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Modelling of dynamic interactions in cervical spine during car collision

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The paper presents a dynamic spatial mathematical model in which a head, two cervical vertebrae, a group of neck muscles, an intervertebral disc, ligaments and intervertebral joints are taken into consideration. The behaviour of modelled body exposed to action of a force corresponding to the real enforcement, which occurred at a head-on collision during the road accident, was simulated, and the model was verified on the basis of data obtained from published experiments.

Key words: cervical spine, mathematical modelling, crash biomechanics

1. Introduction

Model research provides a non-invasive method for obtaining information on how living organisms behave in dangerous situations. With modern computer techniques it is possible to carry out repeated simulations using biomechanical models [7] with the aim of getting data on their behaviour in different situations. A correctly verified model can be a source of valuable information applicable to designing the various types of equipment and facilities intended for increasing the safety of road users. When modelling living objects one encounters difficulties connected with identification of the parameters of a system and their verification, especially when this is a model of a man [2], [8], 10]. Because the tests may be dangerous the biomechanical models of collisions are verified with participation of people only within the range of safety speeds. Beyond these limits, animals, dummy men or dead bodies are used instead [15].

Despite the great progress in many fields of science, models that are being constructed and need an interdisciplinary approach are still imperfect and involve simplifications [15].

A model covering a head, two upper vertebrae of a spine, a group of neck muscles, ligaments, an intervertebral disc and joints which are, in the major part, responsible for mobility of the whole segment of the cervical spine (figure 1), has been described. The model was subjected to the action of time-varying force, simulating the load to which the upper parts of human body are exposed in the case of a real accident [5], [9]. The objective of the paper was to verify the accepted mathematical model of the whole segment of cervical spine, which is described in detail in [12], [13].

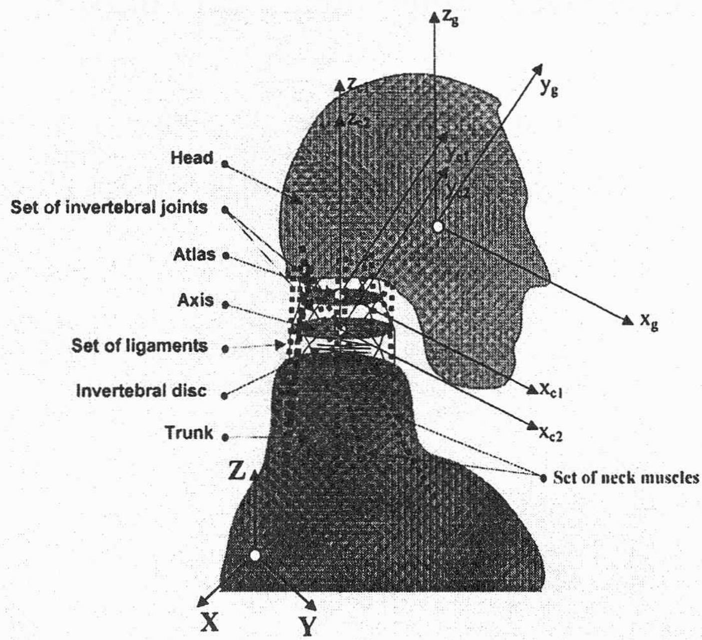

Fig. 1. Accepted model

2. Basic assumptions

For modelling purposes the following assumptions have been made:

• An atlas, an axis (figures 2, 3) and a head are considered as rigid bodies with six degrees of freedom; limitations of their movement resulting from the contact with adjacent segments are determined by forces in joints, ligaments and muscles, depending on mutual positions of segments; it has been assumed that a trunk and other cervical vertebrae make an immovable base (assumed masses and moments of inertia of segments are given in table 1).

• Intervertebral ligaments are modelled as parallel bands, acting on adjacent vertebrae with tension dependent on the actual elongation, along a straight line connecting the conventional points of attachment of bands to vertebrae processes.

