Acta of Bioengineering and Biomechanics
Vol. 1, No. 1, 1999

Model investigation of the role of multi-joint muscles in vertebral column mechanics

VLADIMIR P. TREGOUBOV

St. Petersburg State University, Institute of Mathematics and Mechanics

Analysis of human body model development has showed that the importance of spine muscles was belittled or totally disregarded in the previous models. To eliminate this disadvantage some simple models, where multi-joint muscles were represented, have been proposed. These models allowed elucidating the especial role of multi-joint muscles in stability of spine and its dynamics under vibration.

Keywords: mechanics, modelling, multi-joint muscle, vertebral column

1. Introduction

Ever since the first mechanical model (Fig.1) was used for the study of human body dynamics during a pilot ejection [6] a rich variety of attempts at modelling the human body have been made. In the succeeding models increasingly more attention was focused on vertebral column. It was presented (Fig. 2) as a uniform elastic or visco-elastic rod [4, 5, 14], as a sequence of rigid bodies connected with springs and dampers [1, 15] (Fig. 3, 4) and as a system of rigid and deformable bodies arranged in series [8, 10] (Fig. 5). The importance of spine muscles was belittled or totally disregarded in these models, although it is well known that a vertebral column devoid of muscles is not able not only to support a human posture but even to provide its own stability. That is why we are to consider the muscles to be responsible for the dynamics of spinal system. In doing so we must remember that spine muscles are most often the multi-joint ones.

The model of Soetching and Pasley [13], where the spine musculature was represented as a distributed surface traction with feedback (Fig. 6), was very likely the first attempt to define the role of the muscles in spine dynamics at least in response to lateral deceleration.

Models designed for solving the orthopaedic problems have more complicated structures. Even the first ones [2, 11, 12] provided a possibility of the 3D analysis for the forces and deformations arising in the vertebral column including ligaments but excluding muscles (Fig. 7).

The most comprehensive description of human body structure has been made in the model of Dietrich, Kedzior and Zagrajek [3], where spine muscles were considered to be active generators of the contraction forces (Fig. 8). Nevertheless, a multi-joint nature of these muscles was not analysed.

2. What are the multi-joint muscles necessary for?

First of all this question arises on consideration of extremity structures where one-joint muscles and two-joint muscles operate one and the same joint. But since the

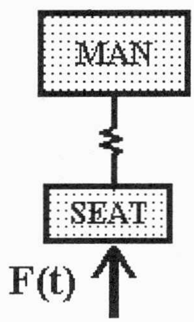


Fig. 1. Simplest model [6]

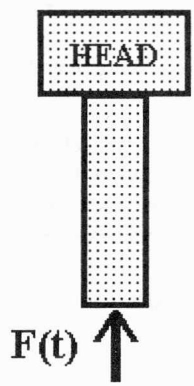


Fig. 2. Model with distributed parameters [5]

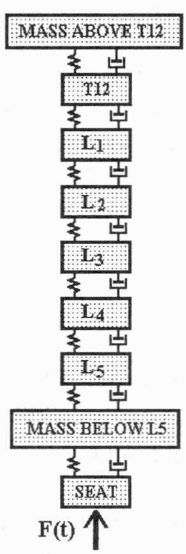


Fig. 3. Toth's model of lumbar spine

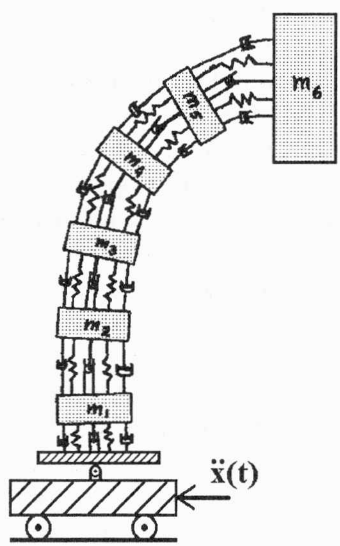


Fig. 4. Aquino's model of lumbar spine

muscles can be considered as a special kind of links, this question can be reformulated in a more general form. Namely, what are the multi-joint links necessary for and are they necessary at all? Searching for an answer to this question we can find different and sometimes opposite answers. On the one hand, designers of multi-joint systems

