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# Seat-cushion and soft-tissue material modeling and a finite element investigation of the seating comfort for passenger-vehicle occupants

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A B S T R A C T

Improved seating comfort is an important factor that most car manufacturers use to distinguish their products from those of their competitors. In today's automotive engineering practice, however, design and development of new, more comfortable car seats is based almost entirely on empiricism, legacy knowledge and extensive, time-consuming and costly prototyping and experimental/field testing. To help accelerate and economize the design/development process of more-comfortable car seats, more extensive use of various computer aided engineering (CAE) tools will be necessary. However, before the CAE tools can be used more successfully by car-seat manufacturers, issues associated with the availability of realistic computer models for the seated human, the seat and the seated-human/seat interactions as well as with the establishment of objective seating-comfort quantifying parameters must be resolved.

In the present work, detailed finite element models of a prototypical car seat and of a seated human are developed and used in the investigation of seated-human/seat interactions and the resulting seating comfort. To obtain a fairly realistic model for the human, a moderately detailed skeletal model containing 16 bone assemblies and 15 joints has been combined with an equally detailed "*skin*" model of the human. The intersection between the two models was then used to define the muscular portion of the human. Special attention in the present work has been given to realistically representing/modeling the materials present in different sections of the car seat and the seated human. The models developed in the present work are validated by comparing the computational results related to the pressure distribution over the seated-human/seat interface with their open-literature counterparts obtained in experimental studies involving human subjects.



## 1. Introduction

Today, in the industrialized world, sitting is the most common working posture and perhaps the most frequent leisure posture. It is well-recognized that constrained sitting postures can lead to discomfort and health disorders (e.g. back, neck and shoulder pain, etc.) which translates into a major cost to society through missed work and reduced work-effectiveness/productivity [1]. Consequently, furniture manufacturers and car-seats manufacturers are forced to more aggressively address seating ergonomics in order to gain a competitive edge. In the automotive industry, the ever increasing customer demand for vehicles with improved performance has been complimented by an equally strong demand for vehicles with improved comfort. As a result, vehicle manufacturers use car-seat/interior comfort as an important selling point and a way to distinguish themselves from their competitors. (Vehicle seats and the comfort level they can offer to the seated individual are the subject of the present work.) The current state of the car-seat manufacturing industry is such that development and introduction of new, more-comfortable car seats is based almost entirely on empiricism, legacy knowledge and extensive, time-consuming and costly prototyping and experimental/field testing.

Considering the fact that Computer Aided Engineering (CAE) has made major contribution and has become a indispensible tool to many industries, one should expect that CAE should be used more aggressively by the car-seat manufacturing industry in order to address the issue of seating comfort. That is, the use of computer models of a human and seat, and the analysis of their interactions could facilitate, accelerate and economize the process of development and introduction of new, more comfortable car seats. Specifically, in the early stages of the seat-design process, a new design can be tested for its degree of comfort by carrying out computer simulations of the seated-human interactions with the seat. However, before these computer simulations can become reliable, high-fidelity seating-comfort assessment tools, a critical problem of identifying/defining the objectives and measurable comfort-quantifying parameters/measures and the establishment of their

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correlation with the subjective feeling of comfort has to be solved. Among the comfort-quantifying parameters, the ones most frequently cited are: (a) the average human/seat contact pressure; (b) the maximum human/seat contact pressure; (c) the human/seat contact-area size and (d) the extent of symmetry of the human/seat contact-area [2–14]. All of these comfort-quantifying parameters are based on measurements of the distribution of human/seat contact pressure over the contact area and these measurements commonly suffer from several limitations, e.g. [15,16]: (a) they are relatively difficult to perform reproducibly and with high accuracy; (b) the obtained contact-pressure distributions do not provide any information about internal stresses and deformations of the human soft tissues and (c) the contact pressure distributions measured provide only information about the normal stresses at the contact human/seat interface whereas it is well established that significant shear stresses can be present at the human/seat interface, e.g. [17–22]. In addition, the contact-pressure distribution-measurement approach has major deficiencies in its ability (or total lack thereof) to provide information about the level of muscular activity and about the magnitude of joint forces, two quantities which are certainly related to the seating comfort.

To address some of the shortcomings of the contact-pressure distribution-measurement approach, various human-body/seat coupled computer models and computational analyses were proposed. For example, a finite-element based modeling approach was introduced by Verver et al. [23] and a rigid-body mechanical based model was suggested by Langford et al. [24], etc. While these approaches were able to provide estimates for some of the parameters that are either difficult or impossible to obtain via direct measurements, so far however, it has not been possible to create a model that can calculate how muscular activity and joint forces are affected by changes in sitting conditions. The main reason for this is that the human body, in general, and its muscular and skeletal systems, specifically, are quite challenging mechanical systems to model.

