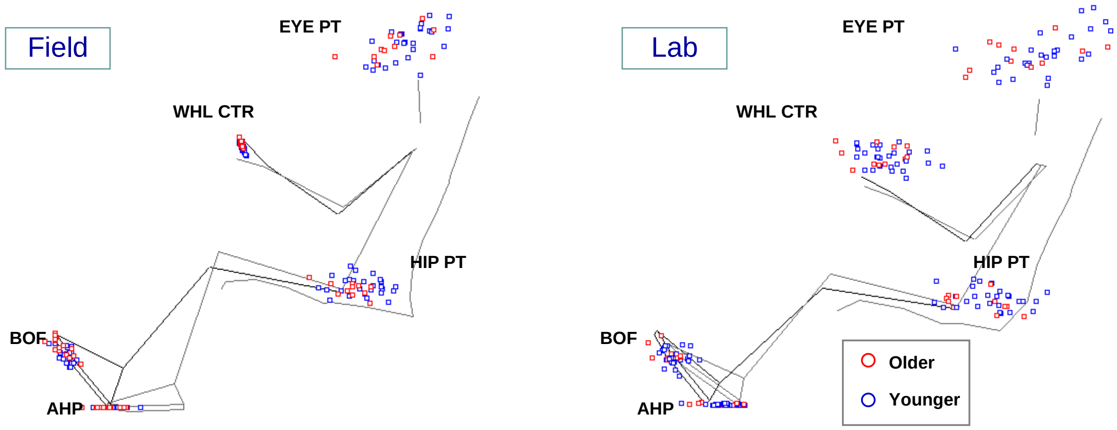


Figure 57. Ranges of hard points - Car S by Age

From these results, it is concluded that the older group preferred more flexed angles in the neck, torso, and/or knee than the younger group.

Ranges of hard points - Car/Seat U

Similar to the S case, wider ranges of the hard points were found in the lab session. The range of each hard point is depicted in Figure 58. As before, results from the lab session formed a maximal adjustment range covering from AF 1st to AM 99th percentiles.

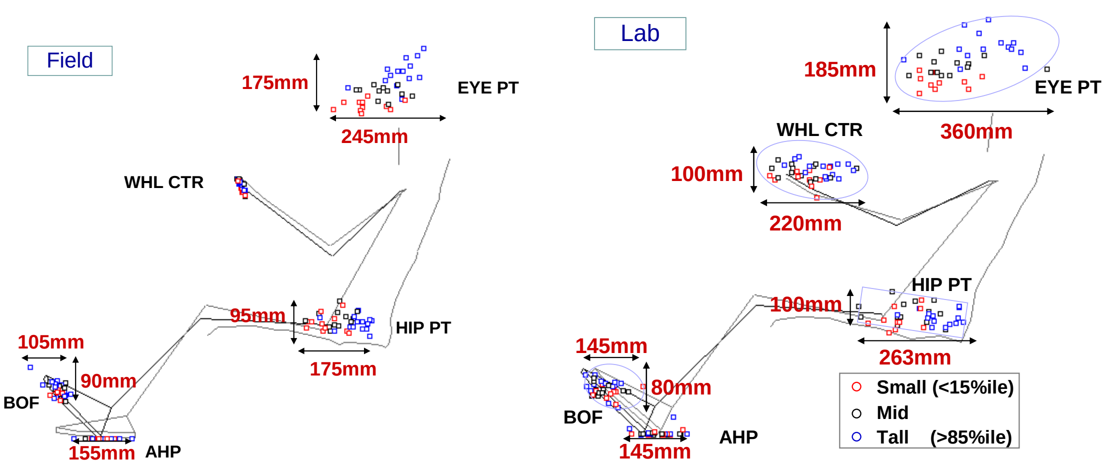


Figure 58. Ranges of hard points - Car U by Stature

The same trend was found when comparing the two age groups; the older group had narrower ranges of hard points than the younger group, which were closer to the steering wheel and formed the lower limits of the ranges (Figure 59).

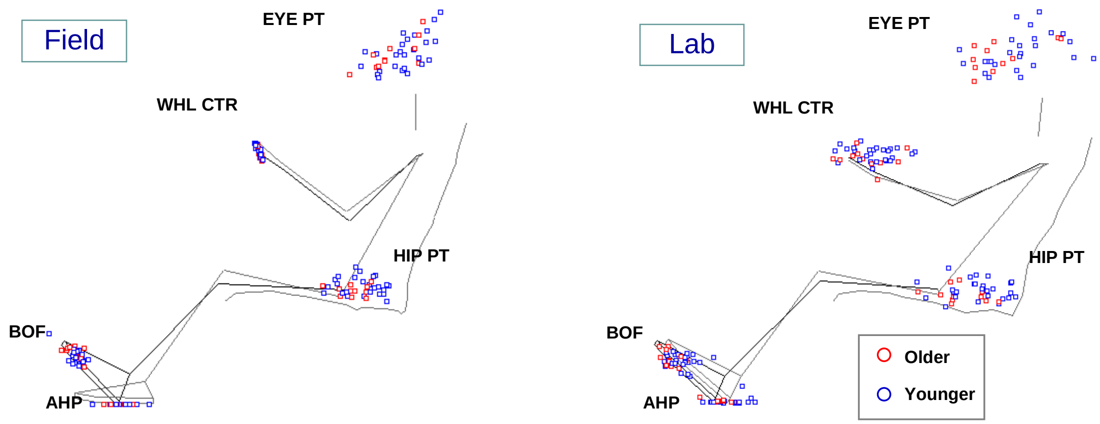


Figure 59. Range of hard points - Car U by Age

3.3. Reviews of SAE recommended practices

Two SAE practices, SAE J1517 (1998b) and SAE J941 (2002), were reviewed which describe a driver's seat position and eye position, respectively.

<u>SAE J1517 - driver selected seat position</u>

SAE J1517 provides 7 equations (Figure 60, graphically in Figure 61) for driver selected seat positions over a range of 2.5th - 97.5th percentiles (of stature, 159cm - 179cm) with regard to drivers' seated heights (z in the equations). These would seem to account for a sufficient range (95% of population). However, due to the use of a mixed population (male to female ratio = 1:1) to formulate the equations (SAE, 1998b), it actually covers a relatively narrower range than desired. In fact, both AM 95th % (188cm) and AF 5th % (151cm), which are thought to be more appropriate extreme population groups to consider (Hanson et al., 1999), have been excluded from SAE J1517 (8~9cm difference in stature). Consequently, it is more likely that a seat track will not accommodate these extreme groups well if it is designed solely using SAE J1517.

$$
\begin{aligned}
{}^{x}97.5 &= 936.6 + 0.613879z - 0.00186247z^2 \\
{}^{x}95 &= 913.7 + 0.672316z - 0.00195530z^2 \\
{}^{x}90 &= 885.0 + 0.735374z - 0.00201650z^2 \\
{}^{x}50 &= 793.7 + 0.903387z - 0.00225518z^2 \\
{}^{x}10 &= 715.9 + 0.968793z - 0.00228674z^2 \\
{}^{x}5 &= 692.6 + 0.981427z - 0.00226230z^2 \\
{}^{x}2.5 &= 687.1 + 0.895336z - 0.00210494z^2
\end{aligned}
$$

Figure 60. SAE J1517- driver selected seat positions (SAE, 1998b)

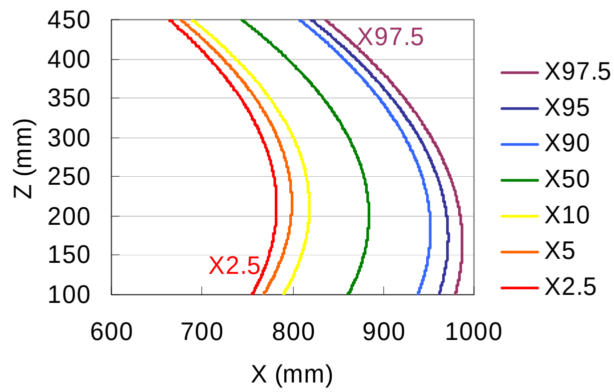


Figure 61. SAE J1517- driver selected seat positions (SAE, 1998b)

<u>SAE J941 - drivers' eye locations</u>

As indicated in the SAE J941 (2002) document, the 95th % eyellipse (tangent cutoff) in 2D, which is frequently used to check in/exterior visibility when designing a car, contains only 74.15% of the American population’s eye locations (Table 23 and Figure 62). Again, due to the use of a mixed population, it has the same limitation of excluding two extremes of the population (i.e., AF 5% and AM 95%). Indeed, the eyellipse inclusive of 95% of eye locations is described in SAE J941. Its size is almost 1.5 times larger than that of the 95% tangent cutoff eyellipse. The 99.66% inclusive eyellipse is similar in size to the boundary of eye locations formed in the current study for the sedan (Figure 56).

Table 23. 2D inclusive eyellipse vs. tangent cutoff eyellipse - adjustable seat (SAE, 2002)

2D Inclusive (side view)	Tangent Cutoff	X Axis Length	Z Axis Length
74.15%	***95.00%***	***206.4***	***93.4***
90.00%	98.41%	266.0	121.8
93.32%	99.00%	287.1	132.1
95.00%	***99.28%***	***301.2***	***139.0***
95.61%	99.38%	307.3	142.0
99.66%	***99.96%***	***406.5***	***191.2***

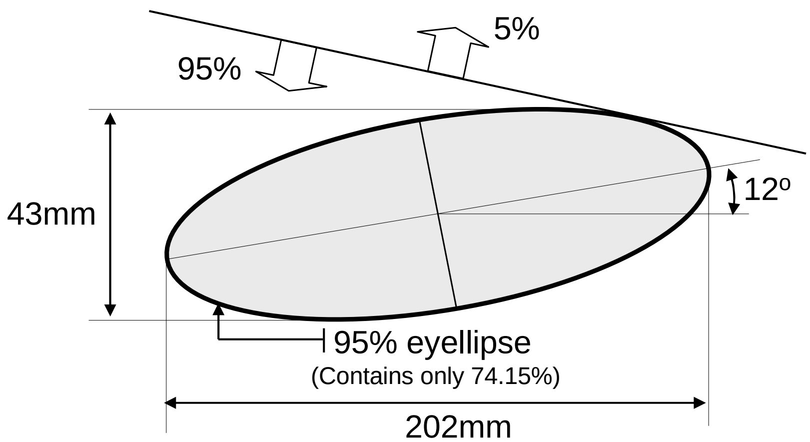


Figure 62. SAE J941's 95% tangent cutoff eyellipse (SAE, 2002)

Ankle joint angle (SAE practices vs. MCMD method)

In the current study with the aim of maximized comfort and minimized discomfort (MCMD) in driving posture, two planes (foot plane and shoe plane) were used for calculating ankle angle (Table 24 and Figure 63). For this, each participant's shoe was measured before the first experiment and the participants were asked to wear the same shoes throughout the sessions. The SAE method does not allow for an angular difference of the ankle according to either seat height difference between vehicle segments or shoe difference between people (SAE, 1998b).

Table 24. Comparison of ankle angle calculation methods

Methods	SAE	MCMD	
	Sedan/SUV	Sedan	SUV
Angle between Foot and Shoe Plane	Fixed (6.5°)	Variable (Mean 3.4°)	
Ankle Angle (from Shoe Plane)	Fixed (80.5°)	Variable (90.8°)	Variable (94°)
Ankle Angle (from Foot Plane)	Fixed (87°)	Variable (94.2°)	Variable (99.5°)

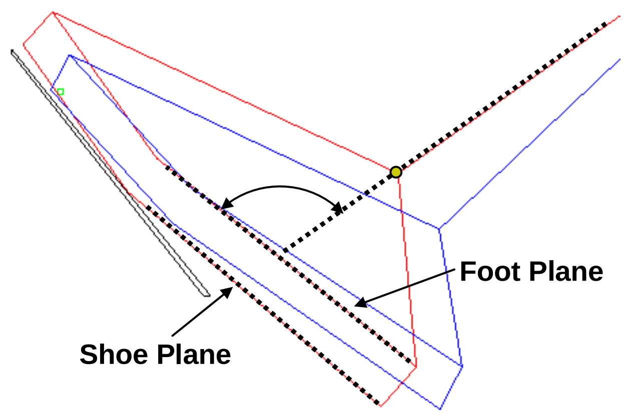


Figure 63. Two planes used for calculation of ankle angle

3.4. Revised MCMD method combining SAE practices and MCMD results

SAE practices have been used as procedures for some regulation compliance tests (e.g., transparent area test, visibility test, etc) as well as instruments for inter-vehicle comparison for the purpose of benchmarking, and will be used as such, though some revisions on them may be continuously made. Therefore, the initial package solution should be determined by SAE methods for the above reasons, but in due consideration of their limitations, it should be modified to allow for more appropriate population sizes. As described above, SAE J1517 and J941 seem to provide limited boundaries for drivers' hip and eye locations, whereas the current MCMD method provides larger boundaries, covering 100% of each gender group among the 38 participants. To clarify this difference, more detailed comparisons between MCMD and SAE practices are made below.

<u>MCMD vs. SAE J1517</u>

In the case of SAE J1517, Ball of Foot (BOF) positions are measured without the accelerator pedal pressed, whereas in the case of MCMD, BOF positions were determined solely by the participants' preference (i.e., they were allowed to press the accelerator pedal as much as they wanted.). As a result, the BOF data in the current study were distributed widely around the accelerator pedal center (95~145mm wide and 80~100mm high) as shown in Figures 56 - 59. Due to divergent approaches, some modifications to the MCMD results were needed in order to compare directly the two methods. First, all MCMD data (for both S and U) were merged into one file in such a way that they had the same floor height and the same X coordinate for the accelerator pedal center. In this way, they would be most similar to conditions of SAE J1517, though not exactly the same (MCMD uses horizontal distances between the accelerator pedal center and each participant's HJC, whereas SAE J1517 uses horizontal distances between each participant's BOF and HJC.). After this modification, two boundaries were compared, (Figure 64). Indeed, it was found that the population accommodation problem when applying SAE J1517 arose severely at the lower extremes of the population, but not at the upper extremes. Therefore, a more forward placement of the seat track than determined by SAE J1517 (X2.5) should be possible to accommodate smaller and older people.

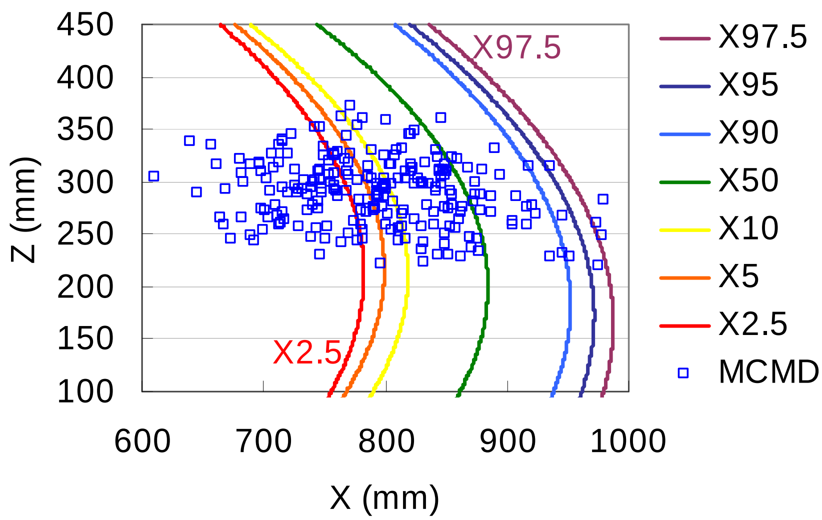


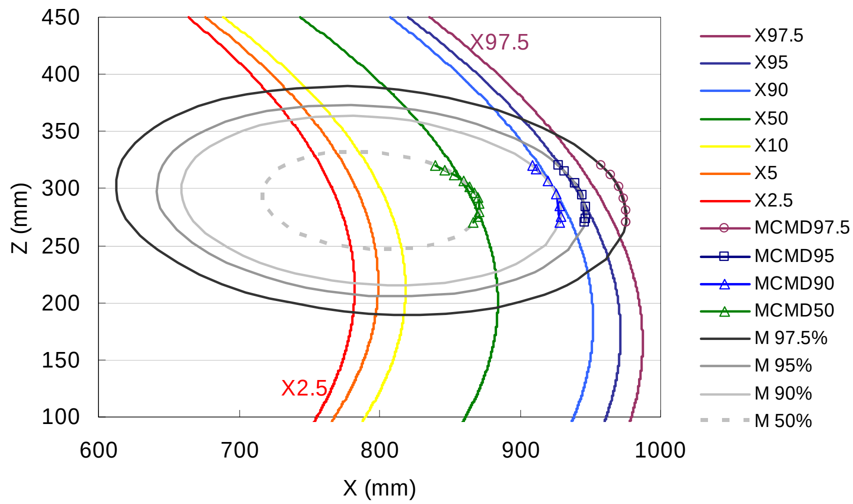
Figure 64. Hip location comparison

By incorporating both the SAE J1517 and MCMD results, the core regions as well as the final recommendations for the seat track design were determined, and summarized in Table 25. It is, however, of benefit to allow for an additional forward margin and vertical margin to accommodate more people, especially older and smaller people as shown in Figures 56-59.