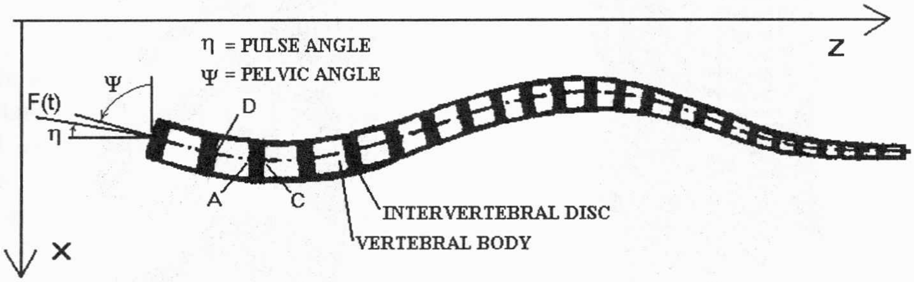


Fig. 5. Model of vertebral column under impact [10]

every so often try to avoid using the multi-joint links. The most dramatic examples are artificial fingers and wrist with one-joint links, whereas all human finger muscles are multi-joint. On the other hand, multi-joint links are used in prostheses with cable-control systems. One more such an example is a big excavator in which bucket is operated by multi-joint cables. In both these cases the multi-joint links are used for the control purpose and supposed to be flexible and inextensible.

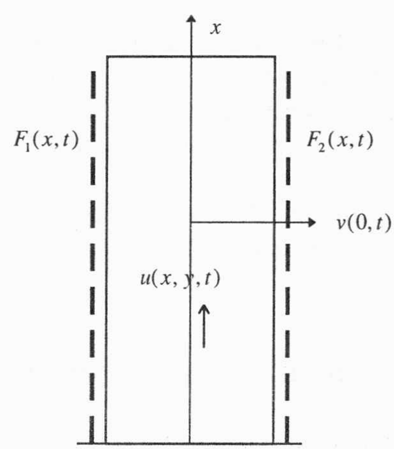


Fig. 6. Model of spine musculature

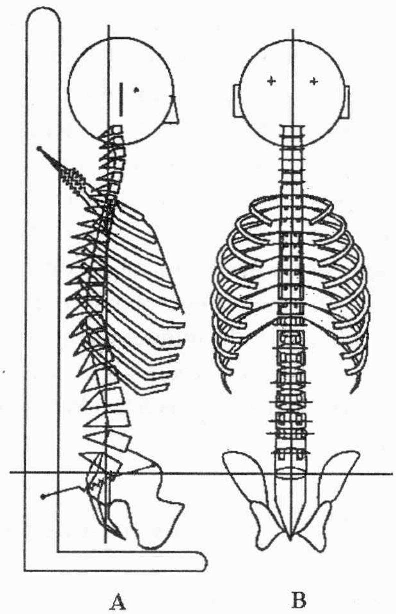


Fig. 7. 3D model of spine [2]

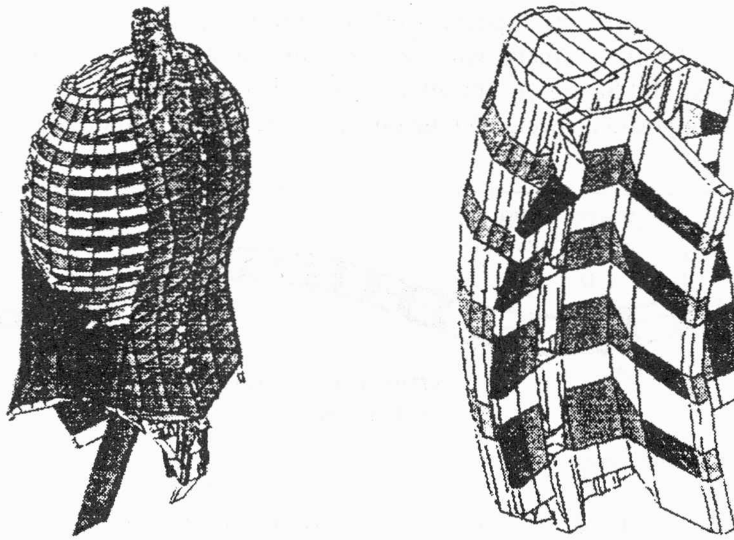


Fig. 8. Finite-element model of spinal system [3]

