International Journal of Industrial Ergonomics 40 (2010) 345–355

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Musculoskeletal computational analysis of the influence of car-seat design/adjustments on long-distance driving fatigue

M. Grujicic [a,*], B. Pandurangan [a], X. Xie [a], A.K. Gramopadhye [b], D. Wagner [c], M. Ozen [c]

[a] Department of Mechanical Engineering, Clemson University, 241 Engineering Innovation Building, Clemson, SC 29634-0921, USA
[b] Department of Industrial Engineering, Clemson University, Clemson, SC 29634, USA
[c] Ozen Engg., Inc., 1210 E. Arques Avenue, Suite: 207, Sunnyvale, CA 94085, USA

ARTICLE INFO

Article history:
Received 13 April 2009
Received in revised form
2 November 2009
Accepted 14 January 2010
Available online 1 February 2010

Keywords:
Biomechanics
Musculoskeletal modeling
Driver fatigue
Back-rest inclination
Friction
Lumbar support

ABSTRACT

The main causes for long-distance driving fatigue experienced by vehicle drivers are investigated computationally using musculoskeletal modeling and simulation methods. A rigid-body model of a prototypical adjustable car seat is constructed as a part of the present work and combined with a public-domain musculoskeletal model of a seated human. Seated-human/car-seat interactions associated with typical seating postures of the vehicle driver are analyzed using the inverse-dynamics approach while the "*minimum-fatigue*" criterion is utilized to deal with the muscle redundancy problem (i.e., with the problem that human-body contains more muscles than what would be typically needed to drive various body joints).

The results obtained show that various seat adjustments (e.g., back-rest inclination, seat-pan horizontal track position, etc.), driver's back supports (e.g., presence/absence of lumbar support) and the nature of seat upholstery (e.g., fabric vs. vinyl) can have complex influence on the muscle activation, joint forces, soft-tissue contact normal and shear stresses, all of which not only affect the comfort perception of the driver but also their feel of fatigue. Subsequently, the results of the present work along with relevant public-domain literature findings (e.g., subjective driving-fatigue assessments provided by human test subjects and human-body/seat contact-force measurements) are used to construct a preliminary long-distance driving-fatigue function.

Relevance to industry: it is argued that the computer-aided engineering analysis introduced in the present work should help speed-up the design of new high-comfort car seats. These seats are currently being mainly designed using empiricism, legacy knowledge and extensive, time-consuming and costly prototyping and experimental/field testing.

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 pain, neck–shoulder complaints, etc.) causing a major cost to the society through missed work and reduced work-effectiveness/productivity (Johansen and Johren, 2002). Consequently, furniture manufacturers and car-seats manufacturers are forced to more aggressively address seat ergonomics in order to gain a competitive edge. In the automotive industry, the ever increasing demand by the customers for vehicles with improved performance has been complemented 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. Car seats and their role in the subjective perception of long-distance driving fatigue is the subject of the present work. The state of the car-seat manufacturing industry today is that the 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 an indispensible tool for 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 human and seat and the analysis of their interactions could facilitate, speed-up and economize the process of development and introduction of new, more-comfortable car

* Corresponding author. Tel.: +1 864 656 5639; fax: +1 864 656 4435.
E-mail address: mica.grujicic@ces.clemson.edu (M. Grujicic).

0169-8141/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.ergon.2010.01.002

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 relations with the subjective feeling of comfort/fatigue 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 (Bluthner et al., 2008; Ebe and Griffin, 2001; Inagaki et al., 2000; Ippili et al., 2008; Kamijo et al., 1982; Lee et al., 1995; Milvojevich et al., 2000; Park and Kim, 1997; Park et al., 1998; Reed et al., 1991; Tewari and Prasad, 2000; Thakurta et al., 1995; Uenishi et al., 2000; Yun et al., 1992; Zhao et al., 1994; Siefert et al., 2008; Kyung et al., 2008; Kyung and Nussbaum, 2008; Nag et al., 2008; Mehta et al., 2008). All 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., Bader and Bowder, 1980, Oomens et al., 2003) (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; (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., Bader and Bowder, 1980; Bennett et al., 1979; Chow and Odell, 1978; Krouskop et al., 1990; Reichel, 1958; Scales, 1982). In addition, a major deficiency of the contact-pressure distribution-measurement approach is that it does not provide any information about the level of muscular activity and about the magnitude of joint forces, two quantities which are certainly related to the seating comfort and fatigue perception.

To address some of the limitations of the contact-pressure distribution-measurement-approach, various human-body/seat coupled computer models and computational analyses have been proposed. For example, a finite-element based modeling approach was introduced by Verver (Verver et al., 2004), a rigid-body mechanics based model was suggested by Langsfeld (Langsfeld et al., 2000), 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 (AnyBody Technology A/S, 2008) at Aalborg University in Denmark in collaboration with three furniture manufacturers initiated recently 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 (AnyBody Technology A/S, 2008) and its associated public-domain library of body models are being fully utilized and further developed. In its most recent rendition (Damsgaard et al., 2006), the AnyBody Modeling System enables creation of a detailed computer model for the 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 (Mandal, 1984, 1987) 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° in the seated-human posture (by tilting the seat-pan forward and/or the back-rest backward). Moreover, in a recent work carried out by Rasmussen et al. (Karlsson et al., 2007; Rasmussen et al., 2007, 2009; Rasmussen and de Zee, 2008) it was shown that forward seat-pan inclination indeed reduces the spinal-joint loads. However, it may also 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.

The main objective of the present work is to explore the capabilities of the AnyBody Modeling System in predicting the aspects of human-body/car-seat interactions which affect car-driver fatigue during long-distance driving and to device a long-distance driving-fatigue function. The issue of long-distance driving-induced fatigue in drivers was addressed by Michida (Michida et al., 2001) using laboratory and on-road tests. These tests involved subjective evaluations of fatigue provided by human test subjects as well as objective measurements obtained using contact-pressure sensor-array mats and non-invasive electromyography (EMG, a muscle-activity measuring technique). The results obtained by Michida et al. (Michida et al., 2001) can be summarized as follows:

(a) While the interactions between human-body and the car-seat-pan could contribute to seating discomfort via contact shear stresses (can in general lead to soft-tissue trauma) and via normal contact pressures, the interactions between the car-driver's back and seat back-rest tend to play a critical role in increasing long-distance driving fatigue;
(b) In general, three main back/back-rest contact conditions were identified which are conducive to long-distance driving fatigue: (i) insufficient lumbar support; (ii) insufficient thorax support and (iii) excessive thorax support; and
(c) As will be discussed in greater detail in Section 3, the aforementioned three driving-fatigue-controlling factors can be related to the kinematics of pelvis and lumbar and thoracic regions of the spine and with the required activities of the muscles to maintain the most comfortable seating posture.

The organization of the paper is as follows. A brief overview of the AnyBody Modeling System is provided in Section 2.1. The musculoskeletal human-body model, the concepts of muscle recruitment and muscle-activity envelope, the car-seat model and the issues related to seated-human/car-seat kinematics and contact interactions are discussed in Sections 2.2–2.6. The definition of the problem analyzed in the present work is discussed in Section 2.7. The results obtained in the present work are presented and discussed in Section 3. A discussion of the driving fatigue-relevant public-domain literature and the formulation of a preliminary long-distance driving-fatigue function are presented in Section 4. The main conclusions resulting from the present work are summarized in Section 5.