Table 25. Seat track recommendations

		MCMD – Core Region (from Sensitivity Analysis)		MCMD - Final (horizontal span of data)	
Segment		Sedan	SUV	Sedan	SUV
Initial H30		285 mm	320 mm	285 mm	320 mm
Tilt Angle		9.45^o	5.6^o	9.45^o	5.6^o
Axis Length	X	138 mm	143 mm	265 mm	270 mm
	Z	44 mm	35 mm	60 mm	50 mm
Left Bottom		(730T,280H)	(710T,295H)	(700T, 275H)	(690T, 290H)

Figure 65 shows the MCMD HJC accommodation curves for 97.5th, 95th, 90th, and 50th percentiles. Inclusive ellipses were used to draw each curve, one of the concepts used for the construction of the SAE eyellipses. One of the contributing factors for the difference between the SAE and MCMD accommodation curves seems to be the scope of vehicular segments. The SAE accommodation curves were determined using sedans, SUVs, coupes, and MPVs, whereas the MCMD accommodation curves involved only sedans and SUVs. Therefore, it should be noted that the MCMD results are only applicable to those two segments and a limited z range (e.g., 270mm ~ 320mm). In the case of 95th, 90th, and 50th percentiles, both methods show very similar results, but the MCMD 97.5th percentile accommodation curve is located behind the SAE 97.5th percentile curve.



(M 97.5%, 95%, 90% means 97.5, 95, and 90% inclusive HJC curves, respectively)

Figure 65. MCMD accommodation curves

MCMD vs. SAE J941

When comparing the SAE 99.96% inclusive eyellipse (not tangent cutoff) with MCMD initial boundary for eye locations, a similarity in their sizes was found except that the MCMD forward slanted angle is steeper (sedan: 14.7°, SUV: 12.5°) than that of SAE J941 (12° for both cases). Therefore, an eyellipse used for any in/exterior visibility check can be selected from the table that SAE J1517 provides (Table 23), but caution should be exercised when deciding its size and slanted angle. It is recommended that at least the 95% inclusive eyellipse (not 95% tangent cutoff eyellipse) be used to accommodate 95% of people, and its forward slanted angle should be different by vehicle segment (14.7° in case of sedans and 12.5° in case of SUVs). Differences in the boundary of eye locations between MCMD and SAE J941 and the final recommendations are summarized in Figure 66 and Table 26.

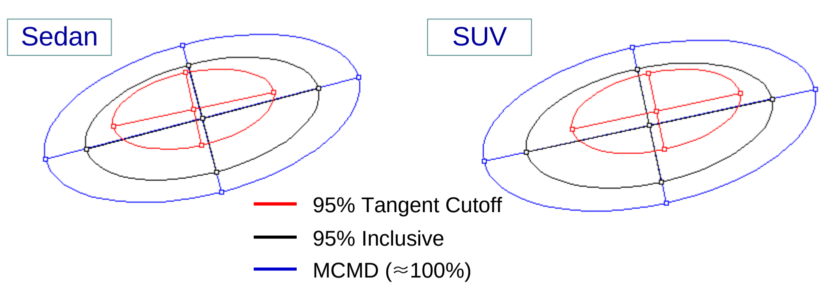


Figure 66. Eyellipse comparisons

Table 26. Eyellipse comparisons and recommendations

		95% Tangent Cutoff	MCMD - Initial		MCMD - Final	
		Current Method [A]	100% Inclusive		95% Inclusive	
Segment		All	Sedan	SUV	Sedan	SUV
Tilt Angle		12^o	14.7^o	12.5^o	14.7^o	12.5^o
Axis Length	X	206.4 mm	395 mm	360 mm	301.2 mm	301.2 mm
	Z	93.4 mm	200 mm	185 mm	139 mm	139 mm
Offset from A	X	0 mm	11 mm	-8 mm	11 mm	-8 mm
	Z	0 mm	-12 mm	-17 mm	-12 mm	-17 mm

MCMD ankle angle

SAE J1517 sets the right ankle angle of the SAE manikin to 87^o when measuring interior dimensions such as driver's leg room, for which any justifiable reasons are not given in the relevant documents (i.e., how it was determined or whether it was within the range of comfortable ankle angle, etc). SAE has also relaxed this restriction recently. For example, SAE J1516 (1998a) (Accommodation Tool Reference Point) allows the manikin ankle angle to exceed 87^o. With no recommended angle for the ankle joint available, standard angles which take into account right ankle comfort are needed. To provide this, the data collected in this study have been analyzed, and the recommended angles were determined (Table 27).

Table 27. Ankle angle for sedan and SUV

Segment	Ankle Angle	Group
Sedan	83^o (81-85^o)	Flexed/Upright
	112.5^o (110-115^o)	Relaxed
SUV	89^o (82-96^o)	Flexed/Upright
	127^o (117-136^o)	Relaxed

4. Conclusions

The present study investigated the sensitivity of driving postures in several groups of participants in two different vehicle segments (sedan and SUV). As a result, it was found out that there was a difference in postural sensitivity between gender, age, and stature groups, respectively. In addition, by using the results of the sensitivity analysis, a core boundary for seat track adjustment for two segments was determined. SAE guidelines (i.e., SAE J1517, J941) were also reviewed, and it was determined that SAE J1517 does not adequately consider extremes of a population (5^{th} % female, 95^{th} % male), and should be used with caution. In the case of J941, it was recommended that inclusive eyellipses instead of tangent cutoffs should be used for a better accommodation of driver population.

Chapter 7: Specifying comfortable driving postures for ergonomic design and evaluation of the driver workspace

Abstract

Specifying comfortable driving postures is essential for ergonomic design and evaluation of a driver workspace. The present study sought to enhance and expand upon several existing recommendations for such postures. Participants (n=38) were involved in six driving sessions that differed by vehicle class (sedan and SUV), driving venue (lab-based and field), or seat (from vehicles ranked high and low by vehicle comfort). Sixteen joint angles were measured in preferred postures to more completely describe driving postures, as were corresponding perceptual responses. Driving postures were found to be bilaterally asymmetric, and distinct between vehicle classes, venues, age groups, and gender. A subset of preferred postural ranges was identified using a filtering mechanism that ensured desired levels of perceptual responses.

Relevance

Accurate ranges of joint angles for comfortable driving postures, and careful consideration of vehicle and driver factors, will facilitate ergonomic design and evaluation of a driver workspace, particularly when embedded in digital human models (DHMs).

Keywords: digital human model; driver workspace; comfortable driving posture; preferred driving posture; filtering

1. Introduction

With expanding use of digital human models (DHMs) for proactive as well as retrospective ergonomic analysis of automotive interior design, there is a concomitant need for accurately predicting and specifying driving postures (Chaffin, 2007; Hanson et al., 1999; Reed et al., 2002). The driving posture selected for a DHM influences driver workspace design in terms of drivers' postural comfort, alertness (Diffrient et al., 1990), reach and visibility (Chaffin, 2007). Several studies have provided recommended 'comfortable' or 'preferred' joint angles ranges for driving postures (Bubb, 1992; DIN, 1981; Dupuis, 1983; HdE, 1989; Park et al., 2000; Porter and Gyi, 1998; Rebiffé, 1969; Vogt et al., 2005). Perceptual responses (e.g., comfort or discomfort) associated with these recommendations, however, have not been specified or published, perhaps because perceptions were not elicited when measuring joint angles, or due to the proprietary nature of the data. These studies sought to ensure that ‘preferred’ driving postures were adopted, by allowing participants to freely adjust their postures and/or several parts of a driving rig, sometimes with extended adjustment ranges (i.e., beyond those available in production vehicles). Yet, it is unclear whether participants actually felt comfortable in their ‘preferred’ driving postures, the latter being those from which the recommended joint angles ranges were obtained.

Many of the existing studies on driving posture implicitly assume that the car seats and/or package geometries (spatial relationships among interior parts) used in experiments would be sufficiently comfortable for drivers. As a result, all postural data were incorporated when determining recommended joint ranges. Chapter 2, however, showed that some participants experience more than minimal discomfort (i.e., up to -5 on a scale from -10 to 0, corresponding to a perceptual response of ‘strong discomfort’). This occurred even though they were allowed to freely adjust the automotive interior geometry beyond the ranges allowed in actual cars. Hence, joint angles adopted by drivers may not be necessarily associated with comfortable postures, and the potential for further improvement of interior packaging would thus seem to exist. To ensure the quality of recommended driving postures used for vehicle interior design and analysis, it may be of value to include only those joint angles that are coupled with desired levels of comfort and discomfort.

Comfort and discomfort are generally acknowledged to be complementary but independent entities, yet it is rare for studies of the sitting experience to consider perceptions of comfort and discomfort in a separate but simultaneous fashion (de Looze et al., 2003). Exceptions are the studies of the sitting experience in office chairs by Zhang et al. (1997) and in car seats in Chapter 2. The latter separately measured these two responses and suggested a method for using them to evaluate car seats. In order to compare alternative driving postures during the evaluation of driver workspace design, and to ensure the reliability and quality of the final driving posture of a DHM, it would seem necessary to provide recommended joint angles, with which expected levels of perceptions are explicitly specified.

Whole body driving postures can be effectively described and specified by a set of joint angles, which are defined by pertinent bodily landmarks, their geometric relationships, and the locations of adjacent joint centers (Reed et al., 1999). A complete set of joint angles describing comfortable driving postures, however, is rarely available. Hanson et al. (2006) indicated that this is partly due to the assumption that driving postures are bilaterally symmetric. As a result, measures are obtained from only one side of the body. In addition, several major joints are not included in existing recommendations (e.g., neck, wrist, shoulder, torso, and/or ankle), which hinders specifying an entire driving posture with a DHM.

There is also a compatibility issue that should be considered when measuring joint angles. Specifically when measuring ankle angles, shoe dimensions (e.g., heel height and shoe length) need to be measured or controlled in order to compare results with those specified by SAE J1517 (1998b) or other existing recommendations. As a *de facto* standard, SAE J1517 is widely referred to when designing driver workspace and determining driver accommodation level (e.g., leg room, head room). Another standard, the SAE J826 (1995) H-point manikin, is a physical model representing drivers. It has a specific ankle angle for use in a vehicle, which can be either 87 deg (when measured between the lower leg and foot bottom plane) or 80.5 deg (between the lower leg and shoe bottom plane). This manikin's feet and shoes are of fixed size, though its legs are adjustable to simulate several percentiles. Compatibility with these standards is also needed in order to compare new data with that which has accumulated over several decades (e.g., the AutographTM database, , 2003).

Recommended ranges of joint angles have been specified extensively for sedan-type vehicles, in settings that are representative of standard or extended sedan interior geometries. In contrast, recommended joint angles for other vehicle classes (e.g., SUVs, trucks, vans, sports cars) are quite scarce. To the authors' knowledge, the only published comparison between vehicle classes is by Diffrient et al. (1990), who specified seat back rest angle (similar to torso angle defined later in this study) for several vehicle classes, but other joint angles were not included. As each vehicle class has a distinct package geometry and dissimilar adjustment ranges (Autograph, 2003; Diffrient et al., 1990; Reed et al., 2000), different ranges of joint angles are very likely to be observed between vehicle classes.

Comfortable driving postures may be influenced by individual differences such as age, gender, and stature. Older individuals in particular might have different needs for interior vehicle geometry due to postural (Milne and Lauder, 1974) and/or physiological changes (Warnes et al., 1993) that occur with age. Younger drivers will likely adopt a different (i.e., more relaxed or reclined) posture than provided by current vehicles (Chapter 6). Similarly, there may be gender differences in preferred driving postures, as was found for both shoulder and elbow joint angles among Korean drivers (Park et al., 2000). Since current car seats appear optimized for individuals with average stature, and this group as a whole reports higher comfort and lower discomfort levels (Chapter 2), stature effects on driving postures are also very likely. Thus, further investigation is warranted to determine whether sitting postures differ by driver attributes such as age, gender, and stature.

The primary goal of this study was to provide recommended driving postures with specific intended application to DHMs. To achieve this, the following were emphasized: 1) provide comfortable ranges (angles) of all major joints, compatible with the pertinent standards, 2) determine whether there are effects of vehicle factors (class, venue, seat) and driver factors (age, gender, stature) on joint angles, 3) determine whether driving postures are symmetric, and 4) for two respective vehicle classes (sedan and SUV), generate recommended ranges of joint angles that account for reported levels of postural comfort and discomfort.

2. Experimental methods

2.1. Overview of experiment

The experiment from which the current data were obtained has been described earlier (Chapter 2). An overview of the general procedures is provided here, and the reader is referred to the noted chapter for details (with the exception of postural measures, which are fully described below). Each participant was involved in six driving sessions (Table 28) that were a subset of the factorial combination of two vehicle classes (sedan [S] and SUV [U]), two seats (from vehicles ranked high [1] and low [2] on overall comfort) from each vehicle class, and two driving venues (lab-based [-L] and field [-F]). J. D. Power and Associate's Comfort Scores (2005) were used to select these seats and vehicles. S2 and U2, seats from lower-rated cars, were used only in the lab setting (i.e., no S2-F or U2-F).

Table 28. Six driving sessions and codes

	Vehicle class			
	Sedan [S]		SUV [U]	
Seat (1, 2)*	S1	S2	U1	U2
Driving Venue (Lab: L, Field: F)	Lab and Field (S1-L & S1-F)	Lab Only (S2-L)	Lab and Field (U1-L & U1-F)	Lab Only (U2-L)

* From vehicles rated high (1) or low (2) in comfort by J.D. Power and Associates (2005)

An adjustable driving rig was used in the lab-based sessions that involved simulated driving, and two cars were used for the field sessions that involved on-the-road driving. In both cases, driving was conducted for 20 minutes. Before and during driving, participants adjusted the seat and steering wheel to best support their preferred driving postures. A modified method of fitting trials (Jones, 1969; Chapter 2) was used for this procedure. After driving, and while maintaining their preferred postures, participants rated their postures in terms of comfort, discomfort, and a combination of these two. Lastly, coordinates of bodily landmarks were obtained and used to determine joint angles.

2.2. Participants

Thirty-eight participants completed the study. Criteria for inclusion were: possession of a valid driving license for a minimum of two years, normal or corrected-to-normal eye vision in both eyes, and no self-reported current musculoskeletal disorders. Both genders participated, and spanned a range of ages and statures (Table 29). Each participant completed an informed consent procedure, approved by the local Institutional Review Board, prior to the first experiment session.

Table 29. Participant descriptions and anthropometry

Stature group	Age group	# of participants (male, female)	Mean (SD) stature (cm)	Mean (SD) BMI⁺ (kg/m²)
Short (<165 cm)	Y*	9 (0, 9)	158.4 (4.4)	22.9 (2.9)
	O**	5 (1, 4)	158.4 (6.7)	23.2 (5.8)
Middle	Y	9 (4, 5)	169.9 (3.9)	25.3 (3.6)
	O	3 (2, 1)	170.2 (2.0)	27.4 (2.6)
Tall (>175 cm)	Y	9 (8, 1)	183.9 (6.4)	22.6 (2.5)
	O	3 (3, 0)	182.5 (6.2)	27.4 (5.9)
Total	Y	27 (12, 15)	170.7 (11.7)	23.6 (3.2)
	O	11 (6, 5)	168.2 (11.7)	25.5 (5.2)
Grand Total	-	38 (18, 20)	170.0 (11.6)	24.1 (3.9)

*: Younger (≥ 20 and ≤ 35), **: Older (≥ 60), ⁺: Body Mass Index

2.3. Subjective ratings

Perceived comfort and discomfort were measured at both local and overall levels, with only local ratings used in the current analysis. Comfort and discomfort scales (see Chapter 2) were derived from earlier versions presented by Borg (1990) and Corlett-Bishop (1976). Briefly, the comfort scale ranged from 0 (no comfort) to 10 (extreme comfort), and the discomfort scale from -10 (extreme discomfort) to 0 (no discomfort). For some joints perceptual responses were solicited for the localized region whereas other joints were obtained by averaging the ratings of adjacent body parts.

2.4. Joint angles

A set of joint angles describing a driving posture were calculated by defining and measuring corresponding surface landmarks and joint centers. Hardware and Software from Faro (Digital Template 1.1; Lake Mary, FL) were used to record landmark coordinates. Additional software (Rhinoceros 3.0; McNeel, Seattle, WA) was used to generate 3-D stick figures, with joint centers and segments determined by these landmarks, and to obtain 2-D joint angles in the sagittal plane. Surface markers and joint centers were located following methods given by Reed et al. (1999). Some joint centers (i.e., elbow, knee, and ankles) were assumed to be co-located with a landmark, whereas the others (i.e., neck, shoulder, wrist, and hip) were obtained from two or more landmarks and spatial relationships among them. For example, the hip joint center was defined using relative distances between the anterior superior iliac spines (ASISs) and pubic symphysis (PS), as suggested by Seidel et al. (1995) and Reed et al. (1999). Specific spatial relationships used to define other joint centers (i.e., the neck, shoulder, and wrist centers) are available in Reed et al. (1999).

In order to more completely represent driving postures (Figure 67; Table 30), the current study added one landmark (head of the third metacarpal) and two planes (foot and shoe planes). These were used to define six additional joint angles (the former for wrist angles, and the latter for two ankle angles). As a result, 16 angles were used to define driving postures. Most joint angles (i.e., shoulder, elbow, wrist, hip, and knee) were obtained bilaterally and as included angles between neighboring body segments. Neck and torso angles, in contrast, were defined relative to the vertical. Ankle angles were obtained two ways (using the foot and shoe planes) to allow for comparison with values in the SAE J826 and J1516 standards (Chapter 6; SAE, 1995, 1998a). To construct a 2-D shoe, bottom lengths and heights of each participant's right shoe were measured before the driving sessions. At the end of each driving session, several reference points were obtained from both shoes to determine ankle joint angles while the participants maintained their driving posture.