The similar kinds of links are used for fastening the mast aerials by means of stretching cables, which provide a stability of the construction. This construction is similar to cervical spine, where multi-joint neck muscles provide a stability of a head. However, being a distributed parameter system, the aerial is not the multi-joint one and the stretching cable may not be spoken of as multi-joint link but rather as "non-local connections". Nevertheless, these links or connections have the same nature and their functions can prompt one to answer the posed question.

So then even cursory examination of using the multi-joint links in engineering gives us two possible variants of their utility, namely they provide a stability of a system and they provide an effective control.

As to living systems, many specialists in biomechanics can say, during which movements multi-joint muscles play a positive part and when a negative one. From the anatomists' standpoint the utility of multi-joint muscles lies not in their special function but in their genesis. The matter is probably that the Nature had not other possibility to provide a mobility of living multi-joint construction than multi-joint muscle. Typical examples of this situation are fingers, where all muscles are multi-joint. Because of the above different experts give different answers. We will try to give the answer from the mechanical point of view.

3. The role of multi-joint muscles in providing a stability

First of all let us look at the muscles as passive elements. For this purpose we consider the mechanical system presented in Fig. 9. It consists of the hinged rigid bodies connected by means of both the one-joint elastic links and the multi-joint ones. Then suppose for a moment that one-joint links are absent and consider the equilibrium conditions for this system. It is not difficult to prove that the force developed in multi-joint link is a function of linear combination of the relative rotation angles q_i, if all joints are of a roller form and the link slides around a roller, that is

$$F_{123} = (F\,(aq_1 + bq_2 + cq_3), \tag{1}$$

where a, b, c are the radii of the specific roller joints. As result, such a force remains constant if this combination in the brackets remains unaltered during an alteration of q_i. If joints are of more complicated form than the roller, linear combination of the angles q_i should be substituted for more complicated function of q_i, that is $f(q_1, q_2, q_3)$, but the general sense is conserved, namely, if the function $f\,(q_i)$ remains constant the force F_{123} remains constant, too. This means that this system has only the neutral equilibrium position or, in other words, the multi-joint elastic links cannot provide a stable equilibrium position. The situation is fundamentally changed when one-joint links are incorporated. In this case the following one must replace Eq. (1):

$$F_{123} = F(aq_1 + bq_2 + cq_3) + F_1(q_1) + F_2(q_2) + F_3(q_3), \tag{2}$$

where $F_1(q_1)$, $F_2(q_2)$, $F_3(q_3)$ are the forces developed by one-joint links. One can see that now the stable equilibrium is provided.

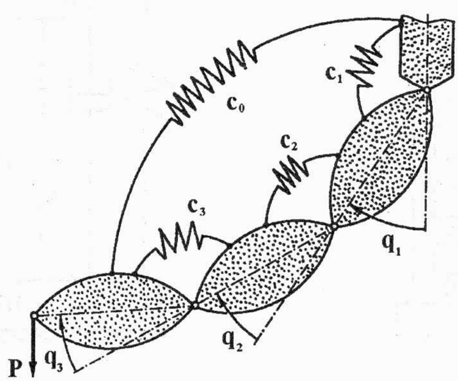


Fig. 9. 2D model with multi-joint links

Thus, in order to provide the stable equilibrium position or to balance the gravity force the one-joint links must be attracted if only the weak ones exist.

Furthermore, the elastic multi-joint links cannot balance the gravity forces applied to the system [16] and as well as the above one-joint links must be attracted for this purpose.

It may also be pointed that the potential energy Π_0 accumulated by multi-join links differs from that accumulated in the one-joint links (Π). In the simplest linear case (the joints of the same roller form with the equal stiffness coefficients are given) we can write down for the one-joint links:

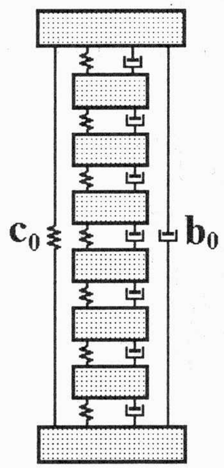
$$\Pi = \frac{rc}{2}(q_1^2 + q_2^2 + q_3^2), \quad (3)$$

and for the multi-joint links:

$$\Pi_0 = \frac{rc}{2}(q_1 + q_2 + q_3)^2, \quad (4)$$

where r denotes the roller radius and c is the stiffness coefficient.