2. Material and methods

2.1. The AnyBody Modeling System (AnyBody Technology A/S, 2008)

The AnyBody Modeling System (AnyBody Technology A/S, 2008) developed at Aalborg University and used in the present work is a general-purpose musculoskeletal modeling and simulation program. The essential features of this computer program can be summarized as follows:

(a) The musculoskeletal model is typically constructed as a standard multi-body dynamics model consisting of rigid bodies, kinematic joints, kinematic drivers and force/moment actuators (i.e., muscles) which can be solved using standard multi-body dynamics simulation methods;
(b) Complex geometries of the muscles and their spatial arrangement/interactions (e.g., muscles wrapping around other muscles, bones, ligaments, etc.) can be readily modeled within AnyBody Modeling System (AnyBody Technology A/S, 2008);
(c) It is well-established that a typical musculoskeletal system suffers from the so-called "*muscle redundancy problem*": i.e., the number of muscles available is generally larger than those needed to drive various body joints. Within the living humans and animals, this problem is handled by their Central Nervous System (CNS) which controls muscles activation/recruitment. To mimic this role of the CNS, the AnyBody Modeling System (AnyBody Technology A/S, 2008)] offers the choice of several optimization-based muscle-recruitment criteria;
(d) A typical musculoskeletal multi-body dynamics problem is solved using computationally-efficient inverse-dynamics methods within which the desired motion is prescribed while the muscle activity required to produce this motion is computed;
(e) Within the AnyBody Modeling System (AnyBody Technology A/S, 2008), the muscle-recruitment problem is solved using an optimization-based approach in the form:

Minimize the objective function:

$$G\left(f^{(\mathrm{M})}\right) \tag{1}$$

Subjected to the following constraints:

$$Cf = d \tag{2}$$

$$f_i^{(\mathrm{M})} \geq 0, \quad i \in \left\{1, \ldots, n^{(\mathrm{M})}\right\} \tag{3}$$

where the objective function G (a scalar function of the vector of $n^{(\mathrm{M})}$ unknown muscle forces, $f^{(\mathrm{M})}$), defines the minimization object of the selected muscle-recruitment criterion (assumed to mimic the one used by the CNS). Eq. (2) defines the condition for dynamic mechanical equilibrium where C is the coefficient matrix for the "*unknown*" forces/moments in the system while d is a vector of the "*known*" (applied or inertia) forces. The forces appearing in vector f in Eq. (2) include the unknown muscle forces, $f^{(\mathrm{M})}$, and the joint reaction forces, $f^{(\mathrm{R})}$. Eq. (3) simply states that muscles can only pull (not push) and that the upper bound for the force in each muscle $f_i^{(\mathrm{M})}$ is the corresponding muscle strength, N_i;

(f) While there are a number of functional forms for the objective function, G, the one most frequently used is the so-called "min/max" form within which the objective function (to be minimized) is defined as the maximum muscle activity defined for each muscle i as $f_i^{(M)}/N_i$; i.e.,:

$$G\left(f^{(\mathrm{M})}\right) = \max\left(f_i^{(\mathrm{M})}/N_i\right); \tag{4}$$

This formulation offers several numerical advantages over other popular forms of G and, in addition, it appears to be physiologically sound. That is, under the assumption that muscle fatigue is directly proportional to its activity, Eqs. (1) and (4) essentially state that muscle recruitment is based on a minimum muscle-fatigue criterion;

(g) The problem defined by Eqs. (1)–(4) can be linearized using the so-called "*bound formulation*" (Dendorfer and Torholm, 2008) resulting in a linear programming problem with muscle forces and joint reaction forces as free variables. Relations between these two types of forces are next used to eliminate the joint reaction forces yielding a linear programming problem with the number of unknowns equal to the number of muscles in the system; and
(h) While for a fairly detailed full-body model containing around one thousand muscles, this constitutes a medium-to-large size problem which can be readily solved by a variety of design-optimization methods (e.g., Simplex, Interior-point methods, etc.), the min/max problem is inherently indeterminate and must be solved iteratively. This can be rationalized as follows: The min/max criterion only deals with the maximally-activated muscles and with muscles which help support the maximally-activated muscles. Since the system, in general, may contain muscles that have no influence on the maximum muscle activity in the system, the forces in these muscles are left undetermined by the min/max formulation presented above. To overcome this shortcoming, the muscle-recruitment optimization problem is solved iteratively, so that each iteration eliminates the muscles with uniquely determined forces and the procedure is repeated until all muscle forces are determined.

2.2. Musculoskeletal human-body model

The musculoskeletal model of the human-body used in the present work was downloaded from the public-domain AnyScript Model Repository (AnyScript Model Repository 7.1, 2009; AnyBody Technology A/S, 2008) (Fig. 2). The model was originally constructed by AnyBody Technology using the AnyBody Modeling System (AnyBody Technology A/S, 2008) following the procedure described in details by Damsgaard (Damsgaard et al., 2006).

2.2.1. Model taxonomy

A detailed description of taxonomy of the human-body model used in the present work was recently reviewed by Grujicic (Grujicic et al., 2009). Hence, the relevant details pertaining to the human-body taxonomy will not be repeated. It should be mentioned however that the human-body model includes all the essential elements of the skeletal system and more than 500 individual muscle units. Hence, it can be considered as a fairly detailed description of the human musculoskeletal system.

2.2.2. Model validations

The mechanics of the model is implemented as a full three-dimensional Cartesian formulation and includes inertial body forces (in the static problem under consideration, only gravity inertial forces are present). Integral validation of whole-body musculoskeletal models is very difficult to conduct. To the best knowledge of the present authors, validation of the whole-body musculoskeletal model is still lacking (due to major challenges which would be associated with such validation).

2.3. The muscle-activity envelope

As originally recognized by An (An et al., 1984), the min/max muscle-recruitment formulation, discussed in Section 2.1, defines effectively a *minimum fatigue criterion* as the basis for muscle recruitment, i.e., the aim of the proposed muscle-recruitment strategy is to postpone fatigue of the "*hardest-working*" muscle(s) as far as possible. The physiological consequence of this strategy is that muscles tend to form groups with muscles within the same group having comparable activity levels. In particular, in the muscle group associated with the maximum muscle activity there will be usually many muscles which, in a coordinated manner, carry a portion of the load comparable with their individual strengths. Consequently, in this group, many muscles will have the same activity level, which will be referred to as *"the muscle-activity envelope*". The linearity of the reformulated min/max criterion discussed earlier guarantees that the optimization problem defined by Eqs. (1)–(3), is convex and, hence, that the solution to the problem is unique and corresponds to the global optimum. In other words, there is no other muscle-recruitment strategy which can reduce the muscle-activity envelope further. Moreover, since the muscle-activity envelope represents the maximum muscle activation in the model, it can be interpreted as the fraction of maximum voluntary contraction necessary to support the imposed load (gravity in the present case) while maintaining the prescribed posture. Thus, the muscle-activity envelope appears to be an important parameter/measure for ergonomic-design optimization, in the sense that designs which are associated with lower envelope levels may be perceived as less fatigue-inducing.

2.4. Car-seat model

A rigid-body model of a prototypical seat is developed for use in the present work, Fig. 1. The car-seat model comprises of the following rigid bodies: head-rest, back-rest, seat-pan, leg-rest and the foot-rest. Revolute joints were used to enable back-rest and seat-pan inclination angle adjustment and a prismatic joint was used for seat longitudinal-track position adjustment.

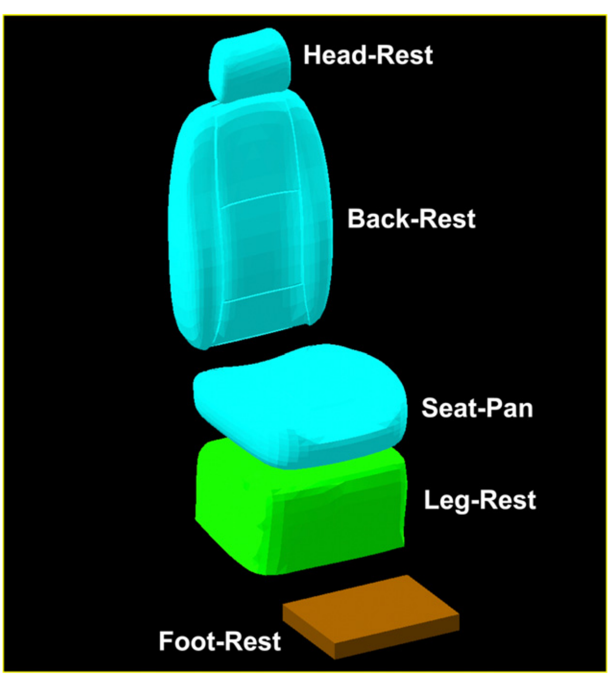

Fig. 1. Rigid-body model for the car seat used in the present work.