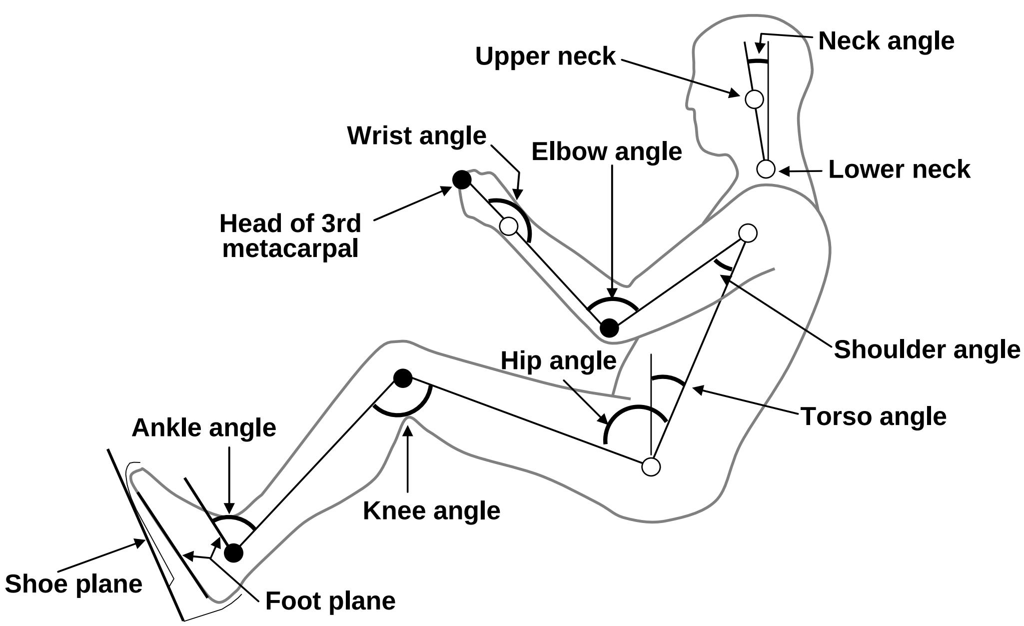


Figure 67. Joint angle definitions. All angles shown above are positive. Solid circles indicate joint centers defined by a surface landmark, while hollow circles are joint centers determined by spatial relationships between landmarks (as defined in Reed et al. 1999).

Table 30. Joint angles, joint centers and landmarks (see Figure 67 for graphical definitions)

Joint angle	Joint center	Adjacent joints and geometrical elements used to define joint angle
Neck	Lower neck joint (C7, suprasternale)**	Upper neck joint (infraorbitale and tragion) and vertical line
Shoulder*	Shoulder joint (acromion, C7, suprasternale)	Elbow and hip joints
Elbow*	Elbow joint (lateral humeral condyle)	wrist and shoulder joints
Wrist*	Wrist joint (radial and ulnar styloid processes)	Elbow joint and head of 3rd metacarpal
Torso	Hip joint (anterior superior iliac spines, pubic symphysis)	Shoulder joint and vertical line
Hip*	Hip joint	Knee and shoulder joints
Knee*	Knee joint (lateral femoral condyle)	Hip and ankle joints
Ankle*	Ankle joint (lateral malleolus)	Knee joint and foot or shoe plane

*angle measured bilaterally
**surface landmarks used to define joint center in parenthesis

2.5. Determining comfortable joint angle ranges

Comfortable ranges of joint angles were determined after first ‘filtering’ postures based on criteria derived from the subjective ratings of comfort and discomfort (Figure 68). If postural data from a given session did not have corresponding subjective rating that met the criteria, they were excluded when determining recommended joint angles. Such filtering was deemed essential to determine comfortable ranges, as some drivers felt uncomfortable even in their preferred driving postures (Chapter 2). This filtering was termed the MCMD (Maximal Comfort and Minimal Discomfort) method. Though alternatives could have been employed, the specific criteria were selected to achieve three goals: 1) reasonably strict levels of subjective ratings (weak discomfort or less, and somewhat strong comfort or more) to include data close to the optimal perceptual status (i.e. no discomfort and maximal comfort); 2) in contrast, criteria should not be so stringent as to exclude a majority of the data; and 3) consideration of inter- and intra-variability in ratings for the same stimuli due to “differences in perception” or “differences in judgment criteria” (Brown et al., 1990, p. 5). The latter supported the need for a range rather than a point criterion.

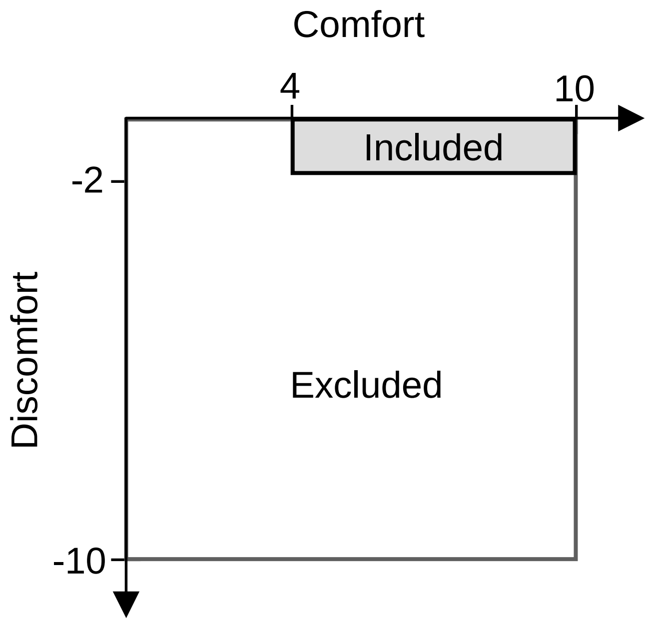


Figure 68. Inclusion/exclusion criteria for joint angles. Angles are included if corresponding perceptions meet the criteria of discomfort ≥ -2 (weak) and comfort ≥ 4 (somewhat strong).

2.6. Data analysis

Effects of Seat Condition (6 levels, within subject), Age (younger, older), Gender, and Stature (short, middle, tall) were determined, with dependent measures being driving postures described by 16 joint angles. Seat Condition represents the six driving sessions defined above, combining vehicle classes (S and U), driving venues (-L and -F), and seats (two seats within one vehicle class; S1, S2, U1, and U2). Repeated-measures multivariate analysis of variance (MANOVA) was conducted prior to univariate repeated-measures analysis of variance (ANOVA), as suggested by Weinfurt (1994). Subsequently, four-factor repeated-measures ANOVAs were conducted for each joint angle, followed by Tukey's Honestly Significantly Different (HSD) test for post-hoc pairwise comparisons. Several linear contrasts were also used to identify effects of vehicle class (sedan vs. SUV; S1-L+S2-L+S1-F vs. U1-L+U2-L+U1-F), driving venue (lab vs. field; S1-L vs. S1-F, U1-L vs. U1-F), and seat design (S1-L vs. S2-L, U1-L vs. U2-L).

As the contrast of vehicle class was found to be significant for 8 joint angles (see Results), effects of driver attributes from the initial ANOVAs are not included in the Results section.

Instead, joint angle data were divided by vehicle class, and then three additional analyses were done for each vehicle class. First, initial repeated-measures MANOVAs were conducted to assess the effects of Age, Gender, and Stature. Second, repeated-measures ANOVAs were used to evaluate effects of these same driver attributes (i.e., Age, Gender, and Stature) on driving postures. Third, matched-pairs t-tests with a Bonferroni correction were used to examine whether driving postures were bilaterally symmetric and to determine whether comfort and discomfort ratings differed between bilateral joints. For both MANOVA and ANOVA models, interaction effects were not included due to the unbalanced design and missing cells. These analyses also included all the postural data (i.e., without filtering as described above). Effects were considered 'significant' when $p \leq 0.05$, with potential trends highlighted when $0.05<p\leq0.1$.

MCMD data ranges (following filtering as in Section 2.5) were qualitatively compared with previously recommended joint angles. As the existing datasets did not differentiate between bilateral joint angles, unions of bilaterally paired joint angles obtained in this study were used for comparison. Data from Hanson et al. (2006) were also converted in this way. Comparisons were done only for the shoulder, elbow, hip, knee and ankle as these joints are provided in all or most of the existing recommendations included in this study.

3. Results

3.1. Effect of Seat Condition on joint angles

Using the entire dataset, initial MANOVA revealed significant main effects of Seat Condition, Age, Gender, and Stature for the overall data ($p\leq0.0001$). From subsequent ANOVAs, effects of Seat Condition were significant ($p\leq0.046$) for 13 of the 16 joints; a trend was found for the left wrist ($p=0.076$), and a nonsignificant effect for the torso and right knee.

The contrast of vehicle class (sedan vs. SUV) was significant ($p\leq0.02$) for the right shoulder, both elbows, both hips, left knee, and left ankle (both planes). Respective mean differences (sedan-SUV) were 2.4, 4.5, 5.6, -5.2, -1.8, -8.3, -6.7, and -6.6 deg. A trend ($p=0.056$) with respect to vehicle class was found for the torso, with a mean difference of 0.9 deg.

When driving a sedan, significantly ($p \leq 0.04$) larger angles were found in the field setting (S1-F), on the order of 3.4-12.6 deg, for the neck, shoulders, elbows, and left hip. In the lab setting, significantly ($p \leq 0.025$) larger angles were found for the right wrist, right knee, and four ankle measures, with mean differences of 4.0-11.3 deg. A trend ($p \leq 0.089$) in venue effect was also found for the left wrist and torso, with larger angles found in the lab setting (mean differences of 4.5 and 1.1 deg).

When driving an SUV, the contrast between venues (U1-L vs. U1-F) was significant ($p \leq 0.047$) for the right shoulder, hips, and left knee, with the field setting (U1-F) yielding larger angles (2.9-5.1 deg.). In the lab setting (U1-L) significantly ($p < 0.0001$) larger angles were found for the right ankle defined using the shoe (10.3 deg) and foot planes (10.1 deg).

The contrast of sedan seat design (S1-L vs. S2-L) was significant ($p = 0.03$) for the right hip, and exhibited a trend ($p = 0.075$) for the right knee, with mean differences (S1-L - S2-L) of 2.9 and 3.1 deg. The contrast of SUV seat design (U1-L vs. U2-L) was significant ($p \leq 0.025$) for the left hip and left knee. The respective mean differences were -3.1 and 3.9 deg.

3.2. Effects of driver attributes and postural asymmetry

Sedan

Initial MANOVA revealed significant main effects of Age, Gender, and Stature for the sedan data ($p \leq 0.0002$). Significant effects of Age were found on the right elbow angle ($p = 0.043$), with respective values of 124.5 (22.3) and 111.3 (13.5) deg for the younger and older groups, on the left hip ($p = 0.02$), with respective values of 100.0 (8.3) and 94.0 (9.8) deg, and a trend in this effect for the right hip ($p = 0.06$) with corresponding values of 105.3 (10.1) and 100.2 (8.4) deg. Gender had a significant ($p = 0.027$) effect on the left elbow, with angles of 132.5 (21.5) and 119.5 (18.9) observed for males and females, respectively. The left ankle angle (using the shoe plane) showed a significant effect of Stature ($p = 0.049$) with values of 96.2 (12.6), 88.3 (7.8), and 90.6 (6.8) deg for the short, middle, and tall groups, respectively. A trend in Stature effect ($p \leq 0.099$) was found on the left hip with means of 101.7 (10.1), 97.7 (10.2), and 94.8 (7.5) deg, and on the neck with means of -2.7 (9.6), 0.7 (13.6), and -7.5 (9.6) deg, for the same stature groups.

SUV

Initial MANOVA revealed significant main effects of Age, Gender, and Stature for the SUV data ($p<0.0001$). The effect of Age was significant ($p\leq0.031$) for the right elbow, left hip and left knee, whereas trends ($0.05<p\leq0.094$) were observed for the left elbow, right hip, and shoulders. For all six of these joints, the younger group assumed more extended angles. Mean differences in joint angles between the two age groups ranged from 4.9 (right hip) to 14.8 deg (right elbow). The effect of Gender was significant ($p<0.035$) for both elbows. Males assumed more extended angles, with specific values for the left and right elbow of 128.7 (19.4) and 120.7 (20.0) deg for males, and 114.5 (16.3) and 109.9 (15.7) deg for females. The left ankle angle (using the shoe plane) showed a significant effect of Stature ($p=0.03$) with respective angles of 102.9 (11.5), 94.9 (7.8), 97.2 (6.6) deg for the short, middle, and tall groups. There was a trend ($p=0.097$) with respect to the effect of Stature on left hip angle, where the corresponding values were 107.3 (9.4), 103.4 (11.6), and 98.9 (8.1) deg.

Asymmetry of driving postures

Several joint angles were not bilaterally symmetric, with significant ($p<0.0001$) differences found for the elbows, hips and knees in sedans, and significant ($p\leq0.003$) differences in the shoulders, elbows, hips, knees, and ankles in SUVs. Respective mean differences (right-left) were -5.2, 5.6, and 11.1 deg for sedan, and -1.7, -6.2, 2.2, 3.8, and -6.5 deg for SUV. Bilateral differences were also found for perceptual ratings at several joints. Bilateral differences in comfort and discomfort ratings were found for the ankles in both sedans ($p\leq0.046$) and SUVs ($p\leq0.0009$), and discomfort ratings for the knees were asymmetric ($p\leq0.042$) in SUVs. There were also trends evident for bilateral differences in the wrists and knees in SUVs ($0.05<p\leq0.09$). A summary of these bilateral differences in postures and perceptual responses is given in Figure 69.

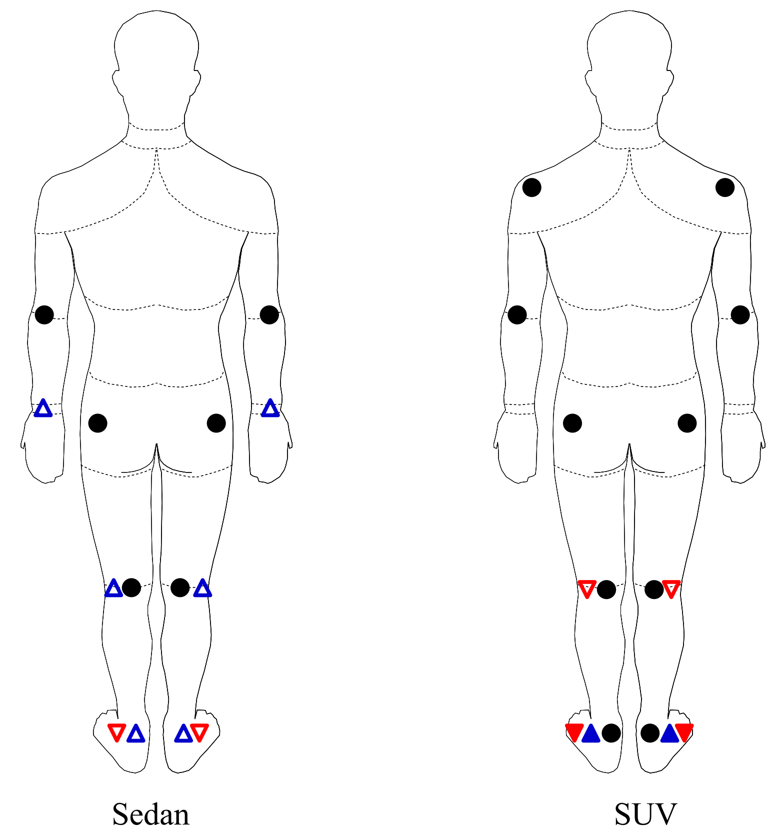


Figure 69. Bilateral asymmetry of joint angles and perceptual ratings (● - angle; ▲ - comfort; ▼ - discomfort; solid – statistically significant; hollow - trend)

3.3. Comfortable joint angle ranges by vehicle class

Comfortable driving postures were determined for each of the 16 joint angles using the inclusion/exclusion criteria described earlier as the MCMD method (Section 2.5). For most joints, angles excluded (i.e., postures were perceived as uncomfortable) were in the middle of the observed ranges, thereby forming two disjointed comfortable subgroups (angular ranges). These subgroups were termed MCMD-1 and MCMD-2, corresponding respectively to smaller and larger angles. When comparing joint angle ranges with previous recommendations, these two subgroups were included along with the initial data range prior to filtering (termed 'Unfiltered').

<u>Sedan</u>

A summary of recommended joint angles from the current and previous studies is given in Tables 31 and 32. In the current work, each joint excepting the neck had two distinct subgroups of comfortable angles (Table 31). Previous studies (Bubb, 1992; DIN, 1981; Dupuis, 1983; HdE, 1989; Park et al., 2000; Porter and Gyi, 1998; Rebiffé, 1969; Vogt et al., 2005) have included a subset of the 16 joints provided here, and have not provided bilateral postures (Table 32). One exception is the study by Hanson et al. (2006) that provided bilateral angles but did not include the neck, torso, and ankle angle with the foot plane (Table 31).