As $(q_1 + q_2 + q_3)^2 \geq q_1^2 + q_2^2 + q_3^2$ if all q_i have the same sign, so the potential energy accumulated in the multi-joint elastic links is higher than energy accumulated in the one-joint elastic links. This comparison leads us to the thought that multi-joint links could be more effective in supporting an equilibrium position if only they could provided it in the absence of one-joint links.



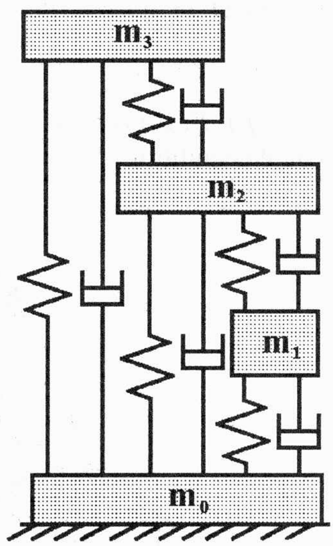


Fig. 10. 1D Model with multi-joint links Fig. 11. Model of generalised chain structure

Thus, although muscles are not of, course, springs, the first important (and contradictory) inference can be made as follows.

In order that multi-joint muscles can provide a stable equilibrium position, any one-joint elastic links that need not muscles must be present. In doing so multi-joint muscles are more effective than one-joint links only.

Exactly such a situation we can see in a vertebral column, where vertebrae are connected by elastic intervertebral disks, which are one-joint links. In addition to this, multi-joint muscles clasp entire groups of vertebrae, providing stability and mobility of the spine.

4. Peculiarities of multi-joint muscles controlling spine movements

Now we must make some remarks, which concern the control peculiarities of multi-joint muscles and follow from previous subchapter. These remarks have a conflicting character. Let us consider, for example, the problem of control of head movements. Really, on the one hand, it is simpler to have the movements under control by means of one multi-joint muscle than by the set of one-joint muscles. On the other hand, the movements are realised by muscle shortening and we have established above that the length of multi-joint muscle, i.e., the function $f(q_1,... q_n)$, cannot be uniquely defined by the position of spine, i.e., by the set of q_i. As a consequence, we have the problem of ambiguous control. From the standpoint of mechanics if the muscle length is the single control criterion, the addition of the one-joint links does not improve the situation. It would take place if both the length and force of muscle were the criteria of control. To be more precise, in the absence of one-joint links the control is ambiguous at the continuous set of values of q_i, for which the function $f(q_1, ... q_n)$ is constant. In the presence of multi-joint links the control is single-valued at all values of q_i except the several ones. In such a living system as the human organism, there are many criteria of control but this question is beyond our investigation.

5. The role of multi-joint muscles in dynamics of the human body under vibration

5.1. Passive multi-joint links

To focus attention on the role of multi-joint muscles in the dynamics of human body vibration it is necessary to apply a simple 1D model of a chain structure and to supplement it with multi-joint links connecting the first mass and the last mass (Fig. 10). These multi-joint links were thought as passive deformable elements (springs and dampers) as well as the one-joint links.

The comparative investigation of the frequency properties of the mechanical system with incorporated multi-joint links, which can be called as the system *of generalized chain structure*, and traditional mechanical model of chain structure shows that their amplitude-frequency characteristics (AFC) fundamentally differ.

