



Review of modelling studies of the response of the spinal system to WBV and repeated shock, and recommendations for the direction of future modelling work

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Introduction

Modelling studies of the spinal system to WBV and repeated shock provide a possibility to predict the forces acting on the disks and endplates of vertebrae. These forces can be used to estimate the health risk. Due to the complex structure of the human body, only complex dynamic models based on human anatomy can reflect adequately the dynamic properties of the spine and adjacent parts of the body. The review will concentrate on models of this type. Two types of model are less suitable: (1) Static models do not reflect sufficiently the dynamic properties of the lumbar spine, (2) phenomenological models reproduce input-output relations without considering anatomical structures.

Comprehensive reviews of dynamic models of sitting men can be found in (Buck (1997), Buck, Pankoke and Wölfel (1997), Griffin (1990), Yoganandan *et al.* (1987) and Kitazaki (1994). Sometimes, models are reported without satisfactory verification, although the verification is essential for the validity of predicted

forces. In the ideal case, the verification would rely on forces measured in vivo within the spine. However, such data are not available for several reasons. Therefore, mainly non-invasively measured data on human biodynamics have to be used. They offer the possibility to compare important characteristics of the models with reality. The conformity is a prerequisite for a verified model, it does not, however, provide conclusive evidence for the veracity of the predicted forces inside the spine, merely it increases the probability of their veracity.

This brief review consists of two main parts. The first part provides a catalogue with comments of existing dynamic models of sitting man, the second part suggests recommendations with regard to biodynamic data that can be used for the validation of models.

The aim of the review is to provide a brief, but critical overview of available sources as a basis for discussion and future co-operation in this promising area. It was not intended to repeat the available knowledge

that has been presented in the original papers and reviews listed as references.

Dynamic models of sitting man

This part is mainly based on the research reported by Buck, Pankoke and Wölfel (1997). It is limited to models closely related to human anatomy. Phenomenological models (e.g., Buck *et al.*, 1995; Demic, 1989; DIN 45676, 1992; Fox and Williams, 1976; Guo *et al.*, 1994; Knoblauch, 1993; Knoblauch *et al.*, 1995; Mertens, 1976; Schmid, 1976; Payne and Band, 1971) are not considered. Coupling of various directions of motion is typical for human biodynamics and must not be neglected. Therefore, some anatomically-based models were also not reviewed, because they consider only one, mainly vertical, direction of motion, (e. g., Amirouche *et al.*, 1994; Bajon and Nader, 1986; Coermann *et al.*, 1960; von Gierke, 1968; Kaleps *et al.*, 1971, Muskian and Nash, 1974; Patil *et al.*, 1978; Patwardhan, 1994; Toth, 1967).

Some models simulate the kinematics and inertial properties by a chain of rigid bodies linked by ideal pivot joints. Stiffness and damping are not modelled. Such models can be applied for large slow motions in order to calculate forces acting on the joints including vertebral joints (e.g., Deuretzbacher and Rehder, 1995; Jäger, 1987; Minetti and Belli, 1994). This kind of model is not considered in the review.

Roberts (1969) presented a plane dynamic model of sitting man, consisting of 6 segments (rigid bodies) similar to the inertial properties of humans. These segments were coupled by rotatory and translatory joints with linear stiffnesses related to the degrees of freedom of the latter. Damping was neglected. The model was used to predict reactions during car-crashes. The model was not verified.

Another model was closely linked with the development of ejection seats. Belytschko *et al.* (1976) presented a complete 3-dimensional model of the spine with pelvis, thorax and viscera. Some simplified models were derived from this model (Privitzer and Belytschko, 1980; Williams and Belytschko, 1983). The model by Williams and Belytschko (1983) describes the cervical spine in more detail. These authors included muscles in their model which produce forces counteracting stretch. Further modifications can be found in the models by Belytschko *et al.* (1985) and Privitzer (1985).

Nussbaum and Chaffin (1996) continued the work based on this kind of models. They adapted the model to various individuals and predicted muscle forces and forces acting on the spine during different movements.

Kitazaki and Griffin (1997) developed a two dimensional finite element model of the seated body in the mid-sagittal plane, based on the three dimensional models presented by Belytschko and Privitzer (1978). The model was validated by comparing the modal properties of the model with results from an experimental modal analysis conducted by the authors (Kitazaki and Griffin, 1998).

Amirouche and Ider (1988) presented a model consisting of 13 rigid body segments, coupled by linear springs. Luo and Goldsmith (1991) developed a three-dimensional model of the human trunk and head, without limbs. This model was adopted by Fritz (1996) in order to calculate forces acting on lumbar disks. Dietrich *et al.* (1991, 1992) were the first who presented a finite element model of the sitting man that contained one- and two-dimensional as well as volume elements. A simple model of the disk was used for sub-modelling local effects that

arise from the behaviour of the whole-body model. The model by Qassem *et al.* (1994) produces transmissibility data which contradict experimental results.

Matsumoto (1998) developed lumped parameter models in which model masses represented segments of the seated human body. The models were two-dimensional by incorporating rotational degrees of freedom. The models were validated by using the apparent mass and transmissibilities measured by Matsumoto and Griffin (1998).

Buck (1997) developed a dynamic three-dimensional finite element model with a detailed representation of the lumbar spine and back muscles (102 elements). The complete model of a sitting human was formed, together with relatively simple dynamic models of the upper trunk with arms, neck and head, and of the pelvis and legs. All parts of the model and the complete model were verified by comparisons with experimental data reported in the literature.

Buck, Pankoke, and Wölfel (1997) developed a simplified plane finite element model derived from Buck (1997) for application in occupational medicine. These authors relied on experimental data obtained by FIOSH (Seidel *et al.*, 1997). The model is described in Pankoke *et al.* (1998).

Validation of models, biodynamic data of sitting man

Models can be validated by comparing model calculations with experimental data in the frequency and time domain. Whole-body vibration and transients with a large magnitude require the consideration of non-linearities (cf. Buck, 1997, p. 169; Seidel *et al.*, 1997).

Several reviews summarise the available biodynamic data (cf. Griffin 1990). Significant new results were obtained recently by the partners ISVR (Kitazaki, 1994; Matsumoto and Griffin, 1998) and NIWL (Mansfield and Lundström, 1999a,b). A database with experimental data in the time domain will help to verify newly developed models (e.g., Goudas *et al.* 1999).

Conclusions and proposal of directions for future modelling work

Finite element modelling seems to offer the best suited approach to predict the internal forces acting on lumbar vertebrae during whole-body vibration and shock. The model should be closely related to human anatomy in order to reflect adequately the complexity of human biodynamics. Experimental biodynamic data (e.g. studies of the movements of parts of the body during exposure to whole-body vibration and/or shock, apparent mass, and transmissibility of vibration to different body parts) are of crucial significance for the verification of models and further progress. It would be extremely helpful if such data, as well as results of invasive measurements, could be made available to persons engaged in modelling.

Directions for future modelling work could include:

The development of a dynamic model of sitting human body with consideration of real working conditions. For example:

- suspended seats,
- seat cushions,
- use of backrest,
- variable sitting posture,
- variable anthropometric parameters,
- time-variant muscle forces.

Substructure-techniques to predict the distribution of internal loads within the vertebral segment.

Development of databases for experimental data and modelling.

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