Table 31. Recommended joint angles (degrees) for sedans

Angle		Current Study				Hanson et al. (2006) (N = 76**)	
		Unfiltered (N = 113*)		MCMD ($27 \leq N \leq 102$)			
		Range	Mean (SD)	Group 1	Group 2	Range	Mean (SD)
Neck		-30~29	-3.1 (11.4)	1~27	-	-	-
Shoulder	L	-1~59	29.6 (14.8)	1~29	32~58	14~68	39 (15)
	R	2~64	28.9 (14.9)	3~26	35~59	9~59	30 (13)
Elbow	L	78~177	125.8 (21.1)	85~120	146~165	96~160	128 (16)
	R	78~179	120.6 (20.9)	85~108	133~167	98~163	135 (15)
Wrist	L	117~197	168.9 (14.6)	129~170	173~191	159~216	187 (10)
	R	126~197	169.0 (13.7)	128~154	173~195	130~206	168 (18)
Torso		16~43	29.7 (5.6)	18~26	32-43	-	-
Hip	L	78~128	98.2 (9.7)	79~87	107~118	92~109	100 (4.4)
	R	80~128	103.8 (9.9)	83~92	112~123	68~99	87 (6.3)
Knee	L	81~150	109.3 (12.5)	84~91	118~129	109~157	125 (9.3)
	R	89~152	120.4 (11.4)	93~110	123~142		
Ankle (foot)	L	75~130	96.4 (9.9)	82~88	92~123	-	-
	R	76~132	95.5 (10.4)	77~91	108~112	-	-
Ankle (shoe)	L	73~125	91.9 (10.1)	75~80	84~122	90~111	97 (5.5)
	R	66~131	91.1 (11.1)	68~88	92~113		

* 38 participants × 3 sessions (S1-L, S2-L, and S1-F) - 1 missing data
** 38 participants × 2 times (5 minutes and 20 minutes)

Table 32. Existing recommended joint angles (degrees) for sedans

Joint	Bubb (1992)	DIN 33408 (1981)	Dupuis (1983)	Hanson et al. (2006)	HdE (1989)	Park et al. (1999)	Porter and Gyi (1998)	Rebiffé (1969)	Vogt et al. (2005)
Neck	-	-	-	-	-	-	-	-	-
Shoulder	9~69	38	-	9~68	-	7~31	19~75	0~25	22
Elbow	134~158	120	-	96~163	-	88~137	86~164	80~120	127
Wrist	-	-	-	130~216	-	-	-	-	-
Torso	-	-	-	-	-	-	-	-	27
Hip	101~113	95	105~115	68~109	110	101~127	90~115	95~120	99
Knee	142~152	125	110~120	109~157	145	120~151	99~138	95~135	119
Ankle*	77~115	90	-	90~111	100	86~116	80~113	90~110	103

*shoe plane

Recommendations for five of the joints (i.e., the elbow, shoulder, hip, knee and ankle) are compared in Figures 70-74. ‘Unfiltered’ ranges from the current study covered most of the previous recommended ranges. Some earlier studies exhibit discrepancies with each other, and some ranges do not correspond to both MCMD-1 and MCMD-2. For example, recommended ranges for the elbow angle (Figure 71) by Rebiffé (1969) and Park et al. (2000) roughly corresponded to MCMD-1, while that of Bubb (1992) was within the MCMD-2 range. In the case of DIN (1981) and Vogt et al. (2005), their recommended values (i.e., points rather than ranges) were near the mean of the two MCMD subgroups. Ranges by Porter and Gyi (1998) and Hanson et al. (2006) were located across the two MCMD subgroups, but were narrower than the ‘Unfiltered’ range. Related trends were also observed for other joint ranges. Hence, with respect to each joint angle, results from the current study span most of the preferred driving postures adopted in sedans, whereas some earlier studies recommend somewhat more limited ranges of postures.

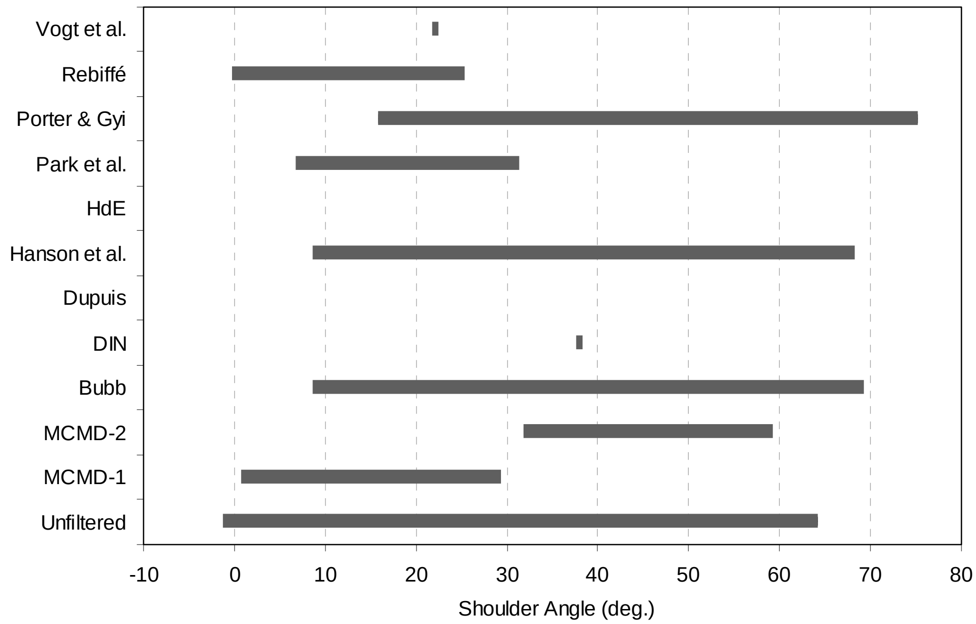


Figure 70. Comparison of recommended shoulder angles - Sedan

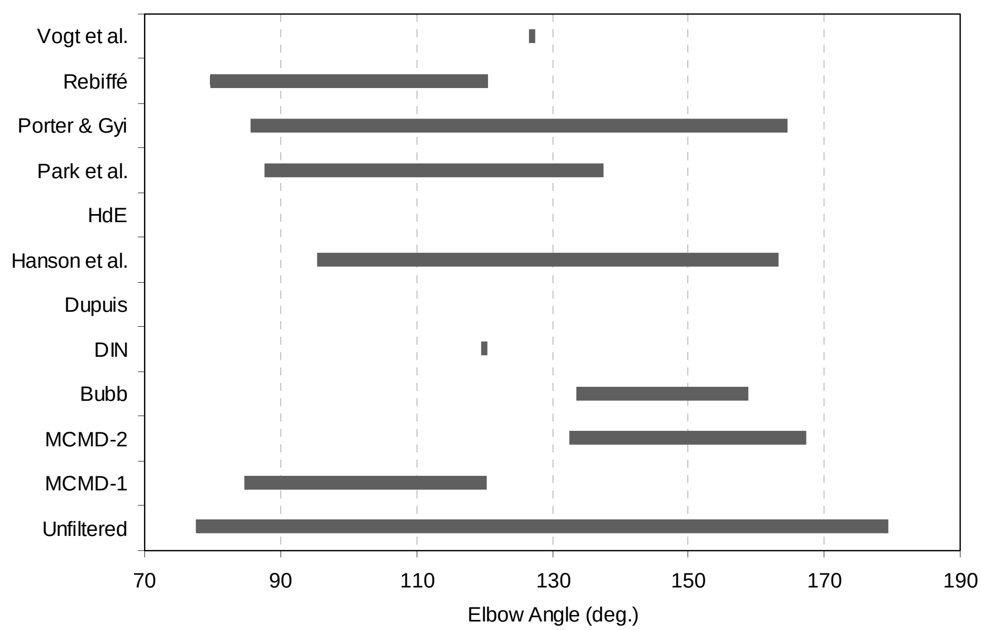


Figure 71. Comparison of recommended elbow angles - Sedan

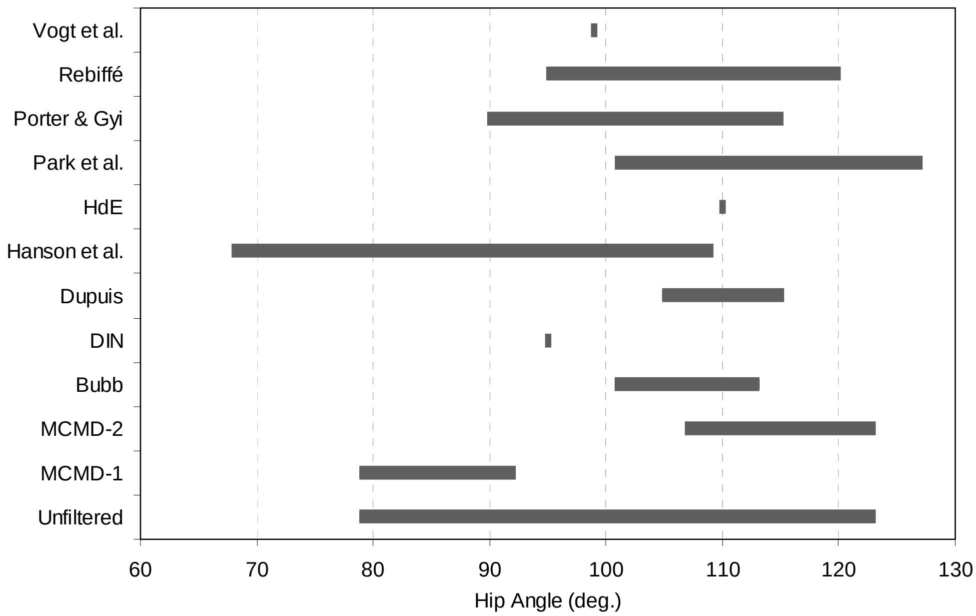


Figure 72. Comparison of recommended hip angles - Sedan

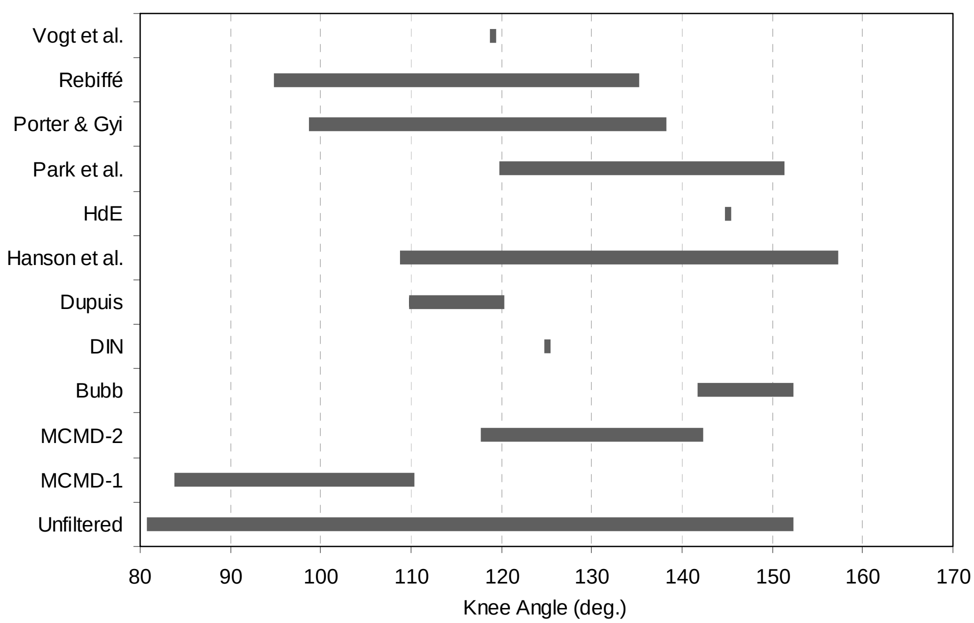


Figure 73. Comparison of recommended knee angles - Sedan

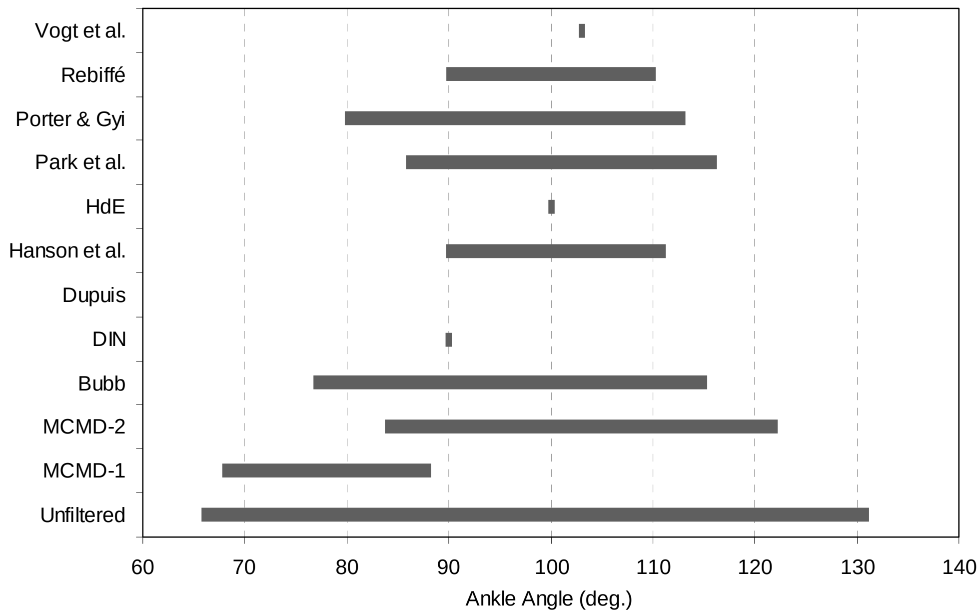


Figure 74. Comparison of recommended ankle angles (shoe plane) - Sedan

SUV

Except for the right wrist and left ankle, each joint had two comfortable angle ranges. As no recommended joint angles are available in the literature for SUVs, only the results from the present study are included (Table 33).

Table 33. Recommended joint angles (degrees) for SUVs

Angle		Unfiltered (N = 113)		MCMD Range (8 ≤ N ≤ 111)	
		Range	Mean (SD)	Group 1	Group 2
Neck		-36~29	-1.7 (11.4)	-30~-1	0~27
Shoulder	L	0~61	28.3 (14.3)	2~11	38~59
	R	1~67	26.5 (14.3)	4~11	37~63
Elbow	L	78~174	121.3 (19.2)	84~116	121~160
	R	83~169	115.0 (18.6)	84~109	117~157
Wrist	L	123~191	168.1 (12.8)	130~166	172~188
	R	118~190	169.4 (13.3)	128~189	-
Torso		14~45	28.8 (5.7)	18~23	35~42
Hip	L	81~134	103.4 (10.3)	84~87	119~126
	R	83~137	105.6 (10.2)	85~91	120~130
Knee	L	94~145	117.7 (10.8)	95~105	135~138
	R	93~151	121.4 (10.5)	97~111	136~139
Ankle (foot)	L	84~131	102.9 (10.0)	94~130	-
	R	77~123	96.5 (9.8)	80~86	108~116
Ankle (shoe)	L	84~126	98.6 (9.6)	93~125	-
	R	70~122	92.1 (9.8)	73~86	102~108

4. Discussion

Comfortable driving postures are crucial when using DHMs for ergonomic design and evaluation of a driver workspace. In contrast to several earlier approaches, the current study used an expanded set of joint angles in order to more completely describe driving postures. In addition, data collection and analysis was intended to provide joint angles compatible with existing standards, to investigate the effects of vehicle factors (class, venue, and seat) and driver attributes (age, gender, and stature) on driving postures, to determine whether driving postures were bilaterally symmetric, and to specify comfortable ranges of joint angles for two vehicle classes (sedan and SUV). With respect to these latter ranges, a method was developed to ensure that recommended joint angles are both preferred and comfortable. Comparisons were made between the present results and existing recommendations. These issues are discussed below, along with several implications and suggestions relevant to driver workspace design.

Drivers' seated postures were defined and measured in this study using 16 joint angles, whereas a relatively limited set of joint angles has been included in previous studies, ranging from 2 (Dupuis, 1983) to 10 (Hanson et al., 2006). Torso angle is essential to position DHMs or physical models inside a driver workspace (virtual or physical), as it determines seatback angle and eye location. It is also related to drivers' anterior-posterior balance, alertness, comfort (Diffrient et al., 1990), and reach. However, it has not usually been included in existing recommendations (1 of 9 studies; Table 32). Similarly, while many studies provide recommended ankle ranges, compatibility with relevant standards (e.g., SAE J1516 and J1517) has not been incorporated when measuring or presenting ankle angle. Ankle angle is relevant and important, however, when defining and measuring interior roominess (i.e., leg room; SAE, 1998b). In addition, existing recommendations have not included neck angle, yet this determines head position and further relates to headrest design and collision safety (e.g., the neck sprains called whiplash), nor have they provided wrist angle, which influences preferred steering wheel location and angle. The current study included torso, neck, and wrist angles and two types of ankle angle in order to achieve a higher level of postural resolution and to facilitate future application in design and compatibility.

Three vehicular effects on driving postures were investigated in this study: 1) vehicle class, which is usually accompanied by a distinct interior geometry that restricts feasible ranges of driving postures, 2) driving venue, which can be expected to provide contextually different driving experiences and to influence driving posture (Hanson et al., 2006), and 3) vehicle seat, design differences in which will affect driving posture. First, the contrast of vehicle class (sedan vs. SUV) was significant for most joints (8 out of 16) with mean differences ranging from 1.8 to 8.3 deg, indicating that a distinct set of recommended joint angles is needed for each vehicle class. Indeed, people should (or are expected to) take a different posture according to vehicle class, due to differences in interior geometries typically available for each vehicle class. For example, sedans have, on average, 60 mm lower seat height and 15 mm higher steering wheel center height than SUVs (Autograph, 2003).

Second, driving venue effects were also apparent in the sedans (i.e., S1-L vs. S1-F). The lab-based sedan setting (S1-L), with a more adjustable (collapsible and extendible) workspace than that offered by an actual vehicle, encouraged larger angles at some lower body joints and smaller angles at some upper body joints (mean differences: 3.4 - 12.6 deg) in comparison to the field-based sedan setting (S1-F). This difference indicates that sedan interior geometry could be improved by positioning the steering wheel closer to the driver, and providing additional leg room.