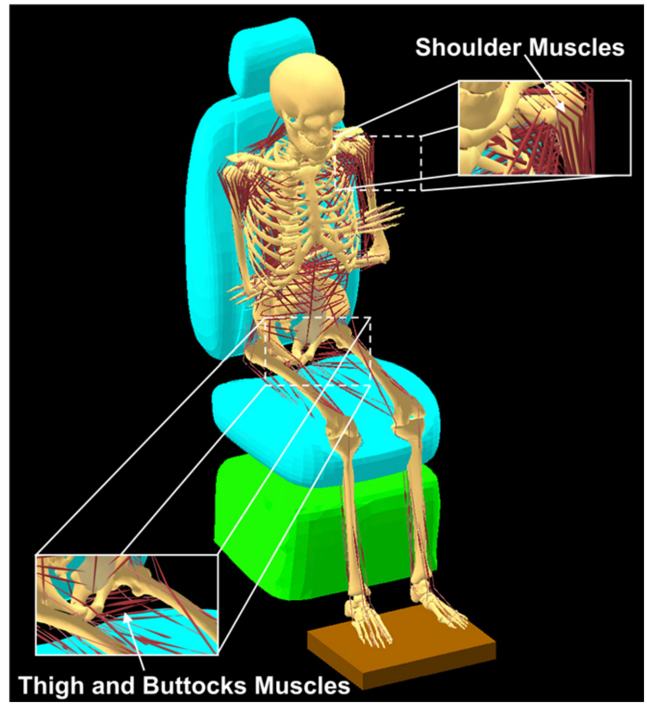

Fig. 2. The musculoskeletal model of a human sitting in the car seat developed in the present work.

To obtain the desired posture of the human for a given adjusted configuration of the car seat (linear and angular) kinematic links were placed at the seated-human/seat contact interfaces (at the back-rest and at the seat-pan). However, these links were not allowed to transmit any forces/moments. As will be discussed below, human-body/car-seat contact forces have been accounted for through the use of "*support points*".

2.5. Seated-human/car-seat kinematics

As mentioned above, the car-seat can be adjusted, as needed, by assigning proper values to the car-seat joint degrees of freedom. Due to the presence of the human-body/car-seat kinematic links, the human-body acquires the appropriate seating posture for each given set of car-seat adjustments. In the process of acquiring the appropriate seating posture, kinematics of the spine is adjusted in accordance with the so-called "*spinal-rhythm*" algorithm. Within this algorithm, a single input, the pelvis–thorax angle, is used to determine the three rotational-joint angles of adjacent vertebrae (under a condition that the passive-elastic elements of the spine are able to force the spine to act kinematically as an elastic beam). The physical soundness of the spinal-rhythm algorithm for the seating posture has been validated by Rasmussen and de Zee using motion capture experiments (Rasmussen et al., 2009).

In acquiring the seated position for the human, an additional algorithm was employed. This algorithm controls the relative magnitudes of hip flexion and pelvis/thorax flexion. Following the experiments of Bell and Stigant (Bell and Stigant, 2007), the ratio of the two angles was set to 2. That is, for a given value of the angle between the thorax and the thigh, the hip-joint flexion angle is twice that of the spine flexion angle.

2.6. Seated-human/car-seat contact interactions

To quantify the extent of and to account for the distributed nature of the human-body/car-seat contact interactions, a number of support points are introduced over the back-rest, seat-pan and the foot-rest surfaces. These support points allow the transfer of reaction forces to the car-seat support elements. To quantify the contact reaction forces at the support points, the so-called "*supporting elements*" are used which can provide compressive reaction forces, R_i, (i is the support-element number) and tangential/friction forces, F_{fi}, (the maximum values of which is μR_i, where μ is the (input) friction coefficient). It should be noted that the compressive reaction forces are perpendicular to the support surfaces while tangential force can be in any direction perpendicular to the corresponding compressive force.

The reaction forces R_i and F_{fi} are unknown for a given seating posture and must be determined. However, due to the fact that a large number of support points was added in order to assess the distribution of contact forces over the seated-body/car-seat contact interfaces, the problem is made statically indeterminate and the solution cannot be obtained by simply solving the mechanical equilibrium equations. To overcome this problem, the unknown contact forces, R_i , are normalized using a large value of the "*artificial-muscle*" strength, N_i, and added to the vector of unknown forces f_i in Eq.(2). The seated-human/car-seat contact forces are then obtained by invoking the same muscle-recruitment algorithm discussed in Section 2.1. This approach, thus, treats the human-body/car-seat contact problem as follows: (a) the human-body is postulated to use the available support points at the back-rest, seat-pan and the foot-rest to minimize its muscle activity and (b) by choosing a large value of the artificial-muscle strength, the supporting elements are prevented from dominating the anatomic-muscle-recruitment process.

2.7. Problem definition

To analyze long-distance driving fatigue, the human-body model reviewed in Section 2.2 is first placed in the car seat described in Section 2.4. Two additional environment segments are then added, one representing the brake pedal/accelerator assembly while the other representing the steering column. Then the human-body was repositioned in accordance with a typical posture associated with vehicle driving. This involved placing the driver's hands on the steering wheel, positioning of his right foot on the accelerator pedal while having his left foot resting on the foot-rest/vehicle-floor. In addition, neck flexion was adjusted to ensure straight-forward vision of the driver. A typical driving posture used in the present work is displayed in Fig. 3(a) and (b). To improve clarity, human-body muscles are not shown in Fig. 3(a) and (b). To mimic the reaction moment experienced by the driver's right foot during the act of acceleration, a 20 N m contact moment is applied to the right-foot/accelerator pedal revolute joint. Where applicable, to account for the presence/absence of lumbar support, the support points on the lumbar section of the spine were added/removed accordingly.

3. Results and discussion

In this section, the main results obtained in the present work are presented and discussed. First, the "*reference-case*" is considered and the key metrics related to long-distance driving fatigue are introduced. Then, several parametric studies are performed within which the effects of key driver/seat kinematic and interaction parameters (e.g., seat-back inclination angle, back-rest/seat-pan upholstery-controlled friction coefficient, seat-pan track/longitudinal position, and the absence/presence of lumbar support) are investigated.

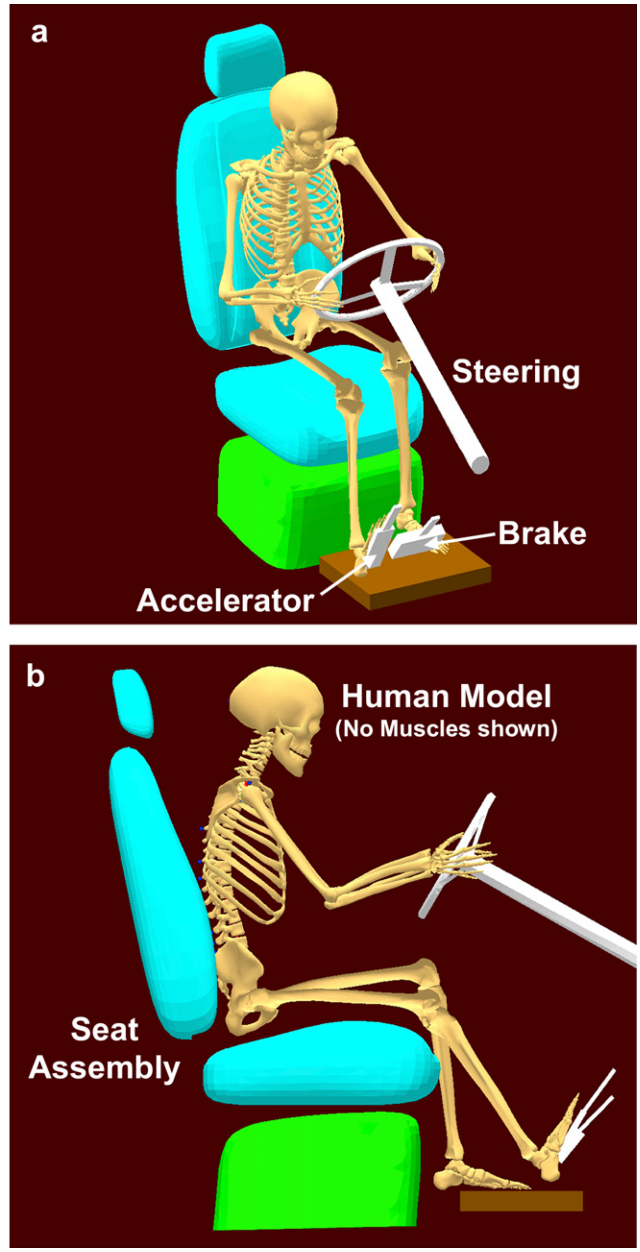

Fig. 3. (a) Isometric and (b) side-view of the car-driver-seat assembly.

3.1. The reference case

Within the reference case, the following driver/seat kinematic/interaction parameters are used: back-rest (backward) inclination angle = 10°; seat-height = 600 mm (relative to the foot-rest); human-body/car-seat friction coefficient = 0.5 (corresponds to a typical value associated with woven wool- or cotton-based fabric seat upholstery); seat-pan track position = 830 mm (corresponds to the distance between the driver's right heel and the driver's right hip); and lumbar support is used.