Although both of these systems have the same number of resonance frequencies, which is equal to the number of degrees of freedom, the number of anti-resonance frequencies (that is zeros of transfer function in the absence of friction) for each mass of the system completed with the multi-joint links is higher by one than in the absence of them. This means that even upper mass has one anti-resonance frequency with the availability of the multi-joint links which is, as known, impossible for the ordinary chain structure. From the mathematical point of view this effect is produced by virtue of the fact that incorporation of multi-joint links into the model structure increases by one polynomial degree of the transfer function for each mass. In the absence of friction forces the AFC numerator polynomial of ordinary system has real roots which are the anti-resonance frequencies. The number of roots for the ordinary chain structure is equal to $n - \pi$, where n is the number of degrees of freedom and π is mass number, starting with the base ($\pi = 0$). Therefore, the upper mass of ordinary system has no anti-resonance frequency but with the availability of multi-joint links it has one.

The simplest model, where introducing multi-joint links is rational, is a system with two degrees of freedom in which m_1, m_2 are masses, c_1, c_2, and b_1, b_2 denote stiffness and damper coefficients of one-joint links, c_0, b_0 are stiffness and damper coefficients of the same two-joint links. In this case the transfer function for upper mass is as follows:

$$H_2(p) = \frac{a_3 p^3 + a_2 p^2 + a_1 p + a_0}{d_4 p^4 + d_3 p^3 + d_2 p^2 + d_1 p + d_0}, \tag{5}$$

where

$$a_0 = d_0 = c_1 c_2 + c_0 c_1 + c_0 c_2,$$

$$a_1 = d_1 = c_1(b_0 + b_2) + c_2(b_0 + b_1) + c_0(b_1 + b_2),$$

$$a_2 = b_1 b_2 + b_0(b_1 + b_2) + m_1 c_0, \; d_2 = a_2 + m_1 c_2 + m_2(c_1 + c_2),$$

$$a_3 = m_1 b_0, \; d_3 = m_2(b_1 + b_2) + m_1(b_1 + b_0), \; d_4 = m_1 m_2.$$

In the absence of dampers $b_1 = b_2 = b_0 = 0$ and the numerator of AFC is

$$c_1 c_2 + c_0(c_1 + c_2) - m_1 c_0 \omega^2. \tag{6}$$

It can vanish at

$$\omega = \frac{c_1 c_2 + c_0(c_1 + c_2)}{m_1 c_0},$$

which is anti-resonance frequency. This is evidently impossible in the absence of two-joint links, i.e., at $c_0 = 0$.

For higher number of degrees of freedom an availability of the multi-joint links allows us to change significantly the shape of the AFC. In particular, in the case of seven degrees of freedom (model of cervical spine) we can see (Fig. 12) that multi-joint links allow us to reduce considerably the first and the second peaks of AFC leading in the same time to the occurrence of anti-resonance frequency between them [17]. It was also shown that in the case of three degrees of freedom AFC might practically have only one peak (Fig. 13).

If the number of degrees of freedom is higher than two, the multi-joint links (two-joint, three-joint and so on) may connect not only the first and the last rigid body but also any two of them (see, for example, Fig. 11). In this case the number of anti-resonance frequencies is growing. In particular, for the upper mass this number can achieve the value equal to $n - 1$, where n is the number of degrees of freedom. Thus, this consideration allows us to formulate the following hypothesis.

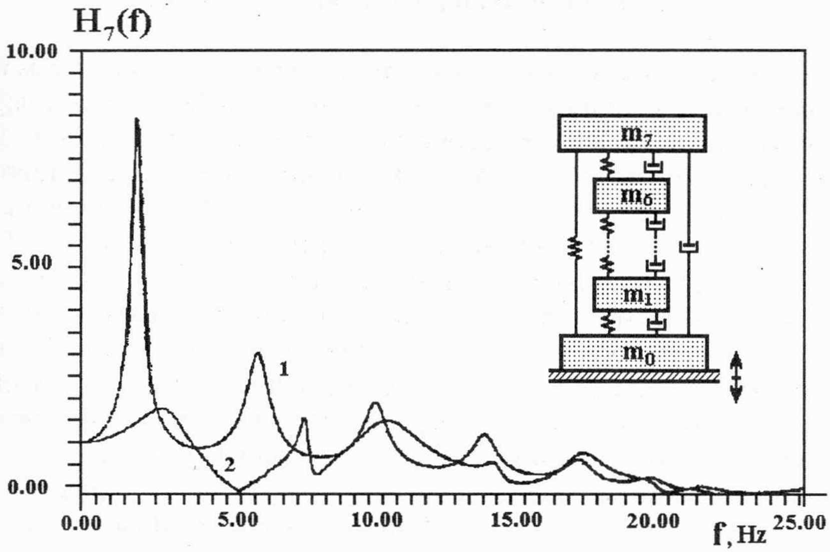


Fig. 12. AFC for models having 7 degrees of freedom:
1 – usual chain structure; 2 – generalised chain structure