Third, a seat effect within vehicle class was observed in sedans. In a previous study (Chapter 2), the seat from a lower-rated sedan (S2-L), according to the J. D. Power and Associate's Comfort Scores (2005), was perceived as more comfortable than the seat from a higher-rated sedan (S1-L). Note that the initial package geometry used in the lab settings for S1-L and S2-L was that of S1. Hence, the only difference between S1-L and S2-L settings was the seat design. In contrast to the perceptual responses, postural measures did not provide such a clear or consistent distinction. Though a significant effect of seat design was observed for the right hip joint angle, local perceptions were not significantly different. Hence, the difference in right hip joint angle seems not to be a major factor influencing the global difference in perceptual comfort. In addition, the remaining 15 joint angles exhibited no seat effects, implying that seat design differences within the same vehicle class do not substantially affect driving postures. It can be also concluded that joint angles only partially impact driver sitting comfort, and do not effectively or predominantly account for other aspects of driver sitting comfort that can result from subtle differences in seat support (Reed et al., 1994) or distribution of contact pressure (Chapter 3; Helander et al., 1987; Sanders and McCormick, 1987).

Several effects of driver attributes (age, gender, stature) on driving postures were investigated as these attributes are acknowledged to influence general postures (Reynolds, 1993), muscular strength (Chaffin et al., 2000; Warnes et al., 1993), and reach (Chaffin et al., 2000), hence potentially affecting driving postures. First, clear age-related differences in postures were found. Older individuals exhibited smaller angles at the right elbow and left hip joints, regardless of vehicle class (mean difference: 6.0-14.8 deg), indicating a tendency to sit closer to the steering wheel (and confirming common observations). Due to this postural tendency, older individuals are expected to have more trouble reading information on in-vehicle visual displays since farsighted vision often occurs with advanced age. Therefore, if a vehicle is especially targeted for older individuals, visual displays should be placed farther away in order to account for their farsighted vision as well as their postural preference.

Second, gender effects were found on the left elbow angle (but not on the right elbow angle), regardless of vehicle class, with more extended left elbow angles (mean differences: 13.0-14.2 deg) obtained from males. This is consistent with the results of Park et al. (2000), though they did not provide bilateral measures or angles for SUVs. Similarly, Dunk and Callaghan (2005), using an office chair, observed gender differences in posture, with females showing more upright posture (hence, implying that females might adopt more flexed elbow angles). However, gender effects on sitting posture can be confounded by stature (the male group was 10-14 cm taller than the female group in these studies).

Third, though relatively minimal, stature effects were found in both vehicle classes for the left ankle angle, with the middle-size group having smaller angles than the other two groups (mean differences: 2.3 deg for both classes). One implication of the findings with respect to driver attributes' effects on driving posture is that boundary postures of DHMs should include those of short older females (as a lower limit) and tall younger males (as an upper limit), though future study is needed to determine if important interaction effects of age and gender exist.

Expanded sets of recommended joint angles are rare, and this is likely a result of assuming bilateral symmetry in driving postures. The present results indicate substantial bilateral asymmetry (mean difference: 1.7-11.1 deg). In SUVs, bilateral differences were found in both postures and perceptual rating. Though no perceptual differences were found, bilaterally asymmetric angles were also observed at the elbows and knees regardless of vehicle class. Hanson et al. (2006) also observed bilateral asymmetries at the hips, shoulders, elbows, and wrists. Therefore, driving postures of DHMs should be described and positioned asymmetrically, and interior parts inside and around the driver workspace should be placed and designed accordingly. This postural asymmetry, potentially because of the different task requirements imposed on each body side (Chapter 3), necessitates further investigation on asymmetric seat design for improved seat support and seated experience.

Another apparent assumption in many earlier studies was that car seats and/or package geometries are sufficiently comfortable for drivers. As such, all postural data were included, without filtering, when determining recommended joint ranges. Yet, joint angles adopted by drivers, even if associated with 'preferred' postures, are not necessarily comfortable angles or postures (Chapter 2). Hence, an initial 'filtering' mechanism was incorporated here, using two perceptual responses (i.e. ratings of comfort and discomfort). From this, a set of 'comfortable' (rather than 'preferred') ranges of joint angles were provided. As recommended by several studies (e.g., Chapter 2; Hanson et al., 2006; Zhang et al., 1996), comfort and discomfort were separately measured at local body parts and levels of these two perceptions were used in the filtering process. If the current recommended joint ranges are used for digital driver models, corresponding postural perceptions are expected to at least 'somewhat strong comfort' and at most 'weak discomfort'. From the MCMD method, two ranges (MCMD-1 and MCMD-2) were identified as comfortable for most joints regardless of vehicle class, implying that there might be at least two sitting strategies, representing relatively flexed and extended postures. Further analysis is needed, however, to specifically quantify these strategies.

Several discrepancies were apparent in the recommended ranges of joint angles between this and earlier studies, and may have been due to differences in joint angle definitions, or due to specific vehicles (and their interior geometries) used in each study that restricted the range of driving postures that drivers could adopt. However, the most substantial source of discrepancy likely resulted from the filtering process and diverse groups of participants used here. Uncomfortable ranges of joint angles, which were especially found around the middle range of the unfiltered data, should be carefully interpreted. Despite reporting uncomfortable feelings at their joints, some participants indeed preferred these ranges (i.e., they adopted these joint angles). This implies vehicle interior design is still suboptimal; with improved design of vehicle interior parts and/or interior geometry, it is likely that more people can feel comfortable in their preferred postures.

There are several potential limitations in this study that should be addressed. Both perceptual responses and postures were obtained after 20 minutes of real or simulated driving. While it is unknown if the results are appropriate for more extended driving, 15 minutes is considered sufficient for drivers to 'settle' in car seats (Reed et al., 1999), and Hanson et al. (2006) found no difference between driving postures after five and 20 minutes of driving. Short-term driving study is also of importance, as it accounts for most driving patterns (82 % of trips in US; Reed et al., 1994). It remains to be explored whether long-term driving postures differ from those in the short-term, and to incorporate any temporal changes in driving posture into vehicle design. It should be noted, however, that as driving duration increases, drivers' comfort and discomfort are likely influenced by factors other than driving posture and/or seat support, such as fatigue (Helander and Zhang, 1997), in-vehicle temperature, and the micro-climate around the seat (Kolich, 2007). Two sets of comfortable joint angle ranges are provided here for only two vehicle classes; comparable results for other vehicle classes (e.g., sports car, van, truck, bus) are not available to the authors' knowledge and should be addressed in future work. Lastly, only sagittal angles were used in this study, yet non-sagittal body movements (e.g., abduction, adduction, supination, and pronation) should be considered in order to more precisely position DHMs in a 3D design space.

5. Conclusions

Descriptions of comfortable driving postures (i.e. ranges of joint angles) for two vehicle classes were obtained, using experimental procedures that facilitated compatibility with existing standards and direct applicability to vehicle interior design and evaluation. Postural differences due to vehicle class and driver attribute (age, gender, and stature), and postural asymmetry identified in this work should be accounted for when using DHMs for driver workspace design. Distinct driving postures observed in more extendible lab settings should also be considered when designing a driver workspace in order to make it more comfortable and usable. Finally, a new filtering method was incorporated, to ensure that recommended joint ranges achieve adequate levels of comfort and discomfort, and to differentiate between comfortable and preferred driving postures.

Chapter 8: Developing accurate digital driver models: Drivers' postural strategies to interact with automobiles

Abstract

Driver workspace design and evaluation is based on assumed driving postures of users, and determines several ergonomic aspects of a vehicle such as drivers' reach, visibility, and postural comfort. Accuracy in prediction and specification of standard driving postures, hence, is a crucial factor to improve the ergonomic quality of driver-side interior space. In this study, a statistical clustering approach was employed to reduce driving posture simulation / prediction errors, based on an assumption that drivers use several postural strategies when interacting with automobiles. Driving postures, described by 16 joint angles, were obtained from 38 people with diverse demographics (age, gender) and anthropometrics (stature, body mass) in two vehicle class conditions (sedans and SUVs). Based on the proximity of joint angle sets, cluster analysis identified three predominant postural strategies for each vehicle class (i.e., 'Lower limb flexed', 'Upper limb flexed', and 'Extended'). Mean differences between clusters ranged from 3.8 to 52.4 deg for the majority of joints, supporting the practical relevance of the distinct clusters. Such strategies should be considered when utilizing digital human models (DHMs) to enhance and evaluate driver workspace design ergonomically and proactively.

Relevance

This study identified drivers' distinct postural strategies, based on actual drivers' behaviors. Such strategies can facilitate accurate positioning of DHMs, and hence help design ergonomic driver workspaces.

Keywords: postural strategies; cluster analysis; asymmetric driving posture; comfortable driving posture; preferred driving posture

1. Introduction

Digital human models (DHMs) have been extensively used in automotive design, especially for driver workspace design, to achieve benefits such as reduced design/engineering costs and time, and ergonomic quality improvement (Chaffin, 2005, 2007; Hanson et al., 1999; Park et al., 2004;

Porter et al., 1993). A variety of methods (e.g., neural networks, regression, Kalman filtering, kinematics, inverse kinematics, and optimization) have been used to model and predict postures and movements of people (Chaffin, 2007; Hanson et al., 1999; Pinho et al., 2005; Reed et al., 2002). DHM tools coupled with these methods, however, are acknowledged as requiring additional sophistication and/or accuracy when used to simulate human postures and movements (Chaffin, 2005, 2007; Chaffin et al., 1999), presumably including those of drivers. To increase the validity of ergonomic design and analysis using a DHM, characteristics of human behaviors identified for postures and movements should be embedded in a DHM tool (Chaffin, 2005).

A 'driving posture' is the posture adopted inside a driving workspace when interacting with a vehicle. It is the resulting posture after the upper and lower extremities reach their respective designated targets. In a vehicle equipped with an automatic transmission, for example, a driver's upper limbs and left lower limb have loosely defined target locations (i.e., anywhere on the steering wheel for at least one hand, and on/around the foot rest, if available, for the left foot), while the right lower limb has relatively fixed target locations (i.e., mostly on the gas pedal or on the brake pedal). After reaching these targets, the arms and the right leg are repetitively engaged in controlling movements for steering and pedaling tasks, with other intermittent reach and control movements for the arms (e.g., for transmission gear shift, ventilation adjustment, and radio tuning). Motion prediction algorithms, such as inverse kinematics, can be used to specify a normal driving posture (e.g., Reed et al., 2002), which is not only a terminal (though not static) posture of these initial reaching motions (to the wheel and pedals), but also an initial or intermediate posture for other reaching and controlling motions throughout the course of driving. It should be noted here that the geometrical relationship between the driver and targets can be altered at any time during and outside of these reaching movements according to any required adjustments of the seat and/or the steering wheel.

Though seated in a fairly confined space, drivers adopt diverse driving postures. Even two drivers of a similar body size may adopt different postures (Kolich, 2007). Besides reaching and controlling movements, drivers tend to change their driving posture intermittently in order to reduce discomfort induced by postural fixity (Akerbloom, 1948; Andreoni et al., 2002; Dhingra et al., 2003; Jenny et al., 2001). Individual attributes (e.g., age, gender, and anthropometry) and vehicle factors (e.g., vehicle class, interior geometry, and driving venue) have also been demonstrated to affect drivers' reaching or sitting postures (Chapter 7; Chaffin et al., 2000; Hanson et al., 2006; Park et al., 2000; Reed et al., 2000). Given that substantial variability exists among driving postures, posture specification and prediction inevitably comes with some degree of error. If these heterogeneous driving postures, however, can be classified by their inherent similarity, errors involved in simulating driving posture are likely reduced. Applying a prediction method to partitioned data would improve accuracy of modeling and simulation of postures and movements, as each subgroup would be more homogeneous than the entire dataset, and several distinct reaching or posturing techniques might be involved when adopting driving postures.

Cluster analysis, an exploratory technique, divides a set of objects (in our case, driving postures) into two or more groups (called clusters), based on the proximity of the objects. The result is that each cluster is internally homogeneous, and highly heterogeneous with other clusters (Hair and Black, 2000). In contrast to Discriminant Analysis, it does not require that the number of clusters be specified *a priori*. Therefore, it seems a more appropriate technique for the current problem of interest (i.e., to determine drivers' postural strategies). Accordingly, cluster analysis can be used to identify homogeneous groups of driving postures, which can be considered as postural strategies or initial reaching techniques. Indeed, cluster analysis has previously been applied to the classification of human movements and postures. Examples include alternative lifting techniques (Park and Singh, 2004) and gait patterns of patients following strokes (Mulroy et al., 2003).

Though a few published studies have addressed classification of sitting or driving postures, none has applied cluster analysis to driving postures described by joint angles. Beach et al. (2005) identified static and dynamic strategies for seated postures lasting 2-hr in an office chair. Static sitting strategy was defined as "maintaining a sitting posture that was within a 15% range of lumbar flexion for at least 85% of the collection time" (p. 148). Using an interface pressure measurement system on a car seat pan, Andreoni et al. (2002) investigated driver sitting strategies, and qualitatively identified two strategies (i.e., "the ischiatic and trochanteric strategies", p. 518) according to the anatomical region at which the peak pressure was observed.

Earlier, Andreoni et al. (1999), using pressure distribution on a car seat back, identified three driver sitting strategies for the upper body (“dorsal sitting” with uniform pressure at the upper back, “upper scapular sitting” with higher pressure at the scapula, and “lumbar sitting” with high pressure at the lumbar area; p. 2). The two studies by Andreoni et al. (1999; 2002) suggest that there may exist six sitting strategies in the context of driving.

None of these earlier strategies, however, can be used to specify driving postures of DHMs because their postural specification does not effectively describe the position/orientation of the entire body. There is also a fundamental limitation in describing quantitatively whole-body posture using interface pressure, because a pressure-based description is inevitably limited to those body parts in contact with the seat (i.e., at best from the upper back to the knees). Additionally, current computer-aided design (CAD) tools have not advanced to the point where driving postures can be effectively modeled based on interface pressure between the driver and seat. Hence, it is necessary to investigate drivers’ postural strategies by quantifying joint angles, rather than interface pressure, in order to specify an entire driving posture (i.e., from the wrists to the neck and down to the ankles) in an easier and effective way within currently available DHM tools.

Confined driver workspaces may hinder drivers from adopting preferred driving postures. A previous study in Chapter 6 revealed that drivers responded distinctly to slight changes in their preferred driving postures. In this study, participants’ hip joint centers (HJC) were randomly moved to one of 20 predefined locations around the original driver-selected HJC location when positioned in an adjustable driving rig that provided more expandable and collapsible adjustment ranges than currently available in standard automobiles. Groups with different age, gender, and stature dimensions showed distinct responses to these altered postures. This suggests that several postural strategies would be adopted when a driver workspace does not provide a sufficient adjustment range or space, prohibiting drivers from adopting their preferred driving posture (i.e., when drivers’ postural adaptation is needed).

SAE standards such as J1517 (1998b) and J941 (2002) have been widely used to measure or determine accommodation levels of the driver workspace. However, these standards are acknowledged to insufficiently accommodate populations at the extremes (e.g., 5th percentile females and 95th percentile males; Chapter 6). Hence, these groups may seek to compensate any spatial deficiency of a driving workspace in a way that minimizes their discomfort. In addition, while determining comfortable driving postures, we conjectured in Chapter 7 that at least two sitting strategies are present, based on the existence of two discontinuous comfortable ranges at most joints. Therefore, further investigation is warranted to determine exactly how many strategies drivers indeed use, and whether these strategies show a clear association with driver attributes, such as age, gender, and stature.

The goal of this study, therefore, was to identify drivers' postural strategies for two vehicle classes (sedan and SUV) and to examine whether these strategies can be clearly divided by driver attributes (i.e., age, gender, and stature). A longer-term goal is to use any identified strategies to increase the accuracy of driving posture simulation and to facilitate valid ergonomic design and evaluation of a driver workspace that involve DHM tools.

2. Experimental methods

2.1. Overview of experiment

This is a secondary analysis of the joint angle data collected and used in a previous study (Chapter 7). As such, experimental methods, except for data analysis, were identical. Only a brief summary of the experimental is given here; for more information on definitions of joint angles, data collection procedures, and experimental conditions, the reader is referred to the earlier chapter. Sixteen joint angles were obtained from 38 participants who completed six driving sessions. These driving sessions combined two vehicle classes (sedan and SUV), two driving venues (lab-based and field-based), and two seats (from vehicles ranked high and low by J. D. Power and Associates (2005)' Comfort Score) per vehicle class. Participants completed three sessions (two in the lab and one in the field) for each vehicle class. Participants were experienced (≥ 2 yr), licensed drivers with no current self-reported musculoskeletal disorders, and were selected from two age groups (27 people aged 20-35 years; 11 people aged 60 years or over), both genders (18 males; 20 females), and three stature groups (14 people < 165cm; 12

people of 165-175cm; 12 people > 175cm). Each participant completed an informed consent procedure, approved by the local Institutional Review Board, prior to the first experiment session.