Table 1. Masses and principal moments of inertia of segments under consideration

	Mass of units [kg]	I_x [kgm^2]	I_y [kgm^2]	I_z [kgm^2]
Head	4.2	$1.9\cdot10^{-2}$	$1.78\cdot10^{-2}$	$2.14\cdot10^{-2}$
C1	0.013	$3.23\cdot10^{-6}$	$1.06\cdot10^{-6}$	$3.86\cdot10^{-6}$
C2	0.021	$2.67\cdot10^{-6}$	$2.16\cdot10^{-6}$	$2.97\cdot10^{-6}$

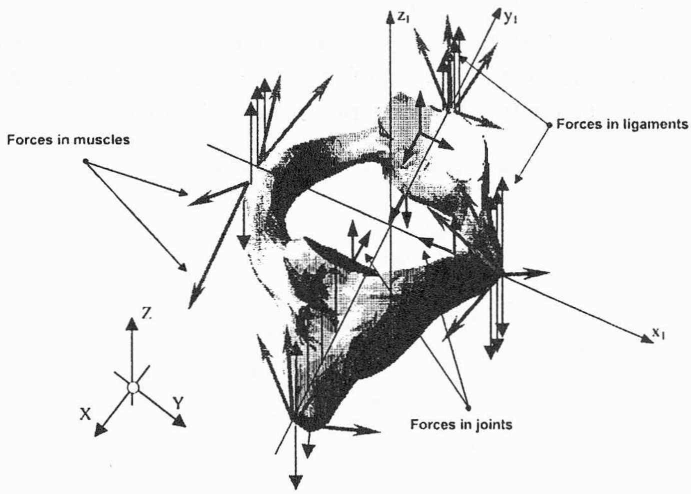

Fig. 2. Model of atlas

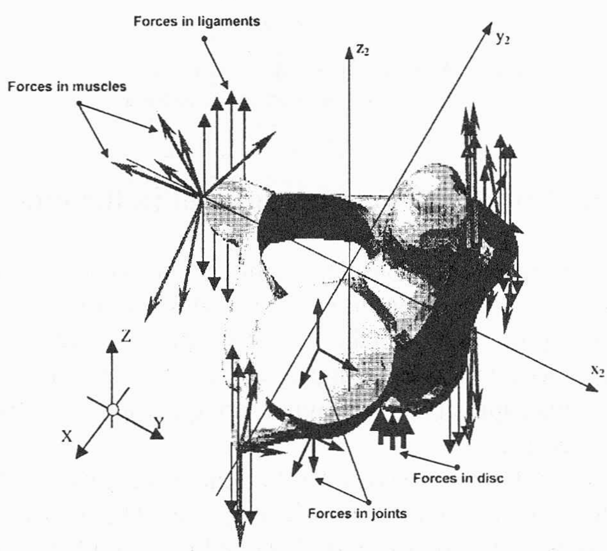

Fig. 3. Model of axis

• An intervertebral disc between C2 and the base is treated as an elastic element, with mass included in neighbouring vertebrae, divided into segments acting on vertebrae with a force dependent on current compression.

• Neck muscles are modelled on the basis of the Hill model; directions of muscular forces depend on current position of the characteristic points of their attachment.

• The functioning of a joint is simulated by a set of forces resulting from the elasticity of cartilages and ligaments, which are dependent on mutual displacements of segments connected by the joint, as well as by additional forces occurring when a normal turning range of the joint is exceeded, and resulting from the fact of spinous processes taking place on bearing surfaces.

• External excitation, defined as a time-varying force, has been applied to the head's centre of gravity on the Y-axis of the absolute coordinate system compatible with acceleration of the centre of gravity presented in figure 4.

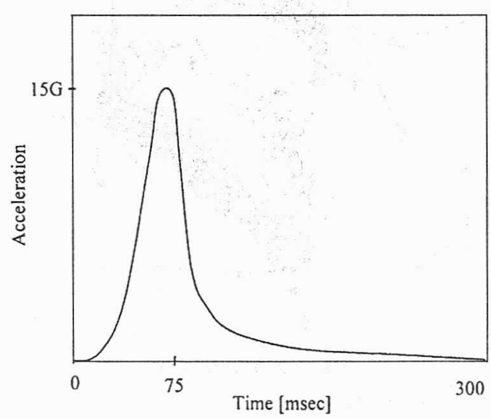

Fig. 4. Acceleration acting on the human head's centre of gravity during simulations

3. Muscular forces considered in the model

The following group of neck muscles, acting symmetrically in relation to the Y–Z plane has been taken into consideration in the model [3]: trapezius, sternocleidomastoid, semispinalis capitis, semispinalis cervicis, splenius capitis, splenius cervicis, longissimus capitis, longus capitis, longissimus cervicis, longus colii, rectus capitis posterior major, rectus capitis posterior minor, obliqus capitis superior, obliqus capitis inferior, scalenus medius.