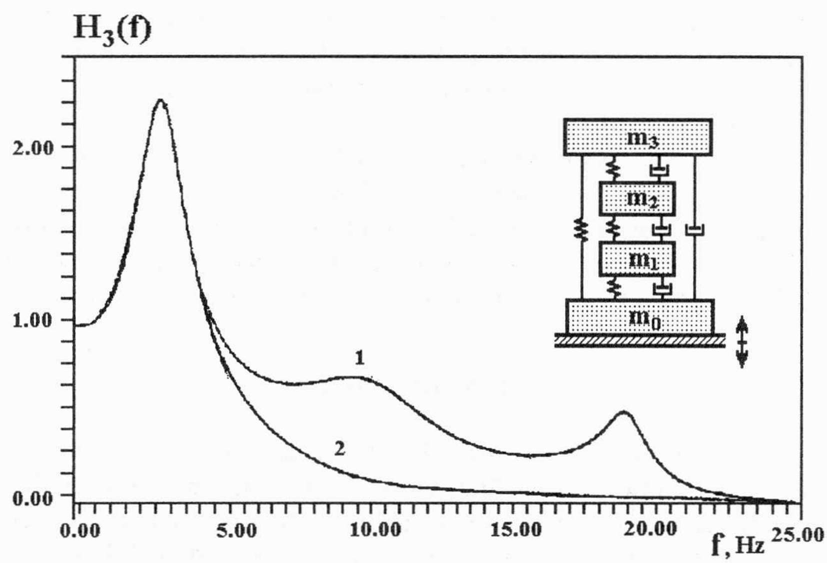


Fig. 13. AFC for models having 3 degrees of freedom:
1 – usual chain structure; 2 – generalised chain structure

Vertebral multi-joint muscles reduce the number of the spine resonance frequencies and reduce amplitudes of oscillations at these frequencies. In other words, multi-joint muscles may reduce transmission of oscillatory actions to the human head.

5.2. Controlled and active multi-joint links

On studying a muscle activity of a sitting man under vibration, it was revealed [7] that the posture activity of the several lumber muscles is increasing at two values of frequency, which correspond to the resonance frequencies. This experimental fact leads us to the conclusion that the model elements representing the muscles must have variable properties. In the case of the vibration exposure this circumstance can be considered in the proposed model by means of making the stiffness of multi-joint links dependent on the frequency, that is $c_0 = c_0(\omega)$. As it is known, the increase in the mechanical system stiffness causes a shift of the resonance frequencies to the right. An alteration of the vibration amplitude is due to damping properties, i.e., $b_0 = b_0(\omega)$. As a result, a mechanical model, which incorporates the multi-joint links having alterable (or controlled) parameters, has much more possibilities of reproducing the experimental evidences.

The dependence of the model parameters: c_0 and b_0 on the frequency ω is the simplest manner of muscle activity modelling. It is warranted only in the case the vibration exposure, otherwise a more complicated way must be adopted. In particular, the reflex activity can be simulated by means of forces that are generated in the model in response to a certain value of strain Δx (or stress Δf) developed in muscles during the stretch with the time delay $\Delta\tau$. Thus, the force must be a time function depending on the parameters Δx and $\Delta\tau$, which are the control parameters. As these forces are generated in multi-joint links, such links can be called active and controlled.

Having the spinal system mechanical models containing the active and controlled multi-joint links we obtain a possibility to study not only direct effects of mechanical actions but also mediated (secondary) ones. Our investigation showed that the reflex response of vertebral muscles may lead both to positive and negative results. In the latter case it can be a reason of certain diseases.