2.2. Data analysis

As effects of vehicle class on driving postures were evident at most joints (i.e., 8 of 16 joints) in Chapter 7, joint angle data divided by vehicle class were used in cluster analysis to group drivers by the similarity of their postures as described by joint angles. The datasets were first standardized (using the mean and standard deviation of each joint angle) and then Ward's method, one of hierarchical clustering procedures, was used to identify several subgroups that would represent different postural strategies. The final number of clusters was determined by visually examining each clustered dendrogram. After repeated-measures multivariate analysis of variance (MANOVA) was conducted (Weinfurt, 1994), univariate repeated-measures analysis of variance (ANOVA) was used to investigate whether joint angles were different between clusters, with the Tukey's Honestly Significantly Different (HSD) test for post-hoc pairwise comparisons. Additionally, to investigate whether drivers adopted the same postural strategies across two vehicle classes and/or across two driving venues, the total number of strategies employed by each driver was counted. Effects were considered 'significant' when $p \leq 0.05$, with potential trends noted when $0.05 < p \leq 0.1$. One female participant finished only the lab sessions, hence the number of joint angle datasets for each vehicle class was reduced from 114 (38 people × 3 sessions per participant per vehicle class) to 113.

3. Results

3.1. Driving posture in sedans

Three subgroups emerged based on the similarity (or dissimilarity) of the 113 sets of 16 joint angles that described driving postures measured in the sedan sessions (Figure 75). The three clusters identified were also different from each other in term of their size and composition (Table 34). The first cluster was composed of 60 datasets, and was characterized as having the smallest mean joint angles for the elbows and shoulders among three clusters. This cluster was termed 'UL-flexed' (upper limb flexed). The second cluster containing 43 datasets had the smallest mean joint angles for the hips, knees and ankles. This cluster was termed 'LL-flexed' (lower limb flexed). The third cluster consisted of the remaining 10 datasets, and came exclusively from younger individuals. This cluster had the most extended driving postures except for wrist angles, and was termed 'Extended' (Figure 76). MANOVA showed that there were significant ($p<0.0001$) cluster effects on the 16 joint angles as a group. Subsequent ANOVA identified significant ($p \leq 0.04$) cluster effects on each of 14 joint angles except for the neck and torso (Figure 76), with mean differences ranging from 4.9 (for the right knee) to 52.4 deg (for the right elbow).

Table 34. Composition of three clusters representing drivers' postural strategies - Sedan

Cluster (Name)	Cluster 1 (UL-flexed)		Cluster 2 (LL-flexed)		Cluster 3 (Extended)	
Total # of Dataset	60 (51/9)*		43 (17/26)		10 (8/2)	
Younger vs. Older	38	22	32	11	10	0
Short (M/F)+	16 (0/16)	13 (2/11)	5 (0/5)	2 (1/1)	6 (3/3)	0
Middle (M/F)	14 (6/8)	3 (2/1)	10 (4/6)	6 (4/2)	2 (2/0)	0
Tall (M/F)	8 (6/2)	6 (6/0)	17 (13/4)	3 (3/0)	2 (2/0)	0
Mean Stature (SD; cm)	167.6 (11.6)		174.1 (10.6)		167.1 (11.0)	

* Number of data collected from lab and field sessions
+ Number of males and females

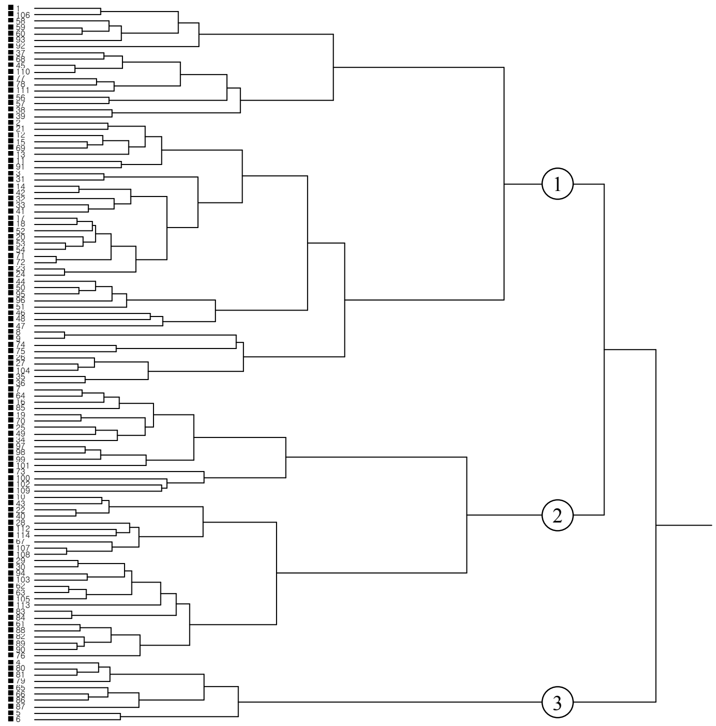


Figure 75. Clustered dendrogram for driving postures in sedans (Cluster numbers are in circles; Branch length indicates dissimilarity between data)

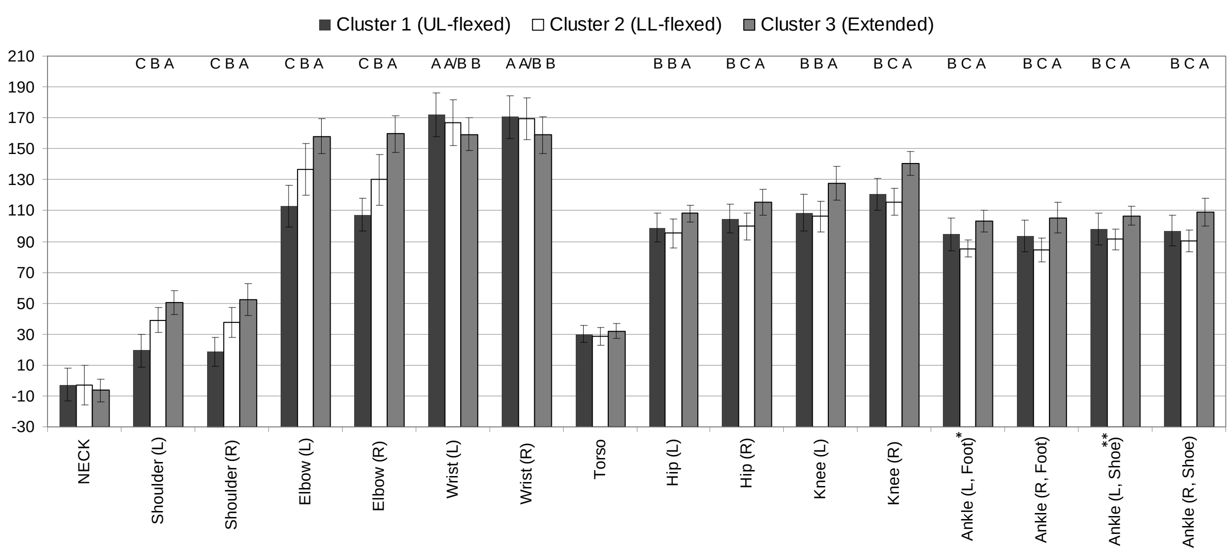


Figure 76. Mean joint angles of three postural strategies - Sedans (All joints are significant except for the neck and torso; Error bars - SDs; Tukey's HSD grouping (A/B/C) is shown at the top; *foot and **shoe planes are defined in Chapter 6.)

3.2. Driving postures in SUVs

Consistent with the sedan sessions, three distinct subgroups were also identified by cluster analysis in the SUV sessions (Figure 77; Table 35). These three groups were termed the same as before, but there were slight differences in size and composition between corresponding clusters from two vehicle classes. The first cluster, very similar to the sedan sessions, consisted of 42 datasets and represented driving postures with the smallest mean joint angles for the elbows and shoulders, and was termed 'UL-flexed'. The second cluster including 39 datasets was characterized as the right lower limb closest to the pedals due to the smallest mean joint angles for the knees and left ankle, and was termed 'LL-flexed'. This group also had the smallest mean joint angle for the right knee as before, but not for the right ankle. The third cluster was comprised of 32 datasets, and most of the data (30 of 32) were from the younger group, similar to the sedan sessions. This third cluster also had the largest joint angles for the upper and lower body except for the wrists and left ankle, and was termed 'Extended' (Figure 78).

MANOVA showed that there were significant ($p<0.0001$) cluster effects on the 16 joint angles as a group. Subsequent ANOVA revealed that there was a significant ($p\leq0.04$) cluster effect on each of the 16 joint angles, with the mean differences ranging from 3.8 (for the right ankle with the foot plane) to 37.8 deg (for the left elbow).

Table 35. Composition of three clusters representing drivers' postural strategies - SUV

Cluster (Name)	Cluster 1 (UL-flexed)		Cluster 2 (LL-flexed)		Cluster 3 (Extended)	
Total # of Dataset	42 (28/14)*		39 (27/12)		32 (21/11)	
Younger vs. Older	25	17	25	14	30	2
Short (M/F)+	11 (0/11)	10 (0/10)	3 (0/3)	4 (2/2)	13 (3/10)	1 (1/0)
Middle (M/F)	11 (4/7)	1 (1/0)	7 (5/2)	7 (4/3)	8 (3/5)	1 (1/0)
Tall (M/F)	3 (1/2)	6 (6/0)	15 (11/4)	3 (3/0)	9 (9/0)	0
Mean Stature (SD; cm)	166.2 (11.4)		175.2 (10.7)		168.8 (10.6)	

* Number of data collected from lab and field sessions
+ Number of males and females

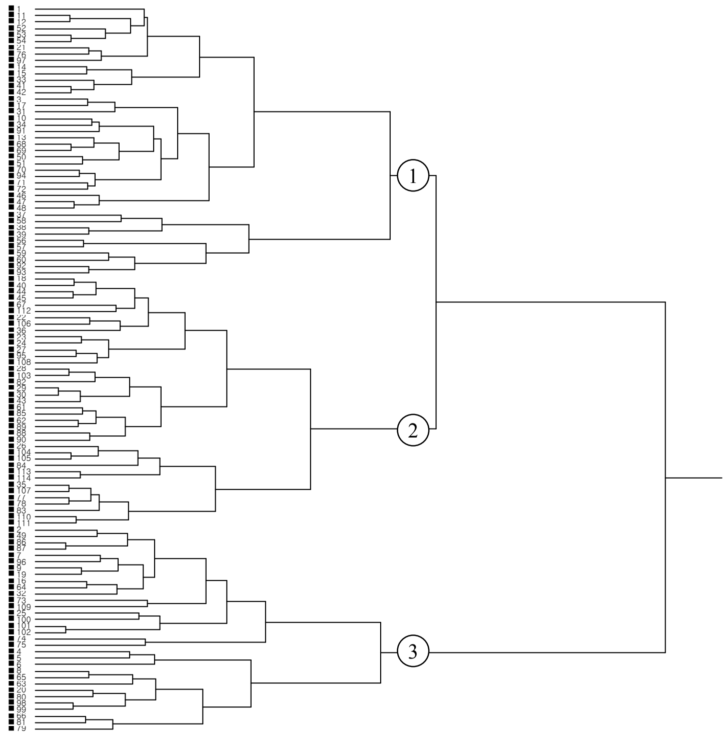


Figure 77. Clustered dendrogram for driving postures in SUVs

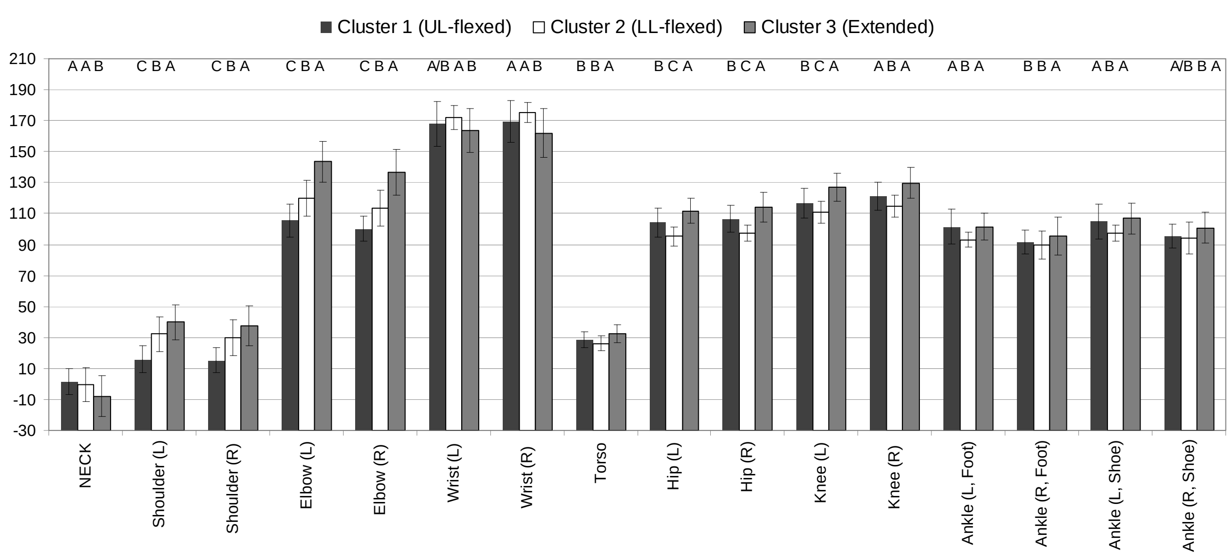


Figure 78. Mean joint angles of three postural strategies - SUVs (All joints are significant; Error bars - SDs; Tukey's HSD grouping (A/B/C) is shown at the top.)

3.3. Consistency of postural strategies

As seen Sections 3.1 and 3.2, three postural strategies were consistently identified in both sedan and SUV classes (Tables 34-35; Figure 79), as well as both driving venues (Tables 34-35). At the individual level, however, inconsistency in the use of postural strategies was observed, in that most drivers did not maintain a single postural strategy. Specifically, only 13 participants (34%) used one strategy across the two vehicle classes and/or the two driving venues, while 16 participants (42%) used two strategies, and 9 participants (24%) used all three strategies.

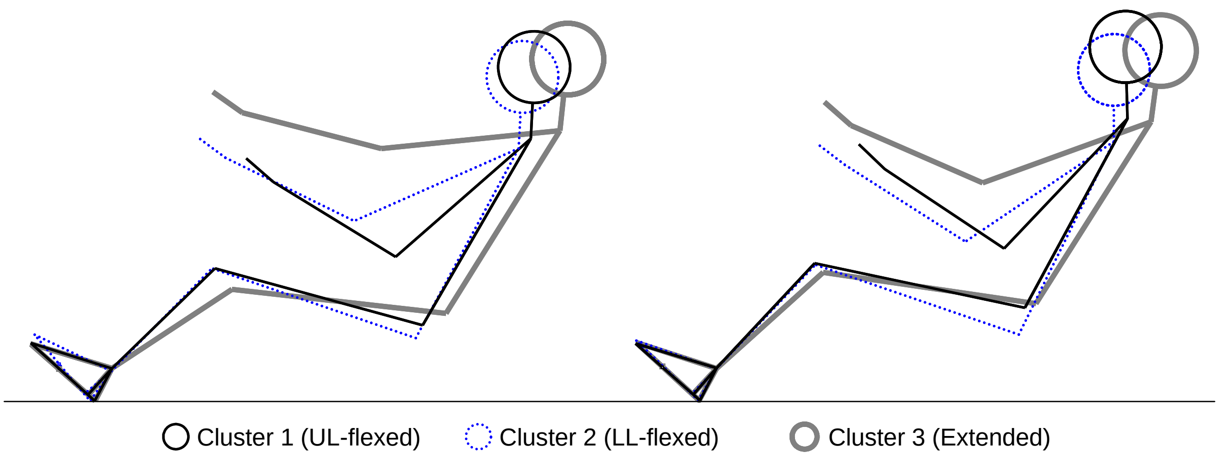


Figure 79. Schematic comparison of three postural strategies of a same-size driver (Left - Sedan; Right - SUV; Left limbs are not shown for clarity; Balls of foot (2/3 from heel) are aligned to a vertical line, and heels are aligned to a horizontal line.)

4. Discussion

DHMs have been widely used during driver workspace design to proactively evaluate and ensure vehicle interior ergonomics without physical prototypes, and to retrospectively investigate and compare competitors' production vehicles with the vehicle under development. More sophisticated DHMs, however, are still needed with respect to their accuracy in specification and prediction of driving postures. The standard driving postures selected for DHMs influence the ergonomic quality of driver workspace in terms of drivers' postural comfort or alertness level (Diffrient et al., 1990), reach and visibility (Chaffin, 2007). Hence, major, if not all, representative behavioral characteristics of drivers should be built into a DHM in order for it to move and pose similar to actual drivers. Based on the findings in the current and previous studies, the following three behaviors, at a minimum, should be considered when modeling a digital driver: 1) postural strategy, 2) postural asymmetry, and 3) lateral imbalance of the whole-body posture. The need for more sophisticated DHMs and the relevance of these three behaviors to the development of more accurate digital driver models are further discussed below.

DHM tools need to be improved further to ensure their validity for use in design and evaluation tasks (Chaffin, 2007). Several commercial software packages such as RAMSIS™ (Human Solutions; Troy, MI, USA), Safework™ (Safework, Inc.; Montréal, Quebec, Canada), JACK™ (Siemens PLM Software; Plano, TX, USA), CATIA V5™ (IBM and Dassault; Armonk, NY, USA) have been used for human modeling and simulation in a virtual design space. Postural discomfort of a DHM is linked to a discomfort database built in the software package. Published literature (e.g., Wisner and Rebiffé (1963), and Diffrient et al. (1990) for the Human Builder module in CATIA V5) has been used as a discomfort reference for DHMs. Since previous studies on comfortable driving postures or human postures have not extensively or explicitly considered individual attributes such as gender, age, and stature (as addressed in Chapter 7; Chaffin et al., 2000; Dunk and Callaghan, 2005; Park et al., 2000), asymmetry of driving postures (as addressed in Chapter 7; Hanson et al., 2006), vehicle factors (as addressed in Chapter 7), or the need of separate measures of comfort and discomfort (as addressed in Chapter 2; de Looze et al., 2003), these limitations remain in the DHM software as well as in its ergonomic analysis.