Among the muscles taken into consideration there is a group of muscles that act on more than two elements of the human skeletal system. The muscles have been distinguished on the grounds of Seireg's study [11] and then divided into bands (figure 5). A model of the Hill type distinguishing components of the muscular force F^M included in excitation F^{MT}, elongation F^{PEE} and velocity of elongation F^{DE} as presented in [6] has been applied for each particular band of muscles.

$$F^M(u,l^M,v^M) = F^{MTE}(a(u),l^M,v^M) + F^{PEE}(l^M) + F^{DE}(v^M),$$

$$F^{PEE}(l^M) = k_2(e^{k_1(l^M - l_0^M)} - 1), \qquad l^M \geq l_0^M, \tag{1}$$

$$F^{DE}(v^M) = k_3 v^M,$$

u – stimulation, l^M – length of muscle, v^m – action velocities, k_1, k_2, k_3 – muscle specific constants.

In numerical experiments presented the modelling of muscular forces was slightly simplified by treating excitation as constant and introducing values of the first component of muscular force as medium value, taken from literature [4], [14] for particular muscles and tuned by preliminary quasi-static simulations.

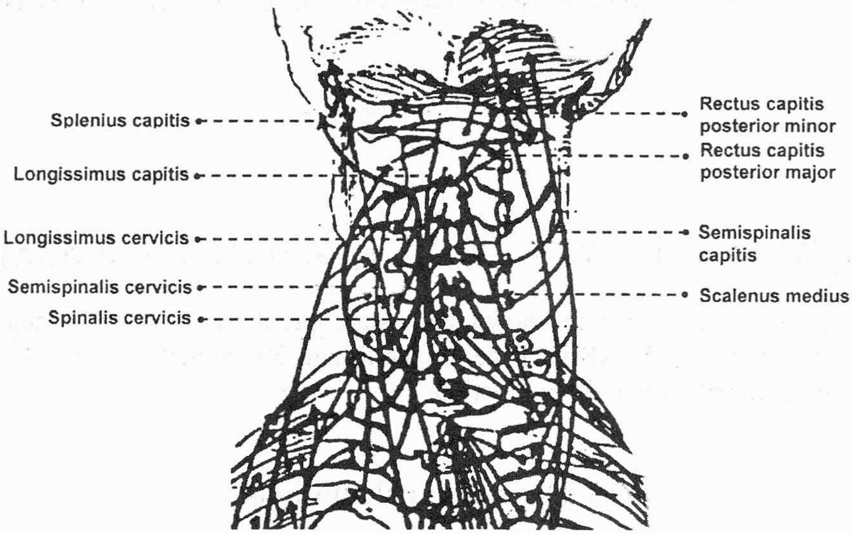

Fig. 5. Scheme of modelled muscle [11]

4. Mathematical model and method for its solving

Based on the assumptions presented above, a mathematical model has been formulated as a system of equations of dynamic equilibrium of head and vertebrae. The equations of equilibrium of forces were written in an absolute co-ordinate system, whereas equations of moments – in a local system, constituting Newton–Euler's set of equations.

$$d\overline{V}_{oi}/dt=\sum\overline{F}_i/m_i,\qquad d\overline{\omega}_i/dt=\overline{\overline{T}}_i^{-1}\cdot\left\{-\overline{\omega}_i\times\left(\overline{\overline{T}}_i\cdot\overline{\omega}_i\right)+\sum\overline{M}_i\right\},$$

where

$$\overline{V}_{oi}=\left[V_{Xoi},V_{Yoi},V_{Zoi}\right]^T,\quad \sum\overline{F}_i=\left[\sum\overline{F}_{Xi},\sum\overline{F}_{Yi},\sum\overline{F}_{Zi}\right]^T,$$

$$\overline{\omega}_i=\left[\omega_{xi},\omega_{yi},\omega_{zi}\right]^T,\quad \sum\overline{M}_i=\left[\sum M_{xi},\sum M_{yi},\sum M_{zi}\right]^T,\tag{2}$$

$$\overline{\overline{T}}_i=\begin{bmatrix} I_{xixi} & -I_{xiyi} & -I_{xizi}\\ -I_{xiyi} & I_{yiyi} & -I_{yizi}\\ -I_{xizi} & -I_{yizi} & I_{zizi}\end{bmatrix}.$$