An example of the results of the present musculoskeletal computational analysis of long-distance driving comfort and fatigue for the reference case is displayed in Fig. 4. In this figure, the extent of actuation of the various muscles is displayed pictorially by the extent of their bulging. Furthermore, muscle groups associated with the largest levels of activation are identified and the typical range of activation is indicated. It is seen that the following three

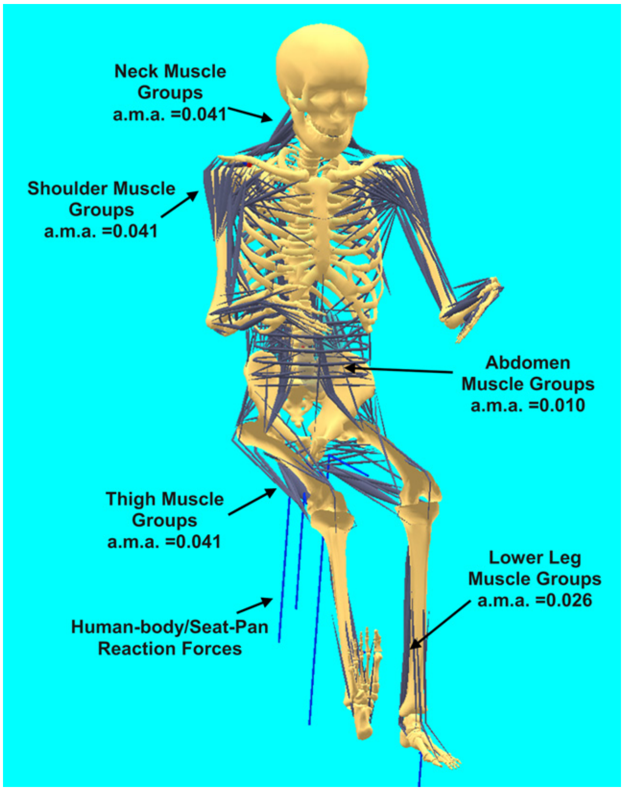

Fig. 4. Muscle groups with the largest values of the average muscle activity (a.m.a.) for the reference case of the driver/car-seat interaction model.

muscle groups are associated with the largest extent of muscle activity (i.e., that the following three muscle groups define the muscle-activity envelope): (a) the *Corachobrachialis*, the *Deltoid* and the *Scapular* muscles located in the forearm/shoulder region; (b) the *Scalene*, the *Infraspinatus*, the *Supraspinatus* neck muscles; and (c) the *Semimembranosus* and the *Rectus Femoris* thigh muscles (all with an average activity of 0.041). The next two groups of highly-activated muscles are the *Soleus* muscles (average activity: 0.026), found in the lower legs and the *Rectus Abdominis* and the *Oblique* muscles found in the abdomen regions, associated with significantly lower levels of activation (average activity: 0.010).

It is well documented that in addition to the activity of the muscles, long-distance driving discomfort and fatigue are affected by shear contact forces present at the human-buttocks/seat-pan interface. In the reference case considered in this section, the total shear contact force was evaluated as 292 N.

When seating discomfort and the associated fatigue are investigated experimentally (e.g., (Verver et al., 2004)) or analyzed computationally using the finite-element method (Grujicic et al., 2009), the maximum contact pressure is found at the human-buttocks/seat-pan and thigh/seat-pan interfaces. As expected earlier, a number of support points were used to model driver/seat contact interactions. Since these points were fairly equally spaced, one can assume that the maximum normal contact force is a good representation of the maximum contact pressure. In the reference case, this force was found to be 615 N.

While it is not fully agreed that the magnitude of the intradiscal compressive forces in the spine contribute to long-distance driving fatigue, their detrimental effect on the spine health is well-established (Frankel and Nordin, 1980). For comparison with the other cases studied in the present work, the intradiscal compressive force between the fourth and the fifth lumbar vertebrae was computed for reference case and found to be ca. 331 N. It is also well-established (Frankel and Nordin, 1980) that intradiscal spine loads are generally higher in the seating posture than in the corresponding standing posture due to the forward rotation of the pelvis around the pelvis/lumbar joints, Fig. 5(a) and (b).

3.2. The effect of back-rest inclination

As mentioned earlier, the (backward) back-rest inclination angle was set to 10° in the reference case. In this section, the effect of

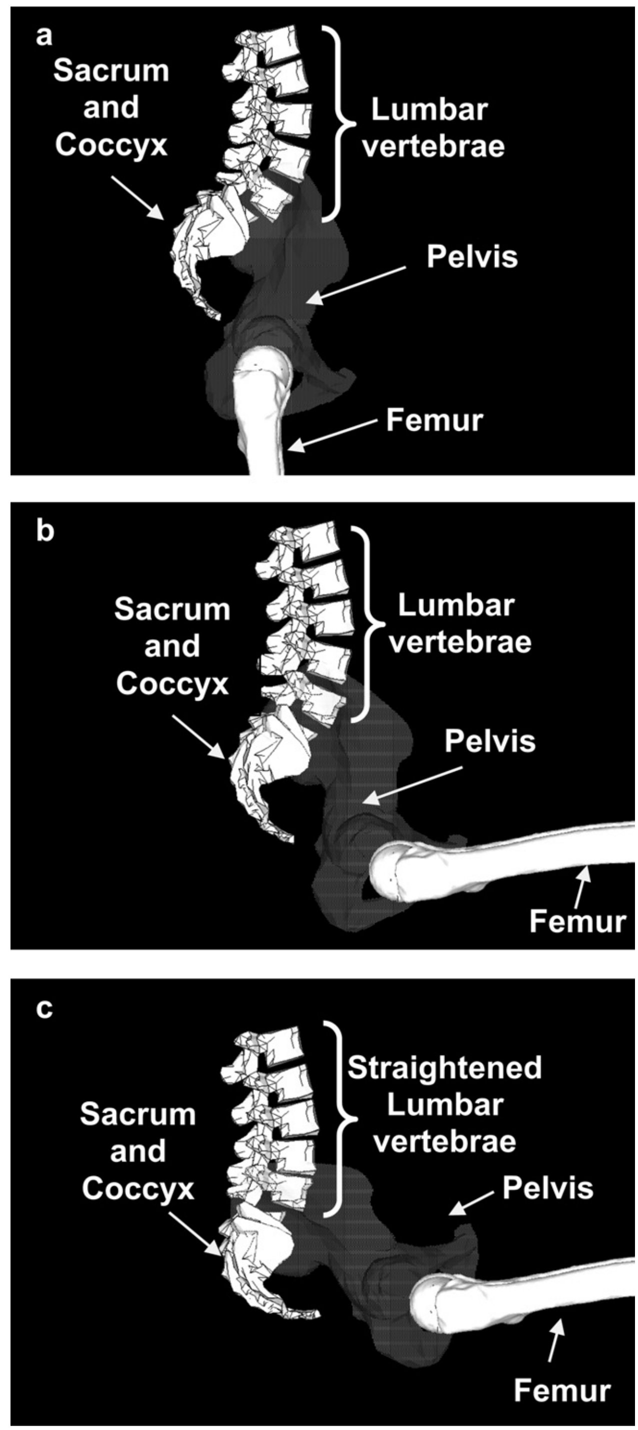

Fig. 5. Evaluation of the kinematics of the human-body pelvis region with a change in posture from: (a) standing to: (b) sitting erect to: (c) sitting in hunch-back posture.

varying the back-rest inclination angle in a 0°–15° range in the increments of 5° is examined.

An example of the results obtained in this portion of the work pertaining to the 0° back-rest-inclination angle is displayed in Fig. 6. The results displayed in this figure show that the following two muscle groups are associated with the highest level of activation: (a) the *Scalene*, the *Infraspinatus*, the *Supraspinatus* neck muscles and (b) the left *Soleus* (lower left leg) muscles all with an average muscle-activity level of ca. 0.041. The next three groups of muscles associated with a high level of muscle activity are: (a) the *Deltoid* (shoulder) muscles with an average activity of ca. 0.035; (b) the *Semimembranosus* and the right *Rectus Femoris* (the lower thigh and the upper thigh muscles, respectively) with an average muscle activity of ca. 0.024; and (c) the *Obliques* and *Rectus Abdominis* (abdomen) muscles with an average muscle activity of ca. 0.010.