The present study identified drivers' postural strategies by dividing diverse driving postures into several homogeneous groups using cluster analysis. Three clusters (strategies) were consistently identified regardless of vehicle class, or driving venue. They are 'UL-flexed' (upper limb flexed), 'LL-flexed' (lower limb flexed), and 'Extended', with each representing a distinct postural strategy adopted by drivers. In particular, the third cluster (Extended) corresponded to the driving postures of younger individuals regardless of vehicle class, indicating that when designing a driver workspace the upper boundary posture should represent those of tall, younger drivers adopting this strategy. In contrast, the demographic compositions of the other two clusters exhibited inconsistency across two vehicle classes, indicating that the interior geometry and/or parts might influence which postural strategy drivers employ. Indeed, inconsistency in postural strategies was observed within an individual driver (i.e., only one-third of drivers adopted one strategy, whereas the rest used two or three strategies). Hence, not all three clusters identified for each vehicle class were clearly divided by demographical variables (age, gender, stature). Rather, the first two clusters were composed of mixed populations, though between the first two strategies, UL-flexed was more frequently adopted by short individuals (47 and 48% of the total dataset for sedan and SUV, respectively), and LL-flexed by tall individuals (46 and 50%).

The main usage of the postural strategies identified in this study is in improving the driver workspace design. If each strategy is considered in driver workspace design process, several important ergonomic attributes can be changed. For example, each strategy can be used to more accurately estimate a driver's seating location and eye location (usually those of a DHM) within the driver workspace. This also results in changes in other major ergonomic quality check points with respect to visibility, hand reach, and roominess. Hence, applying the strategies identified in this study will help design a more ergonomically sound driver workspace.

More general interpretation and application of the current findings are also possible. For example, Faraway (1997)'s quadratic regression model predicts joint angles over time, and includes a term to explain demographic variability in human posture. The current result (i.e., the existence of different strategies) supports that his model might predict driving posture more accurately by including additional terms to account for variability due to postural strategies and effects of vehicle factors (e.g., interior geometry). As identified in this study, drivers' standard posture to interact with a vehicle (i.e., to steer the wheel, control the pedals, and initiate other reaching movements) can be categorized into three strategies. Therefore, the trajectory estimator for driving postures (terminal postures of initial reaching movements) should have three versions, each accounting for each postural strategy, in order to make its estimation more accurate and predict movements more similar to actual driver behaviors. More generally, if these clustering-based strategies are incorporated into the current motion generating algorithms / frameworks such as the memory-based motion simulation by Park et al. (2004) or the motion framework by Reed et al. (2006; Figure 6), the simulated motions of people may be more accurate, and closer to those of actual individuals. The current study identified three strategies in the driving context. Burgess-Limerick (2003) suggested three strategies (i.e., squat, stoop, and freestyle) for manual lifting. Using human posture and motion data partitioned by inherent strategies is expected to reduce errors when predicting human postures and motions, as each partitioned data always has less variability than the entire data. In other words, this strategy-based approach will decompose the variability inherent in human postures and motions, and will provide more homogeneous datasets to the relevant prediction method.

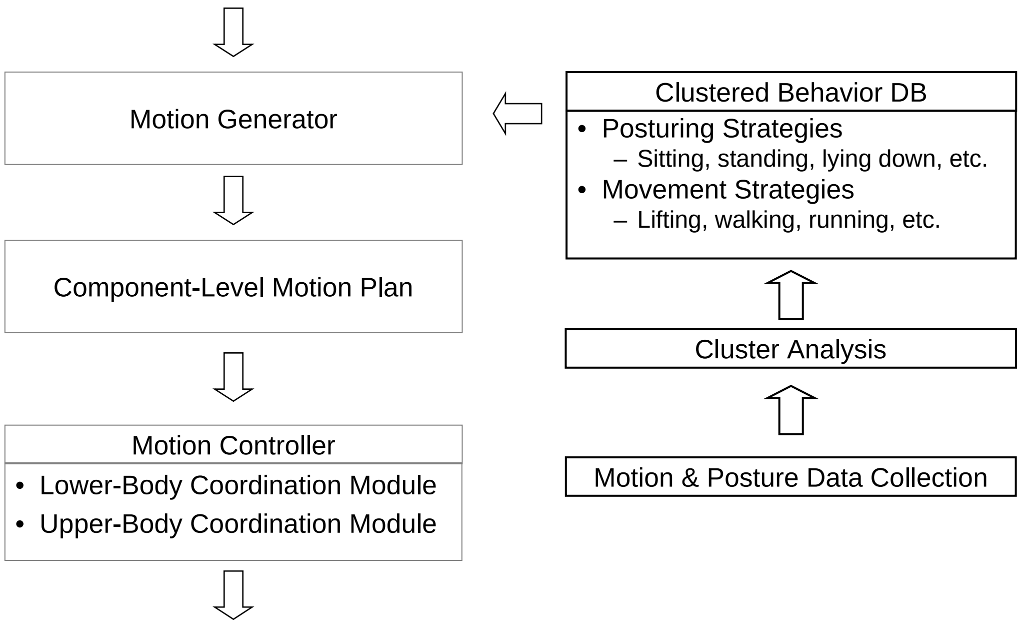


Figure 80. Generalized and revised integrative motion framework (Left side - components of Reed et al. (2006)'s model; Right side - new components

In addition, the driving posture of a DHM specified by each postural strategy should be bilaterally asymmetric for further accuracy and improved workspace design. Though driving postures have been usually assumed bilaterally symmetric by many existing studies on driving postures (Bubb, 1992; DIN, 1981; Dupuis, 1983; HdE, 1989; Park et al., 2000; Porter and Gyi, 1998; Rebiffé, 1969; Reed et al., 2002; Vogt et al., 2005), other recent studies (Chapter 7; Hanson et al., 2006) have showed different results. Considering close relationships between bilateral sides in balance and movement of the whole body, even in a seated posture within a confined driver workspace, the asymmetry of driving postures should be taken into account when specifying driving postures and designing driver workspace.

In addition to the bilateral asymmetry of driving posture in terms of joint angles, there appears to be bilateral imbalance in driving postures. Using interface pressure, a study in Chapter 3 revealed that compared to the right buttock, higher average (peak) pressure and ratio (local to global) were found at drivers' left buttock, indicating that drivers tend to lean toward their left side (in addition to backward leaning). Andreoni et al. (2002) also found a higher peak pressure in a drivers' left buttock. The former authors conjectured that these unbalanced postures were adopted to facilitate the movement of the right foot for controlling pedals, and proposed an asymmetric design for the rear seat cushion area in contact with drivers' buttocks, in order to better support these leftward lean driving postures and ultimately to make the seat more comfortable for drivers. As such, when designing and assessing the driving workspace using DHMs, more sophisticated driving postures based on actual drivers' behaviors should be used in order to ensure valid design and evaluation.

Due to the exploratory nature of cluster analysis, the final number of clusters is somewhat arbitrarily chosen (Hair and Black, 2000). As three postural strategies have been determined by visually examining each clustered dendrogram (Figures 75 and 77), it is still arguable that a different number of clusters can be selected. In both vehicle classes, the third cluster ('Extended') was the most dissimilar (distal) to the other two, and joined the remaining clusters last when the one-cluster solution has been made at the end. If one would like to have two clusters (= two postural strategies), this two-cluster solution is 'Flexed' and 'Extended'. However, this 'Flexed' strategy should be divided again into two groups when positioning DHMs, as the current study showed that the first two clusters were mutually exclusive (i.e., one subgroup had their lower limb(s) flexed, and the other subgroup had their upper limb(s) flexed, but neither group had both upper and lower limbs flexed at the same time). Therefore, the minimally required number of postural strategies appears to be three, which is the choice of this study.

There are some potential limitations in the current study. Three postural strategies were identified for sedans and SUVs, but those for other vehicle classes (e.g., sports car, van, truck, bus) have not been investigated. Prior to cluster analysis, the perception-based data filtering procedure proposed in Chapter 7 to remove uncomfortable joint angles has not been used. Hence, the postural strategies identified in this study do not necessarily represent those for ‘comfortable’ driving postures, but rather for ‘preferred’ driving postures, which are more likely observed in the current cars. In addition, driving postures were obtained after 20 minutes of driving. Hence, it is necessary to explore whether long-term driving postures would be categorized into the same or similar postural strategies. It would also be interesting to investigate whether long-term driving postures can be categorized into static and dynamic sitting strategies, which were previously identified among 2-hr seated office workers (Beach et al., 2005).

5. Conclusions

Using empirical data, three drivers’ postural strategies were identified for two respective vehicle classes. Simple as it appears to be, a driving posture represents one of three distinct interactive techniques. The findings are expected to facilitate DHM-based driver workspace design and evaluation and to increase accuracy in prediction of driving postures. To further generalize the findings of the current study, a larger scale of experiment in terms of participants’ number and ethnicity, vehicle class, and driving duration is warranted. Given that simple driving postures have three distinct strategies, this strategy-based motion-classification method is expected to be very useful when predicting more complex human motions such as drivers’ ingress/egress and reaching motions, and those in manual material handling.

Chapter 9: Conclusions

1. Scope and limitations

The experiments included in this work were performed in both laboratory and field settings (except Chapter 5) to increase the validity of experimental results. However, not all vehicle classes and corresponding seats were considered; only two seats from each of two vehicle classes (sedan and SUV) were used. Also, this work focused on short-term driving duration to investigate sitting comfort / discomfort of non-professional drivers. To investigate the feeling to the level of fatigue, at least one-hour driving duration is required, which is more relevant to professional drivers' sitting experience. Perceptual responses, pressure measures, and postures were all obtained after 20 minutes of real or simulated driving. Hence, it remains to be explored whether the results from long-term driving differ from those in the short-term, and to incorporate any temporal differences into vehicle design. Comparable results for other vehicle classes (e.g., sports car, van, truck, and bus) and corresponding car seats should be addressed in future work.

While many effects were significant, substantial variability remained in the subjective ratings. Such variability indicates that there are other important factors affecting the subjective responses that are yet to be determined. In addition, gender-confounded stature groups, aesthetic effects from other car parts except the seats, and participants' historical driving experiences might have affected the subjective responses. These issues may limit the generality of the relationships between subjective and objective measures reported in this work. Specific seats used in the experiments represent an additional limitation.

Besides sitting comfort / discomfort, a driver's perceptions can be affected by several other factors (e.g., ambient factors, personal factors), but the scope of this study was limited to the quantification of comfort, discomfort, interface pressure, and joint angles. For driving posture, only sagittal plane angles were used in this study, yet non-sagittal body movements (e.g., abduction, adduction, supination, and pronation) should be considered in order to more precisely position DHMs in a 3D design space. Physiological measures were not used in order to minimize intrusiveness of measuring tasks and their potential effect on subjective ratings. Though partially taken into account, cultural factors should be investigated more intensively by considering a broader range of cultural groups and additional measurements. Similarly, though important, psychosocial perceptions were not considered. Other objective data analysis techniques were not included, such as SEAT and VDV, though these are traditionally used as objective measure for discomfort induced by vibration.

2. Validation of Zhang et al. (1996)'s hypothetical comfort/discomfort model

All data regarding perceived comfort and discomfort (a total of 6480 observations) collected in this work were compiled (Figure 81) in order to compare these responses with the comfort / discomfort model proposed by Zhang et al. (1996). Excepting two apparent outliers, the compiled data appeared to support their model; for both the model and experimental data, a clear inverted 'L-shaped' region is apparent. However, there was a more rapid, and sharper transition between comfort and discomfort in the experimental values compared to the model. In the experimental data, perceived discomfort ranged from 0 to -9, while perceived comfort encompassed the entire range of the comfort scale (i.e., 0 to 10). Only 79 data points (1.2%) had a discomfort level < -5 (i.e., strong or more severe discomfort). Up to the levels of 4 (in the case of comfort) and -4 (discomfort), both comfort and discomfort coexisted at levels corresponding to 'somewhat strong feeling' for both perceptions. Thirty seven percent of the data points (2377/6480) had non-zero values (i.e., not located either on the x axis or on the y axis), indicating that the participants perceived both comfort and discomfort simultaneously about one-third of the time when they rated their driving posture.

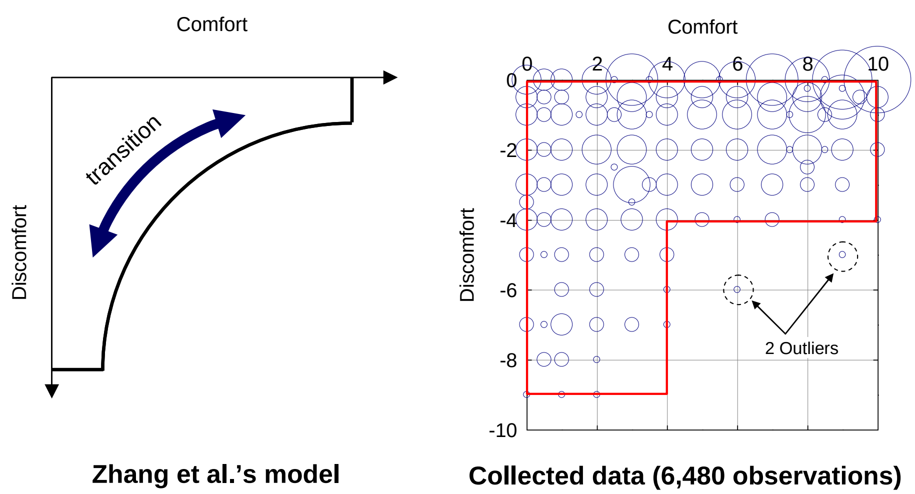


Figure 81. Validation of Zhang et al. (1996)'s model

3. Major outcomes

Three categories of major findings have been identified. The first part of this work investigated drivers' perceptions in relation to driver workspace design and evaluation. Results showed that, regardless of driver attributes, comfort ratings were found to be effective at distinguishing among interface designs. When relating local to global perceptions, the same processes were apparent among a range of individuals (i.e., global comfort as an average of local comforts, and global discomfort predominantly influenced by maximal local discomforts). Alertness was found to be strongly correlated with comfort, whereas seat aesthetic effects on perceptual responses were minimal. A scheme for the use of perceptual ratings was suggested: discomfort ratings for ensuring basic design requirements (pain prevention-oriented) and comfort ratings for promoting advanced design requirements (pleasure promotion-oriented). In addition, this work provided empirical support for an earlier hypothetical comfort/discomfort model which posited these two perceptions as complementary, yet independent entities.

Some differences between age groups and cultural groups were also identified with regard to perceptual responses to driving experiences. The younger North American group reported a better driving experience in sedans than in SUVs, whereas the older North American group perceived experience in SUVs better. In addition, whole body discomfort levels were largely affected by lower back discomfort in the case of the younger group, whereas by upper back discomfort in the case of the older group. Differences between two younger cultural groups were minimal except that the North American group reported a better driving experience in sedans, whereas the Korean group showed no difference, and that the latter group reported more discomfort.

The second part of this work clarified the relationships between perceptual ratings and various types of driver-seat interface pressure. Results showed that interface pressure was more strongly related with overall and comfort ratings than with discomfort ratings. Specific pressure requirements to achieve comfortable seat design were recommended: 1) lower pressure ratios at the buttocks and higher pressure ratio at the back, and 2) bilaterally and superior-inferiorly balanced pressure. Additionally, ranges of most pressure measures were found to be substantially different between driving venues (mostly due to different vibration doses), between age groups (due to differences in preferred driving postures), and between bilateral sides of seats (due to bilateral imbalance of the driving postures), indicating the need of different pressure specifications according to each of these factors.

Lastly, this work specified more rigorous driving postures for digital human models (DHMs). Several behavioral characteristics of drivers were observed and applied to workspace design. With respect to drivers' postural sensitivity, several locations for the hip joint center of driving posture were found to be perceptually equivalent, yet with distinct distributions by driver attributes. Using derived equal comfort contour maps for driving postures, core seat track ranges for two vehicle classes were determined. Reviews of some industry standards (i.e., SAE recommended practices) relevant to driver accommodation showed the need for revisions. Drivers' static behavior (i.e., driving posture), described by 16 joint angles, was found to be bilaterally asymmetric, in contrast to the general assumption made in many existing studies. Driving postures were also distinct between vehicle classes, venues, and by driver attributes. A subset of preferred postural ranges was identified using a filtering mechanism that ensured desired levels of postural perceptions to be associated with the standard driving posture used for the workspace design. In addition, drivers were found to use three distinct postural strategies to interact with automobiles. These strategies can be used to increase accuracy in prediction of driving postures.

These similarities and differences between individuals with different attributes should be carefully considered when designing and evaluating driver workspace. Overall, several important characteristics identified in this work (i.e., bilateral imbalance in terms of interface pressure, bilaterally asymmetric joint posture, and postural strategies identified by cluster analysis) can be embedded in digital human models for proactive design and evaluation, which will provide cost/time-efficient, ergonomic automobile design.