After adding relations between linear and angular velocities and displacements [12], [13] the set of equations describing motion of all segments considered takes the form:

$$\frac{d\overline{X}}{dt}=\Phi\left(\overline{X},\overline{F}_{\text{external}}\right),\tag{3}$$

where

$$\overline{X}=\left[\overline{X}_1,\ldots,\overline{X}_i,\ldots,\right]^T,\quad \overline{X}_i=\left[V_{oXi},V_{oYi},V_{oZi},\omega_{xi},\omega_{yi},\omega_{zi},X_{oi},Y_{oi},Z_{oi},\upsilon_i,\psi_i,\varphi_i\right]^T.$$

The above system (3) with known static-state initial conditions has been solved with the aid of the MATLAB package, by the Runge–Kutta method of the 4^{th} and 5^{th} orders with automatic time step correction.

5. Results of calculations

The calculations have been carried out for a man of an average weight and size (50% male) exposed to accidental acceleration 15G (figure 4). Examples of the results obtained are presented in the form of diagrams showing displacement of the head's centre gravity in direction of the *Y*-axis (figure 6) and *Z*-axis (figure 7) of the accepted absolute co-ordinate system. Location of the head in its natural (free) position has been assumed as the initial position. Data obtained from experiments performed by the team of Ewing with participation of volunteers and then proved by Wismans and Thunissen served for verification purposes [7]. The shape of curves obtained in numerical simulations performed with the model presented is very similar to those reported from other experiments. A slight decrease in displacements is due to the fact of considering only two vertebrae in the model, and probably will be cleared after including other vertebrae.

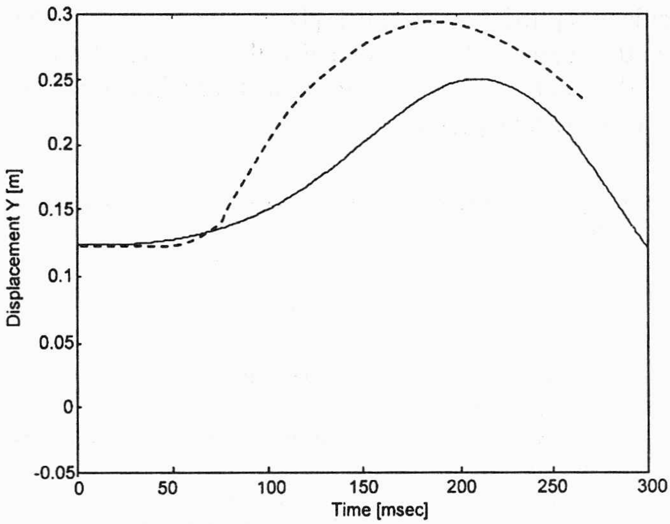

Fig. 6. Displacements in the direction of *Y*-axis of the accepted absolute system: a) results obtained (———), b) data from bibliography (- - - -) [7]

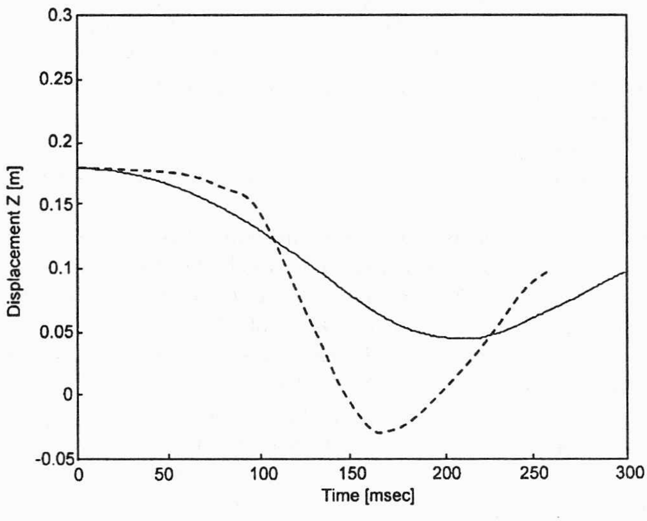

Fig. 7. Displacements in the direction of *Z*-axis of the accepted absolute system: a) results obtained (———), b) data from bibliography (- - - -) [7]

6. Conclusions

A comparison of the results obtained in the course of numerical experiments using the present model with published data describing behaviour of the human body in the case of road accident [1], [5], [7], [9], [10], [15] shows that the model well describes real behaviour. In the nearest future the model will be developed by including successive elements of the neck segment of the human vertebral column, and extensive numerical experiments will be performed.

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