6. Conclusions

In a summary, it should be stressed that the model study of peculiarities of multi-joint muscles has allowed us to find out some their advantages over the one-joint muscles. In the same time it has been established that these advantages can be used only with the availability of any one-joint links, the intervertebral disks, for example. This result, in turn, gives us a possibility to determine a particular function or a special role of this kind of multi-joint links. This allows us to answer the question, what are the multi-joint spine muscles necessary for at this stage of human development but it does not provide any insight into the very nature of them.

References

[1] AQUINO C. F., *A dynamic model of the lumber spine*, Journal of Biomechanics, Vol. 3, No. 5, 1970, pp. 473–486.

[2] BELITSCHKO T. B., ANDRIACHI T. R., SCHULTZ A. B., GALANTER J. O., *Analogue studies of forces in the human spine: computational techniques*, Journal of Biomechanics, Vol. 6, No. 4, 1973, 361–371.

[3] DIETRICH M., KEDZIOR K., ZAGRAJEK T., *FEM modelling of human spinal system*, Lecture Notes of the ICB Seminar, International Center of Biocybernetics, Warsaw, Vol. 20, 1993, pp. 9–37.

[4] HESS J. L., LOMBARD C. F., *Theoretical investigations of dynamic response of man to high vertical acceleration*, Journal of Aviation Medicine, Vol. 29, No. 1, 1958, pp. 66–74.

[5] LIU KING Y., MURRAY J. D., *Theoretical study of the effect of impulse on the human torso*, Proceeding of ASME Symposium on Biomechanics, 1966, pp.167–186.

[6] LATHAM F., *A study on body ballistic: Seat ejection*, Proceedings of Royal Society, B–147, 1957, pp. 121–139.

[7] MAGID E. B., COERMAN R., *Human tolerance to whole body sinusoidal vibration*, Aerospace Medicine, Vol. 31, 1960, pp. 915–924.

[8] MC. KENZIE J. A., WILLIAMS J. F., *Dynamics of cervical spine during whiplash*, Journal of Biomechanics, Vol. 4, No. 6, 1971, pp. 477–491.

[9] MUKSIAN R., NASH C. D., *A model for response of seated human to sinusoidal displacement of the seat*, Journal of Biomechanics, Vol. 7, No. 3, 1974, pp. 209–215.

[10] ORNE D., KING. LIU Y., *A mathematical model of spinal response to impact*, Journal of Biomechanics, Vol. 4, No. 1, 1971, pp. 49–71.

[11] PANJABY M., WHITE A. A., *A mathematical approach for three-dimensional analysis of the mechanics of spine*, Journal of Biomechanics, Vol. 4, No. 3, 1971, pp. 203–211.

[12] SCHULTZ A. B., GALANTER J. O., *A mathematical model for the study of the mechanics of the human vertebral column*, Journal of Biomechanics, Vol. 3, No. 4, 1970, pp. 405–416.

[13] SOECHTING J. F., PASLEY P. R., *A model for the human spine during impact including musculature influence*, Journal of Biomechanics, Vol. 6, No. 3, 1973, pp. 195–203.

[14] TERRY C. T., ROBERTS V. L., *A viscoelastic model of the human spine subjected to* + G_z *accelerations*, Journal of Biomechanics, Vol. 1, No. 2, 1968, pp. 161–168.

[15] TOTH R., *Multiple degree-of-freedom nonlinear spinal model*, Proceeding of 19th Annual Conference on Engineering in Medicine and Biology, San Francisco, California, Vol. V, 1967, p. 102.

[16] TREGOUBOV V. P., GRAFEEV E. V., *Determination of mechanical model structure for man exposed to whole-body vibration*, in: *Whole-body vibration influence on human organism and hygienic assessment*, Vol. 41.2, 1992, pp. 333–339.

[17] TREGOUBOV V. P., YEGOROVA N. K., AZANCHEVSKY V. V., *Multi-joint links in mechanical models of spine and whole body under vibration*, Proceedings of the 9th International Conference on Mechanics in Medicine and Biology, Lubljana, 1996, pp. 408–410.

[18] TREGOUBOV V. P., *Modelling of multi-joint links in spinal systems*, Lecture Notes of the ICB Seminar, International Center of Biocybernetics, Warsaw, Vol. 33, 1996, pp. 14–26.

The work was supported by Russian Fond of Base Research, Grant No 98-10-10062.