To address the limitations of the seating-comfort assessment computer modeling schemes mentioned above, the AnyBody Research Group [25] at Aalborg University in Denmark in collaboration with three furniture manufacturers recently initiated a research project entitled "*The Seated Human*". The main objective of this project is to define a set of seating-comfort design criteria for chairs and to devise the means (based on rigorous computer modeling of the human musculoskeletal system) for reliable assessment of these criteria. Within the project, the recently-developed novel technology for computer modeling of the human-body mechanics and dynamics, namely the AnyBody Modeling System [25] and its associated public domain library of body models are being fully utilized and further developed. In its most recent rendition [26], the AnyBody Modeling System enables creation of a detailed computer model for a human body (including all important components of the musculoskeletal system) as well as examination of the influence of different postures and the environment on the internal joint forces and muscle activity.

The earliest public-domain report related to the human body in a seated posture can be traced back to the pioneering analytical investigation conducted by Mandal [27,28] who used simple physics-based reasoning in place of the traditional empirical and subjective approaches. The main outcome of Mandal's work was that it is beneficial from the spinal-loads reduction point of view to reduce the pelvic rotation (i.e. flexion between the pelvis and the thorax) below a normal value of $90^o$ in the seated-human posture (by tilting the seat-pan forward and/or the backrest backward). In a recent multi-body dynamics based work carried out by Rasmussen et al. [29–32] it was shown that forward seat-pan inclination indeed can reduce the spinal-joint loads. However, forward seat-pan inclination was also found to increase the maximum muscle activity (i.e. muscle fatigue) unless sufficient friction is present at the human-buttocks/seat interface in which case its spinal-joint load-reduction beneficial effect diminishes and is replaced with an comfort-compromising/harmful effect of inducing shear forces in the human soft tissue.

While the work of Rasmussen et al. [29–32] has made major contributions to the field of seating comfort/discomfort, it has also revealed some of the limitations of the multi-body dynamics musculoskeletal approach with respect to modeling the interactions between the seated human and the seat. Simply stated, while the multi-body dynamics approach can in general capture the overall magnitudes of normal and shear interaction forces between the seated human and the seat, the distribution of the forces over the contact interface and their penetration into the human soft tissue could not be addressed. It appears clear that further progress in the area of seating-comfort modeling and simulation will come through additional advances in both the multi-body dynamics musculoskeletal and finite-element analyses of the seated-human/seat interactions and by finding ways to cooperatively and interactively engage these two modeling/simulation approaches.

The main purpose of the present work is to introduce a fairly detailed finite-element model for a seated human and for a generic car seat and to carry out a preliminary computational finite element analysis of the seated-human/seat interactions in order to help identify the factors which affect seating comfort/discomfort. A review of the literature carried out as part of the present work revealed several finite-element models of the seated human. However, all these models suffer from one or more serious limitations such as: (a) over-simplification of the geometry of the skeletal and/or muscular portions of the model [16,19,33–35]. As explained before, the maximum human/seat contact pressure and its distribution are related to the seating comfort. It is well-established that the maximum contact pressure occurs under the *ischial tuberosities* and for a finite-element model to correctly predict the location of the maximum contact pressure it must provide an accurate geometrical description of the skeletal system of the human body; (b) excessive coarseness of the finite-element mesh used in order to reduce the computational cost [36–38] which yields to less accurate computational results and (c) geometrical details of the skeletal and the muscular systems are obtained from different sources and they are somewhat inconsistent [39].

## 2. Modeling and computational procedures

### 2.1. Finite element model of the car seat

A generic car-seat finite element model was constructed within this work, Fig. 1. First, a solid-geometrical model was developed using CATIA V5, a CAD computer program [40]. Then, the CAD model was pre-processed using HyperMesh, a general purpose analysis pre-processing software [41] to construct a meshed model with all the required sections, materials, joints, initial and boundary condition definitions.

The car-seat model comprised five shell components (foot-rest, seat-base, seat-pan back-face, back-rest back-face and head-rest back-face) and three solid components (seat-pan, back-rest and head-rest), Fig. 1. The shell components were meshed using 3,220 three-node first-order shell finite elements while the solid sections were discretized using 21,200 four-node first-order tetrahedron solid finite elements.

The shell sections of the car seat were constructed using low-carbon steel with a Young's modulus of 210 GPa and a Poisson's ratio of 0.3. Since the loading experienced by the seat is solely caused by the weight of the seat occupant, and is hence not excessively high, plasticity of the steel components of the seat was not considered.