4. Expected contributions

This work will contribute to expanding scientific knowledge on driver perceptions and behaviors in a driver workspace, and serve as an integrated methodology for improving driver-vehicle interface design. Practical and fundamental findings of this work will facilitate designing an improved (e.g., more usable, comfortable, and healthier) driver workspace in an efficient and proactive way (i.e., using DHMs), and will provide a healthier and comfortable driving experience for a broader range of individuals. Improved driver-vehicle interface is expected to provide the following potential benefits: reduction of driver distraction induced by uncomfortable interior design, easier focus on the driving task, better driving performance, and safer and more satisfactory driving experience.

5. Future work

Though diverse types of perceptual responses were employed here, other types can be additionally used to measure workspace design quality (e.g., satisfaction, and fatigue for long-term driving). Workload involved in driving task can be measured using NASA-TLX (Hart and Staveland, 1988), SWAT (Reid et al., 1982), and Cooper Harper Scale (Harper et al., 1966). Drivers' situation awareness can be measured using Global Assessment Technique (SAGAT; Endsley, 1988) and Situation Awareness Control Room Inventory (SACRI; Hogg et al., 1995). Similarly, other objective measures can also be used to relate drivers' perception to design, including trajectory of center of pressure (COP). To generalize the findings in this study further, a larger scale experiment is required, which should include the middle-age group, other cultural groups, other vehicle classes, and longer-term driving sessions. Further investigation is needed to determine whether there is a difference between age or cultural groups in terms of perceptual sensitivity. Methods used in this work to determine which perceptions are effective at distinguishing among designs, and to determine their association with users' behaviors and objective measures, are expected to be more broadly applicable when designing and improving any types of human-machine systems (e.g., medical devices, and pilot-cockpit interfaces). Finally, the strategy-based motion-classification method used in this work may be useful to simulate and predict more complex human motions such as drivers' ingress/egress, reaching, and those involved in general manual material handling.

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Appendix A: Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
in Research Projects Involving Human Subjects

Title of Project: User-centered Vehicle Development (Proposal #: 06-0338-08)

Investigator(s): Dr. Maury Nussbaum, Dr. Kari Babski-Reeves, and Gyouhyung Kyung

I. Purpose

The purpose of this project is to determine subjective and objective comfort/discomfort levels related to driving postures, and to use this data to improve vehicle design. The research will involve observing and analyzing your driving posture and comfort/discomfort levels using several techniques, including questionnaires and hardware-based measurements.

Total 36 subjects without any musculoskeletal diseases or disorders will be involved in this study, and their age will be between 20 and 30, between 35 and 45, or over 60.

II. Procedures

It is important for you to understand that we are not evaluating you or your performance in any way. You are helping us to collect the data required to design better cars. Any tasks you perform, or opinions you have will only help us do a better job of designing cars. Therefore, we ask that you perform normally and be as honest as possible. The information and feedback that you provide is very important to this project. The total experiment time will be approximately 4 hours (1 hour / session).

During the course of this experiment you will be asked to perform the following tasks:

1) Read and sign an Informed Consent Form (this form).
2) Show your valid U.S. driver's license.
3) Measure your stature without shoes.
4) Complete simple vision tests.
5) Participate in four driving sessions as described below.
6) Fill out a set of questionnaires at the end of each driving session.

There will be four driving sessions (two in the field and the other two in the lab). In the field session, you are going to drive two cars (a compact sedan and a compact SUV) on a predetermined route, which will start from, end at the Durham Hall on the VT campus and encompass nearby Blacksburg areas. In the lab session using a driving workplace rig, which can be adjusted to have the same package space with either of two experiment cars, you are going to simulate a driving task according to a videotaped driving scene. The lab session will be held in 529, Whittemore Hall (Industrial Ergonomics and Biomechanics Lab) on the campus. In either session, you will make adjustments of interior parts as you like (e.g. select a seat position, seat back angle, and steering wheel angle) without any control of investigator, and then will drive for a short period of time (minimum 20 minutes). After the driving, you need to maintain your driving posture while it is measured by one of investigators. Two objective measures will be gathered for your driving posture. The first is the positions of your body landmarks measured by a coordinate measuring machine, which will be used later to determine your joint angles, and the second is pressure distribution data of your body measured by two pressure mats which will be place on the seat pan and seat back all the time. Finally, you will rate your comfort/discomfort levels and driving posture using questionnaires provided. Before any measures are taken, there can be photographing of your driving posture as a supplemental measure. Some of body landmarks (especially around the hip) may need to be located by you according to guidance of the investigator. In addition, there will be a calibration session where you need to take a posture other than the driving posture to better locate joint locations. In the lab session, a sensitivity analysis of your driving posture will additionally be investigated by adjusting the seat positions by the investigator. The presentation order of the two sessions and two cars will be randomized, and a minimum restriction on the driving posture will be applied when the objective measures are taken (i.e. both hands on the wheel and the right foot on the gas pedal).

III. Risks and Benefits

There are minimal risks to you as a participant in this study as follows.

1) The risk of an accident normally associated with driving an unfamiliar automobile.
2) Possible fatigue due to the length of the experiment. However, you may take rest breaks at any time during the experimental session.
3) A slightly different contact feeling on your legs and back due to the pressure mats which might slightly affect your driving task.

The short driving session in the field will expose you to the risk that is expected in normal driving. During driving in the field, however, nothing will be observed or monitored.

The following precautions will be taken to ensure minimal risk to you.

1) You will be encouraged and reminded to abide by all traffic regulations.
2) You will be required to wear the safety belt restraint system while in the car.
3) In the event of a medical emergency, ISE staff will arrange medical transportation to a nearby hospital emergency room.
4) Upon request, in order for you to be familiar with the field route, the investigator can give a tour of the route before the experiment.

In the event of an accident or injury in an automobile, the automobile liability coverage for property damage and personal injury is provided. The total policy amount per occurrence is $2,000,000. This coverage (unless the other party was at fault, which would mean all expenses would go to the insurer of the other party’s vehicle) would apply in case of an accident for all volunteers and would cover medical expenses up to the policy limit.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation. Under Commonwealth of Virginia law, workers compensation does not apply to volunteers; therefore, if not in an automobile, the participants are responsible for their own medical insurance for bodily injury. Appropriate health insurance is strongly recommended to cover these types of expenses.

This research project will help quantify the driver's comfort levels leading to the development of more comfortable cars that will benefit the general driving population. While this research should yield benefits as stated, no promise or guarantee of benefits has been made to encourage you to participate. You may contact the investigators listed at the end of this consent form to inquire about the results and conclusions of this research.

IV. Extent of Anonymity and Confidentiality

Your personal information and identity will be kept in the strictest of confidence. No names will appear on questionnaires or surveys, and a coding system will be used to associate your identity with questionnaire answers and data. The list associating names with answers will be destroyed one month after completion of data collection. Photographing might occur for assisting in the assessment of participant's driving posture. However, any images used in documentation will have your face blacked out to maintain confidentiality. All information will be collected in a file and locked when not being used, and only the investigators have access to the data. It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

V. Informed Consent

You will receive two informed consent forms to be signed before beginning the experiment; one for your record and one for the experimenter's record.

VI. Compensation

You will be compensated for your participation at a rate of $10 per hour. You will be paid at the end of this study in cash.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations without penalty. If you choose to withdraw while you are driving on the field route, please inform the experimenter of this decision and he/she will provide you with transportation back to the building. There may be circumstances under which the investigator may determine that the experiment should not be continued. In this case, you will be compensated for the portion of the project completed.

VIII. Approval of Research
The Department of Industrial and Systems Engineering has approved this research, as well as the Institutional Review Board (IRB) for Research Involving Human Participants at Virginia Tech.

IX. Participant's Acknowledgments

Check in the box if the statement is true:

- ☐ I have U.S citizenship.
- ☐ I have a valid U.S. driver's license.
- ☐ I have a normal or corrected normal eye vision.
- ☐ I have at least 2-years of driving experience.
- ☐ I am not under the influence of alcohol.
- ☐ I don't have any musculoskeletal diseases or disorders.

X. Participant's Responsibilities
I voluntarily agree to participate in this study. I have the following responsibilities:

1. To read and understand the aforementioned instructions
2. To answer questions, surveys, etc. honestly and to the best of my ability
3. To drive as naturally as possible under each of the experimental conditions
4. To obey all the traffic regulations during the field driving
5. To openly discuss (vocalize) any comforts or discomforts I experience during or in between driving tasks at the moment I experience them
6. Be aware that I am free to ask questions at any point time
7. To refrain from discussing any details of this experiment with others

XI. Participant's Permission
I have read and understand the Informed Consent and conditions of this research project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I reserve the right to withdraw at any time without penalty. I agree to abide by the responsibilities noted above, to the best of my ability, or to inform the investigators if I am unable to comply with these.

____

Participant's Signature Date

____

Experimenter's Signature Date

Signature Page

I have read the description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate with the understanding that I may discontinue participation at any time if I choose to do so.

____

Participant's Signature Date

____

Printed Name

The research team for this experiment includes Dr. Nussbaum, Dr. Babski-Reeves, and Gyouhyung Kyung. Team members may be contacted at the following address and phone number:

Dr. Maury A. Nussbaum
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250 Durham Hall
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(540) 231-6053

Dr. Kari L. Babski-Reeves
Assistant Professor, Ph.D.
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250 Durham Hall
Blacksburg, VA 24061
(540) 231-9093

Gyouhyung Kyung
Ph.D. Candidate
Department of ISE
519K Whittemore Hall
Blacksburg, VA 24061
(540) 922-3010

* ISE: Industrial and Systems Engineering

In addition, if you have any detailed questions regarding your rights as participant in University Research, you may contact the following individual:

Dr. David Moore
Chair, Virginia Tech Institutional Review Board
for the Protection of Human Subjects
Office of Research Compliance
1880 Pratt Drive, Suite 2006 (0497)
Blacksburg, VA 24061
(540) 231-4991

Appendix B: J.D. Power and Associates' Comfort Scores

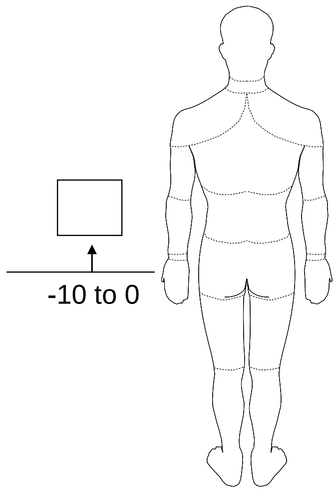
Type	Vehicle Name	2001	2002	2003	2004	2005
Sedan	**S1***	3	**-**	**4**	**4**	**4**
	S2*	3	3	**2**	**2**	**2**
	Ford Focus	3	3	3	2	5
	Saturn Ion	-	-	3	2	3
	Kia Rio	2	2	2	2	2
	Honda Civic	3	3	3	2	4
	Hyundai Accent	2	2	2	2	3
	Hyundai Elantra	3	3	3	3	4
SUV	**U1***	**-**	**-**	**4**	**4**	**4**
	U2*	**2**	**2**	**2**	3	3
	Hyundai Santafe	3	4	4	4	4
	Honda CR-V	2	5	3	4	4
	Kia Sportage	2	2	-	-	5
	Chevy Blazer	2	2	2	2	2
	Chevy Trailblazer	-	2	2	2	2
	Jeep Liberty	-	3	2	2	2

*: Vehicles selected for experiments - Data source: www.cars.com (accessed Dec/2005)

Appendix C: Questionnaire

C.1 Whole Body Discomfort

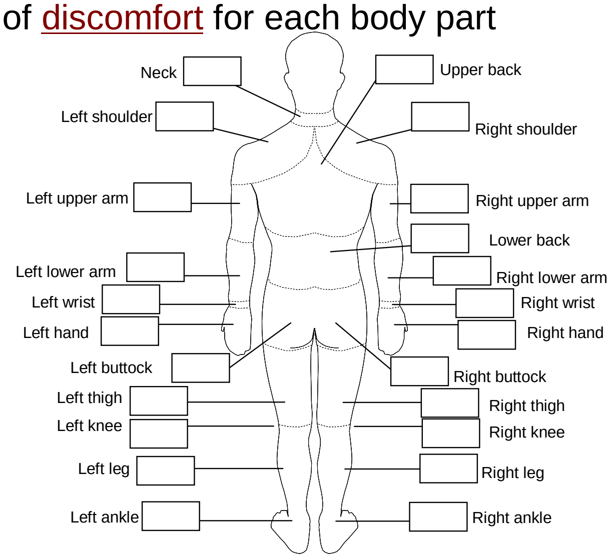
Please, assign a number (-10 to 0) corresponding to your sense of discomfort for your whole body



0 : No discomfort
-0.5: Extremely weak (Just noticeable)
-1 : Very weak
-2 : Weak
-3 : Moderate
-4 : Somewhat strong
-5 : Strong
-6
-7 : Very strong
-8
-9
-10 : Extremely strong discomfort

C.2 Local Body Part Discomfort

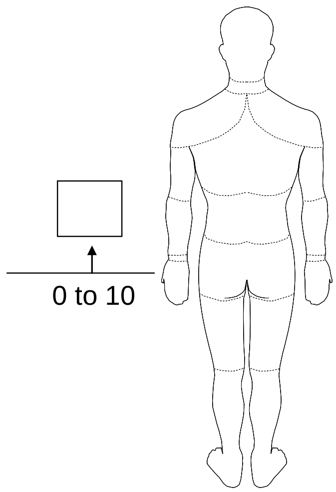
Please, assign a number (-10 to 0) corresponding to your sense of discomfort for each body part



0 : No discomfort
-0.5: Extremely weak (Just noticeable)
-1 : Very weak
-2 : Weak
-3 : Moderate
-4 : Somewhat strong
-5 : Strong
-6
-7 : Very strong
-8
-9
-10 : Extremely strong discomfort

C.3 Whole Body Comfort

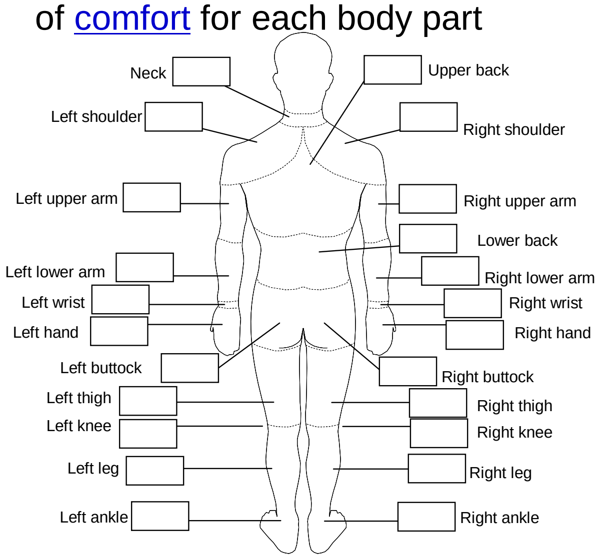
Please, assign a number (0 to 10) corresponding to your sense of comfort for your whole body



0 : No comfort
0.5: Extremely weak
(Just noticeable)
1 : Very weak
2 : Weak
3 : Moderate
4 : Somewhat strong
5 : Strong
6
7 : Very strong
8
9
10 : Extremely strong comfort

C.4 Local Body Part Comfort

Please, assign a number (0 to 10) corresponding to your sense of comfort for each body part



0 : No comfort
0.5: Extremely weak
(Just noticeable)
1 : Very weak
2 : Weak
3 : Moderate
4 : Somewhat strong
5 : Strong
6
7 : Very strong
8
9
10 : Extremely strong comfort

C.5 Overall Posture Rating

- Please, rate your driving posture (0 to 100)

0 : The worst driving posture that I can imagine
With regards to my driving posture, I felt no comfort at all, and felt extremely strong discomfort

100: The best driving posture that I can imagine
With regards to my driving posture, I felt no discomfort at all, and felt extremely strong comfort

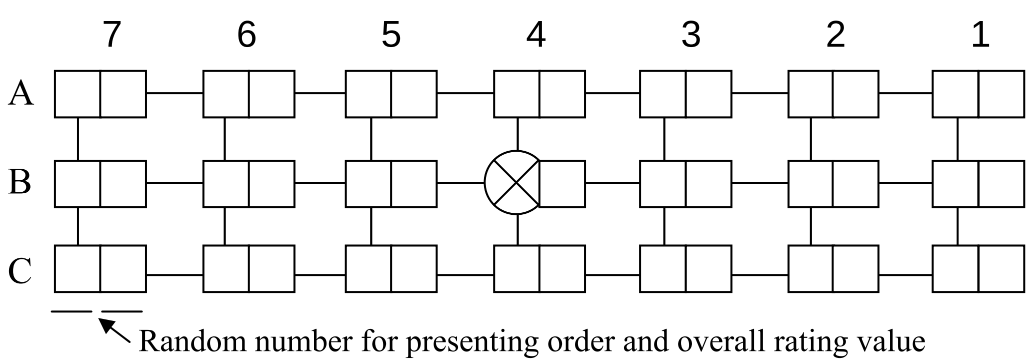
Overall Posture Rating: [ ]

C.6 Alertness Level (Horne and Reyner, 1995)

Please, rate your expected level of alertness (1 to 10).
If in this driving posture for a long period (more than 1 hour),
I am expected to be

1 : extremely alert
2 : very alert
3 : alert
4 : rather alert
5 : neither alert nor sleepy
6 : some signs of sleepiness
7 : sleepy, no effort to stay awake
8 : sleepy, some effort to stay awake
9 : very sleepy, great effort to keep awake, fighting sleep
10: extremely sleepy, can't keep awake

C.7 Sensitivity Analysis



C.8 Seat Design Preference

Based solely on the appearance, the comfort quality of the seat would be

5: Among the best
4: Better than most
3: About average
2: Below average