A comparison of the results displayed in Figs. 4 and 6 reveals several important findings:

(a) While the muscle-activity envelope has not changed, different three groups of muscles define the envelope, i.e., as the back-rest has been brought into the upright position, the thigh muscle group has been substituted by the lower-leg muscle group in the muscle-activity envelope and the shoulder muscles are no longer on the muscle-activity envelope;
(b) As the back-rest is placed in the straight upright position, and the shoulders get close to the steering wheel, the shoulder muscle activity drops from ca. 0.041 to ca. 0.035. This finding is expected since as the shoulder-to-steering-wheel distance decreases and shoulder flexing lowers the center of gravity of the arms, a lower level of muscle activation is required to retain the imposed kinematic configuration of the arms;
(c) The lower-leg muscles whose activation level in the reference case was ca. 0.026, has increased in the 0° back-rest inclination angle case considerably to ca. 0.041. This finding is also reasonable since as the upper body is taking a more upright posture and less vertical support is provided by the seat back-rest, leg muscles' activity has to increase in order to support the human-body weight; and
(d) The abdominal and neck muscles have retained their levels of muscle activity.

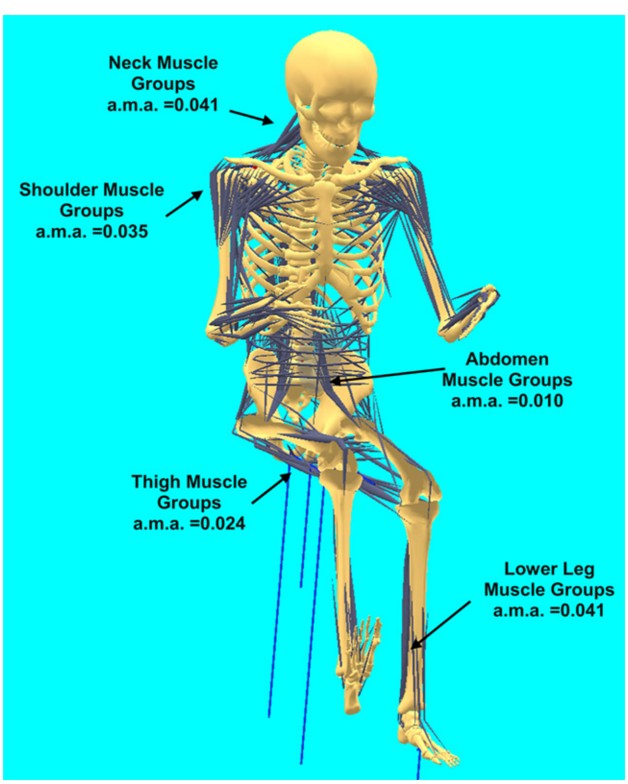

Fig. 6. Muscle groups with the largest values of the average muscle activity (a.m.a.) for the 0° back-rest-inclination angle case of the driver/car-seat interaction model.

The effect of variation of the seat back-rest inclination angle on the average muscle activity of the five muscle groups mentioned above (i.e., neck, shoulder, abdominal, thigh and lower-leg muscle groups) is displayed in Fig. 7(a). The results shown in this figure indicate that, for the most part, the muscle activation changes monotonically with the back-rest inclination angle.

In Fig. 7(b), the effect of variation of the seat-back inclination on the magnitude of the intradiscal L4–L5 compressive force and on the seat-pan/human-buttocks shear force is displayed. The results displayed in Fig. 7(b), which pertain to the effect of seat-back inclination angle on the intradiscal force, are reasonable since as

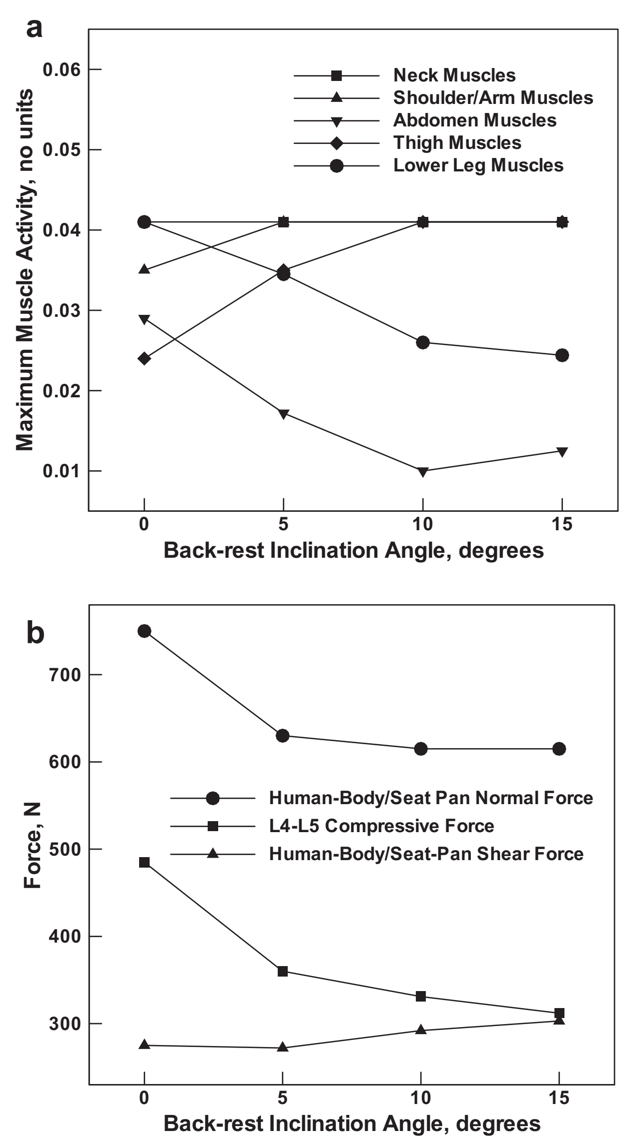

Fig. 7. The effect of variation in the back-rest-inclination angle on: (a) the maximum muscle activity; and (b) the maximum normal and total shear contact forces and the intradiscal L4–L5 compressive forces.

the thorax becomes to lean forward, the line of gravity of the upper-body moves forward and increases the moment which has to be counterbalanced by higher intradiscal forces and higher abdominal muscle activities.

3.3. The effect of friction coefficient

In the reference case, the friction coefficient between the driver and the car seat was set to a value of 0.5 which roughly corresponds to the case of woven wool- or cotton-fabric seat upholstery. Car seats are often equipped with vinyl or leather covering and in these cases the friction coefficient typically takes a significantly lower value (assumed as 0.2, in the present work). In this section, the effect of reduction of the friction coefficient from 0.5 to 0.2 is considered while all other kinematic parameters of the driver and the seat are kept at their reference-case values as defined in Section 2.1.

An example of the results obtained in the present low-friction-coefficient case is displayed in Fig. 8. It is seen that the following four muscle groups define the muscle-activity envelope: (a) the *Infraspinatus*, *Supraspinatus* and *Scalene* (neck) muscles; (b) the *Deltoid*, *Corachobrachialis* and *Scapular* (shoulder) muscles; (c) the *Rectus Abdominis* and *Oblique* (abdominal) muscles; and (d) the *Soleus* (lower leg) muscles, all with an average muscle activity of 0.041. It is also seen that the *Semimembranosus* and *Rectus Femoris* (thigh) muscles display a lower level of muscle activity (muscle activity of 0.023).

A comparison of the results displayed in Figs. 4 and 8 shows that while the muscle-activity envelope has not changed measurably, the muscle groups defining the envelope have changed. That is, the thigh muscles are no longer associated with the highest level of muscle activity (average muscle-activity level = 0.023), while the legs and abdomen muscles have joined the shoulders and the neck muscles as the muscle groups with the highest level of activation (average muscle-activity level = 0.041). This finding is reasonable considering the fact that at a back-rest-inclination angle of 10° and in the presence of a lower value of friction coefficient, the shear/tangential forces originating at the thorax/back-rest interface and propagated to the human-buttocks/seat-pan interface cannot be fully counterbalanced by the friction forces causing the leg and abdomen muscles to be engaged more extensively (in order to prevent the driver from sliding).

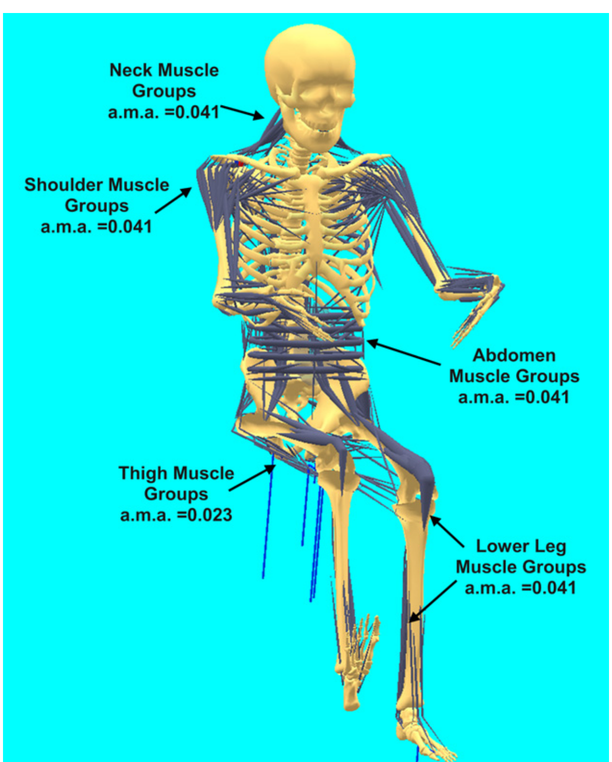

Fig. 8. Muscle groups with the largest values of the average muscle activity (a.m.a.) in the driver/car-seat interaction model for the case of a lower human-body/seat interface friction coefficient.

The human-buttocks/seat-pan total shear force (116 N) is reduced significantly relative to that in the reference case (292 N). This is clearly related to the fact that the maximum tangential force is controlled by the magnitude of the friction coefficient (as well as by the magnitude of the normal force).

Reduction in the friction coefficient from 0.5 to 0.2 has been found to lower the maximum normal contact force by less than 5% relative to that observed in the reference case.

The intradiscal L4–L5 compressive force (345 N) was found to be somewhat higher than that of its reference-case counterpart (331 N). This finding indicates that as the friction coefficient is reduced and lesser support is provided to the thorax by the back-rest, more upper-body weight has to be supported by the spine itself.

3.4. Effect of (front/back) seat track position

In this section, the effect of longitudinal-position adjustment of the seat along the track is considered. Two specific cases are analyzed: (a) forward translation of the seat by 10 cm (no significant differences in the level of activation of the muscle groups analyzed so far or in the magnitudes of the lumbar and shear forces, relative to the reference case are observed); and (b) backward translation of the seat by 10 cm (the results discussed below).

For brevity, no figures will be shown for the 10 cm back-translation case and the key result will only be discussed. Three muscle groups, the shoulder, the neck and the thigh muscles, define the muscle-activity envelope associated with a muscle-activity level of 0.043. This level is somewhat higher than the reference-case level (0.041), and this increase can be attributed to the fact that the steering wheel is farther away (this increases shoulder and neck muscles activity) and since the accelerator pedal is also farther away, lower thigh muscles have to be engaged more extensively to keep the right foot on the accelerator pedal.

One more significant observation was made: the *Erector Spinae* and the *Spinalis* muscle located at the back of the thoracic section of the spine are found to acquire an increased level of activity. This finding can be attributed to the fact that as the arms and the right leg are getting extended, the spine tends to bend to a hunch-back configuration which is supported by the aforementioned thoracic-spine muscles.

The backward translation of the seat by 10 cm has been found to reduce the total shear contact force from 292 N to 254 N. This finding is consistent with the fact that as the spine is becoming to acquire the hunch-back configuration, less contact is expected between the thorax and the back-rest.

The normal force has been found to remain essentially unchanged with the changes in the track position of the seat.

The intradiscal L4–L5 compressive force, on the other hand, is found to increase with the 10 cm backward translation of the seat, from 331 N to 341 N. This increase can be attributed to the effect of lesser support of the thorax by the back-rest in the case of the hunch-back configuration of the spine.

Also, as shown in Fig. 5(c), for the hunch-back configuration of the spine, the forward shift in the upper-body line of gravity is increased significantly which, as mentioned earlier, leads to increased intradiscal forces. Fig. 5(c) also shows that the shape of lumbar-portion of the spine changes (i.e., the lumbar section becomes more straight) which also contributes to an increase in the intradiscal forces.

3.5. The effect of lumbar support

In the reference case, as well as in all other cases analyzed up to this point, lumbar support at the back-rest was used. In this section, the effect of lumbar-support removal is investigated. Again, a complete set of results will be discussed but not shown (for brevity):

An example of the results obtained in the present section is displayed in Fig. 9(a). For comparison, the corresponding results obtained in the reference case are displayed in Fig. 9(b). The comparison of results displayed in Fig. 9(a) and (b) reveals that:

(a) The muscle-activity level corresponding to the muscle-activity envelope has been raised (from 0.041 in the reference case) to 0.058;
(b) Furthermore, two muscle groups define the muscle-activity envelope: (a) the shoulder muscles and (b) the abdomen muscles;
(c) The neck muscle group has retained its muscle activity at the level observed in the reference case (average muscle-activity level of 0.041);
(d) Both the thigh and the leg muscle groups have significantly reduced their level of activity relative to the reference case (0.041–>0.010 and 0.026–>0.010, respectively). This finding is consistent with the fact that as the back-rest support is lowered due to removal of the lumbar support, less shear forces are transferred to the thighs and, in turn, to the legs; and
(e) The level of activity of the muscles in the back of the human-body (supporting the spine) has significantly increased (>0.010) compared to the reference case (<0.005).

The total shear force at the human-body/seat-pan interface has decreased from ca. 252 N in the reference case to ca. 115 N. At the same time, the normal contact force has remained effectively unchanged. As far as the intradiscal L4–L5 compressive force is concerned, it has increased from ca. 373 N in the reference case to ca. 400 N.

4. Discussion

In the introduction section, Section 1, of the present work, it was discussed that the main factors contributing to the long-distance driving fatigue are the maximum level of muscle activity, the magnitude of the driver/car-seat contact total shear force, the maximum contact normal force and the magnitude of intradiscal spine forces (e.g., the intradiscal L4–L5 compressive force). In Section 3, the effect of four driver/car-seat kinematic/interaction parameters (i.e., the back-rest-inclination angle, the friction coefficient, the longitudinal-track seat-position and the presence/absence of lumbar support) on the driving-induced fatigue-controlling parameters was investigated. In the present section, an attempt is made to provide more insight into the problem of long-distance driving fatigue and to set the foundation for future developments of a long-distance driving-fatigue function. Towards that end, available public-domain data pertaining to the subjective input of human test subjects, the contact pressure and EMI measurements will be used.

A review of the public-domain literature showed that there are no driving-induced fatigue functions which can relate the objectively measured or computed driver/seat interaction parameters (e.g., maximum muscle activity, maximum normal contact force, etc.) with the subjective perception of fatigue by the human test subjects. It is interesting to note that Rasmussen and de Zee (Rasmussen and de Zee, 2008) proposed a short-term seating discomfort function, as a linear combination of the squared maximum muscle activity and the squared (properly normalized) total contact shear force. While this function can be a good starting

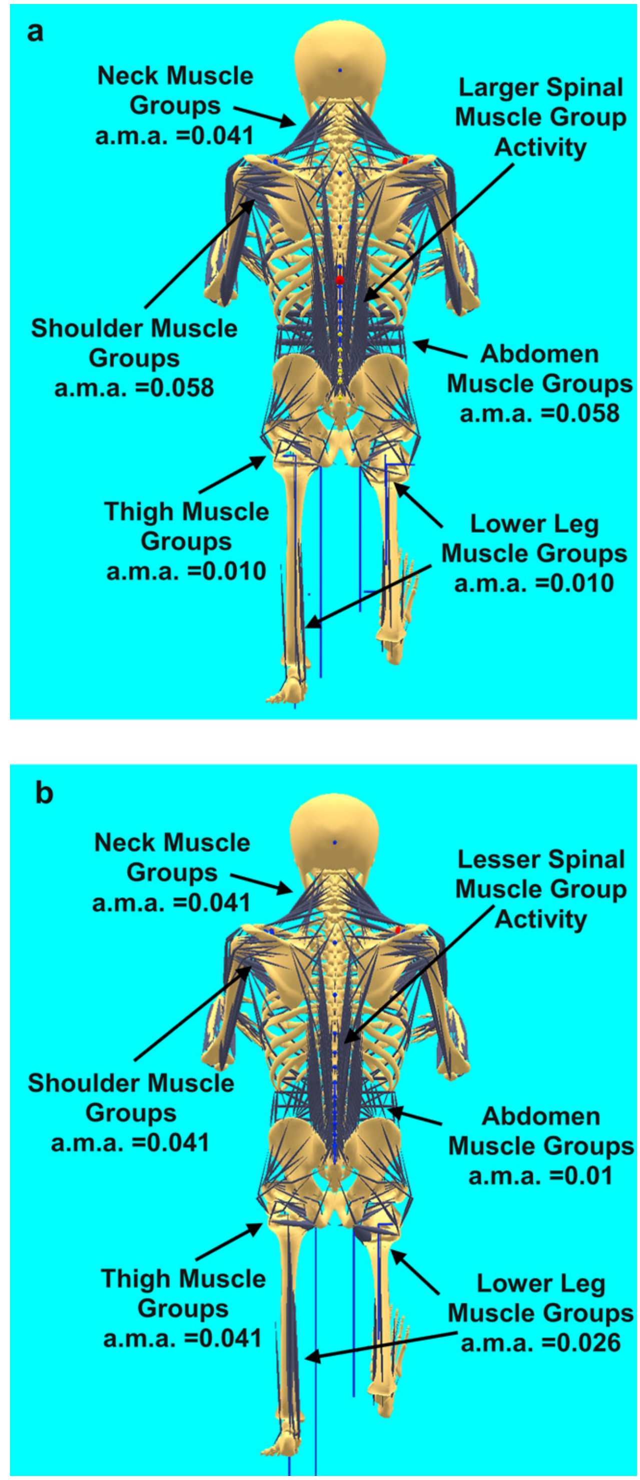

Fig. 9. Muscle groups with the largest values of the average muscle activity (a.m.a.) for: (a) the driver/car-seat configuration without lumbar support; and (b) the reference case.

point in the development of a long-distance driving-fatigue function, one must recognize that fatigue does not only depend on the maximum level of muscle activation but also on the number of muscles or muscle groups associated with the highest level of activation.

The review of public-domain literature further revealed that the long-distance driving-fatigue investigation involving subjective inputs from human test subjects and objective EMI and contact-pressure measurements reported by Michida (Michida et al., 2001) is most closely related to the present work. Hence, a brief summary of the main findings reported by Michida (Michida et al., 2001) is next presented.

The main findings reported by Michida (Michida et al., 2001) can be summarized as follows: (a) Despite significant variations in human test–subjects subjective evaluations, the study clearly established that there are correlations between the perception of fatigue and particular measurable human-body/car-seat kinematics/interaction parameters; (b) The three parameters which were found to most profoundly affect the perception of fatigue were identified as: (i) insufficient support provided by the seat to the lumbar region of the driver's spine, (ii) insufficient thorax support and (iii) excessive thorax support. The three types of supports were quantified via contact-pressure measurements; (c) Furthermore, the study established that depending on the level of support provided by the car seat, the driver test subjects were found to adopt different seating postures. The associated level of muscle activity of different muscle groups were measured and also correlated with the subjective perception of fatigue. Specifically, neck, shoulder, abdomen, thigh, leg and spine muscle groups (i.e., the muscle groups investigated in Section 3 of the present work) were found to be the key contributors to long-distance driving-fatigue perception; (d) Contact normal and shear forces acting on buttocks/thighs were not directly investigated/measured. However, the computational study carried out in Section 3 of the present work clearly established relationships between the back-rest/lumbar-support levels and the effects of normal/shear contact forces; and (e) Intradiscal forces were also not measured since it was assumed that these forces may affect spine health but not play a major role in the fatigue perception. Since this opinion is broadly observed in the literature, it was also adopted in the present work.

Based on the findings obtained in the present work, the overview of the results obtained by Michida (Michida et al., 2001) and other comments made throughout this manuscript, one should expect that the long-distance driving-fatigue function, LDDFF, has the following general form:

$$\mathrm{LDDFF} = \mathrm{func}(\mathrm{CMA}, \mathrm{CNF}, \mathrm{CSF}) \tag{5}$$

where CMA, CNF and CSF denote the cumulative muscle activity, the contact normal force and the contact shear force, respectively. Furthermore, to a first-order of approximation, CMA can be represented by the sum of activity levels of the muscle groups defining the muscle-activity envelope.

To avoid potential complications arising from the fact that CSF could be either positive or negative and that CNF is zero or negative (compressive), Eq. (5) has been rewritten as:

$$\mathrm{LDDFF} = \mathrm{func}\left(\mathrm{CMA}^2, \mathrm{CNF}^2, \mathrm{CSF}^2\right) \tag{6}$$

Since the exact mathematical form for the function "func" is presently not known, the following simple weighted-average form can be used as a starting point:

$$\mathrm{LDDFF} = w_{\mathrm{CMA}}\left(\frac{\mathrm{CMA}}{\mathrm{CMA}^*}\right)^2 + w_{\mathrm{CNF}}\left(\frac{\mathrm{CNF}}{\mathrm{CNF}^*}\right)^2 + w_{\mathrm{CSF}}\left(\frac{\mathrm{CSF}}{\mathrm{CSF}^*}\right)^2 \tag{7}$$

where CMA*, CNF* (=1.0) and CSF* are normalizing factors used to bring CMA and CSF values to a level comparable to that of CNF and $w's$ define the relative weighing coefficients for the three fatigue-controlling factors. The magnitude of the $w's$ quantifies the relative importance of the three fatigue-controlling factors. Since only relative values of the $w's$ are important, w_{CNF} was set to 1.0.

To establish preliminary values of the two remaining weighting coefficients (as well as of the two remaining normalizing factors, CMA* and CSF*), the following simple analysis was carried out: (a) Based on the results displayed in Fig. 7(b), characteristic values for CNF and CSF are chosen as 600 N and 300 N, respectively. Consequently, CSF* is set to 0.5(=300 N/600 N); (b) Since it is well-established that contact shear forces contribute more towards fatigue perception (as well as to muscle trauma/tissue-necrosis (Rasmussen et al., 2007)), w_{CSF} is arbitrarily set to 1.5 (i.e., CSF is assumed to contribute 50% more than CNF to the perception of fatigue); (c) At the prevailing muscle-activity level of 0.041, and a typical number of 66 muscles defining the muscle-activity envelope, CMA* can be defined as 0.0045(=0.041 × 66/600); and (d) While the contact normal and shear forces may play a more critical role in the perception of short-term seating discomfort, the role of cumulative muscle activity is expected to be dominant in the perception of long-distance driving fatigue. Consequently, and arbitrarily, w_{CMA} is set to 5.0. In other words, cumulative muscle activity is assumed to contribute five times more to fatigue perception than the maximum contact normal force.

Based on the analysis presented above, Eq. (7) can be rewritten as:

$$\mathrm{LDDFF} = 5.0\left(\frac{\mathrm{CMA}}{0.0045}\right)^2 + 1.0\left(\frac{\mathrm{CNF}}{1.0}\right)^2 + 1.5\left(\frac{\mathrm{CSF}}{0.5}\right)^2 \tag{8}$$

This function is currently being used in our ongoing work in order to test its validity both against the results recorded by Michida (Michida et al., 2001) and the results being obtained in the ongoing investigation. A detailed account of the findings will be reported in our future communications.

As stated earlier, 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 long-distance driving fatigue. 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. The long-distance driving-fatigue function proposed in this work is an important step in bringing the computational engineering analysis into the field of car-seat design and development.

5. Summary and conclusions

Based on the results obtained in the present work, the following main summary remarks and conclusions can be drawn:

1. Musculoskeletal modeling and simulation technique is employed in order to investigate the problem of long-distance driving fatigue.

2. The effect of several driver/car-seat kinematic/interaction factors (e.g., back-rest-inclination angle, human-body/car-seat interface friction coefficient, longitudinal-track position of the seat and presence/absence of lumbar support) on the factors controlling driving fatigue (e.g., maximum muscle activity, contact normal and shear forces, intradiscal spine forces, etc.) has been investigated.
3. A preliminary long-distance driving-fatigue function (LDDFF) has been constructed in accordance with the findings obtained in the present work as well as the findings reported in the open literature.

Acknowledgements

A portion of the material presented in this paper is based on the use of the AnyBody Modeling System, a musculoskeletal multi-body dynamics software (AnyBody Technology A/S, 2008). The authors are indebted to Ozen Engineering for donating an AnyBody Modeling System license to Clemson University.

References

An, K.N., Kwak, B.M., Chao, E.Y., Morrey, B.F., 1984. Determination of muscle and joint forces: a new technique to solve the indeterminate problem. J. Biomech. Eng. 106, 364–367.
AnyBody 3.0, 2008, AnyBody Technology A/S, Aalborg, Denmark.
AnyScript Model Repository 7.1, 2009. AnyBody 3.0, AnyBody Technology A/S, Aalborg, Denmark.
Bader, D.L., Bowder, P., 1980. Mechanical characteristics of skin and underlying tissues *in vivo*. Biomaterials 4, 305–308.
Bell, J.A., Stigant, M., 2007. Development of a fibre optic goniometer system to measure lumbar and hip movement to detect activities and their lumbar postures. J. Med. Eng. Technol. 31, 361–366.
Bennett, L., Kauver, D., Lee, B.Y., Trainor, F.A., 1979. Shear vs. pressure as causative factors in skin blood flow occlusion. Arch. Phys. Med. Rehabil. 60, 309–314.
Bluthner, R., Seidel, H., Hinz, B., 2008. Laboratory study as basis of the development for a seat testing procedure in horizontal directions. Int. J. Ind. Ergon. 38, 447–456.
Chow, W.W., Odell, E.I., 1978. Deformation and stresses in soft body tissues of a sitting person. J. Biomech. Eng. 100, 79–87.
Damsgaard, M., Rasmussen, J., Christensen, S.T., Surma, E., de Zee, M., 2006. Analysis of musculoskeletal systems in the anybody modeling system. Simul. Model. Pract. Theory 14, 1100–1111.
Dendorfer, S., Torholm, S., 2008. Final Report on Feasibility Study, Report no: 21385/08/NL/PA, presented to ESTEC/ESA by AnyBody Technology A/S.
Ebe, K., Griffin, M.J., 2001. Factors effecting static and seat cushion comfort. Ergonomics 41 (10), 901–992.
Frankel, V.H., Nordin, M., 1980. Basic Biomechanics of the Skeletal System. Lea and Febiger Publications, Philadelphia.
Grujicic, M., Pandurangan, B., Arakere, G., Bell, W.C., He, T., Xie, X., 2009. Seat-cushion and soft-tissue material modeling and a finite element investigation of the seating comfort for passenger-vehicle occupants. Mater. Des. 30, 4273–4285.
Inagaki, H., Taguchi, T., Yasuda, E., Iizuka, Y., 2000. Evaluation of Riding Comfort: From the Viewpoint of Interaction of Human Body and Seat for Static, Dynamic and Long Time Driving. SAE Conference. SAE no. 2000-02-0643.
Ippili, R.K., Davies, P., Bajaj, A.K., Hagenmeyer, L., 2008. Nonlinear multi-body dynamic modeling of seat–occupant system with polyurethane seat and H-point prediction. Int. J. Ind. Ergon. 38, 368–383.
Johansen, U., Johren, A., 2002. Personalekonomi Idag. Uppsala Publishing House. ISBN 9170052026.
Kamijo, K., Tsujimura, H., Obara, H., Katsumata, M., 1982. Evaluation of Seating Comfort. SAE Conference. no. 820761.
Karlsson, D., Osvalder, A.-L., Rasmussen, J., 2007. Towards Better Seating Design – a Discussion and Comparison between Office Chairs and Car Seats. Proceedings of the 39th Nordic Ergonomics Society Conference, Sweden.
Krouskop, T.A., Garber, S.L., Noble, P., 1990. Pressure management and the recumbent person. In: Bader, D.L. (Ed.), Pressure Sores – Clinical Practice and Scientific Approach, pp. 235–248.
Kyung, G., Nussbaum, M.A., Babski-Reevesb, K., 2008. Driver sitting comfort and discomfort (part I): use of subjective ratings in discriminating car seats and correspondence among ratings. Int. J. Ind. Ergon. 38, 516–525.
Kyung, G., Nussbaum, M.A., 2008. Driver sitting comfort and discomfort (part II): relationships with and prediction from interface pressure. Int. J. Ind. Ergon. 38, 526–538.
Langsfeld, M., Frank, A., van Deursen, D.L., Griss, P., 2000. Lumbar spine curvature during office chair sitting. Med. Eng. Phys. 22, 665–669.
Lee, J., Grohs, T., Milosic, M., 1995. Evaluation of Objective Measurement Techniques for Automotive Seat Comfort. SAE Conference. SAE no. 950142.
Mandal, A.C., 1984. The seated man (homosedens) – the seated work position: theory and practice. Appl. Ergon. 12, 19–26.
Mandal, A.C., 1987. The influence of furniture height on back pain. Behav. Inf. Technol. 6, 347–352.
Mehta, C.R., Gite, L.P., Pharade, S.C., Majumder, J., Pandey, M.M., 2008. Review of anthropometric considerations for tractor seat design. Int. J. Ind. Ergon. 38, 546–554.
Michida, N., Okiyama, H., Nishikawa, K., Nouzawa, T., 2001. A Study of Drivers' Fatigue Mechanisms during Long Hour Driving. SAE Conference. SAE No. 2001-01-0381.
Milvojevich, A., Stanciu, R., Russ, A., Blair, G.R., van Heumen, J.D., 2000. Investigating Psychometric and Body Pressure Distribution Responses to Automotive Seating Comfort. SAE Conference. SAE no. 2000-01-0626.
Nag, P.K., Pal, S., Kotadiya, S.M., Nag, A., Gosai, K., 2008. Human–seat interface analysis of upper and lower body weight distribution. Int. J. Ind. Ergon. 38, 539–545.
Oomens, C.W.J., Bosboom, E.M.H., Bressers, O.F.J.T., Bouten, C.V.C., Bader, D.L., 2003. Can loaded interface characteristics influence strain distribution in muscles adjacent to bony prominences. Comp. Meth. Biomech. Eng. 6 (3), 171–180.
Park, S.J., Kim, C.B., 1997. The Evaluation of Seating Comfort by Objective Measures. SAE Conference. SAE no. 970595.
Park, S.J., Lee, Y.S., Nahm, Y.E., Lee, J.W., Kim, J.S., 1998. Seating Physical Characteristics and Subjective Comfort: Design Considerations. SAE Conference. SAE no. 980653.
Rasmussen, J., de Zee, M., Torholm, S., 2007. Muscle Relaxation and Shear Force Reduction May Be Conflicting: a Computational Model of Seating. SAE Conference. SAE no. 2007-01-2456.
Rasmussen, J., de Zee, M., 2008. Design Optimization of Airline Seats. SAE Conference. SAE no. 2008-01-1863.
Rasmussen, J., Torholm, S., de Zee, M., 2009. Computational analysis of the influence of seat pan inclination and friction on muscle activity and spinal joint forces. Int. J. Ind. Ergon. 39, 52–57.
Reed, M.P., Saito, M., Kakishima, Y., Lee, N.S., Schneider, L.W., 1991. An Investigation of Driver Discomfort and Related Seat Design Factors in Extended-duration Driving. SAE Conference. SAE no. 910117.
Reichel, S.M., 1958. Shear force as a factor in decubitus ulcers in paraplegics. J. Am. Med. Assoc. 166, 762–763.
Scales, J., 1982. Pressure sore prevention. Care Sci. Pract. 1, 9–17.
Siefert, A., Pankoke, S., Wö lfel, H.-P., 2008. Virtual optimization of car passenger seats: simulation of static and dynamic effects on drivers' seating comfort. Int. J. Ind. Ergon. 38, 410–424.
Tewari, V.K., Prasad, N., 2000. Optimum seat pan and back-rest parameters for a comfortable tractor seat. Ergonomics 43 (2), 167–186.
Thakurta, K., Koester, D., Bush, N., Bachle, S., 1995. Evaluating Short and Long Term Seating Comfort. SAE Conference. SAE no. 950144.
Uenishi, K., Fujihashi, K., Imai, H., 2000. A Seat Ride Evaluation Method for Transient Vibrations. SAE Conference. SAE no. 2000-01-0641.
Verver, M.M., van Hoof, J., Oomens, C.W., Wismans, J.S., Baaijens, F.P., 2004. A finite element model of the human buttocks for prediction of seat pressure distributions. Comput. Methods Biomech. Biomed. Engin. 7, 193–203.
Yun, M.H., Donjes, L., Freivalds, A., 1992. Using force sensitive resistors to evaluate the driver seating comfort. Adv. Ind. Ergon. Saf. IV, 403–410.
Zhao, L.Q., Xia, Q.S., Wu, X.T., 1994. Study of Sitting Comfort of Automotive Seats. SAE Conference. SAE no. 945243.