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DEVELOPMENT OF A BIOMECHANICAL HUMAN MODEL FOR SAFETY ANALYSIS OF THE OPERATORS OF SELF-PROPELLED MINING MACHINES

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Abstract: In the paper, the authors presented an elaboration of the biomechanical model of a human in a sitting position for the dynamic tests related to the impact loads acting on operators of self-propelled mining machines. Here, the human body was replaced with a one-dimensional multi-mass model (in the form of concentrated masses connected with elastic and damping elements). The models of this type are currently used to study ergonomics in vehicles. However, their use is limited because they are adapted to much lower dynamic loads than those acting on the operator in accident situations in mines. Many models of this type, in which the stiffness and damping characteristics of the elements are constant, have been described in the literature. Due to the specificity of the analysed loads acting on the operator, the literature studies were mainly focused on models for vertical forces analysis. By developing non-linear stiffness characteristics, in the currently used car seat ergonomics linear biomechanical models, it was possible to use simple multi-mass models with several degrees of freedom to analyse the effects of dynamic excitation characterised by large displacements. The validation of the developed characteristics was performed using a full-size dummy in a sitting position positioned in the cabin, on the operator's seat.

Key words: passive safety, mining safety, biomechanics, numerical simulation.

1. INTRODUCTION

The requirements for structures protecting mining machine operators are limited to assessing the effects of machine roll-over (Roll-Over Protective Structure [ROPS]) and assessing the effects of events related to falling objects (Falling Object Protective Structure (FOPS)] [1]. These studies do not take into consideration any injuries the operators may sustain. They only describe the deformation of the cabin's load-bearing structure and analyse if the protected space inside the cabin remains intact. However, the analysis of accident situations shows that it is insufficient to assess the operators' safety [2]. It is necessary to define and evaluate biomechanical criteria, as well as to take into account other factors causing accidents that threaten the health and life of operators.

The analysis of accident situations over the last few decades confirms that the current standards do not provide sufficient protection for the operators while significant vertical loads acting on the machine. The authors considered injuries of the operators caused by the machine being thrown upwards as one of the greatest threats. In underground mines, this is due to the dynamic uplift of the floor or burying of the loader buckets by the material, resulting in throwing the machine in a vertical direction. This often results in permanent injury or even death to the operator, due to the limited space above the head in self-propelled mining machines with low transport heights.

The authors conducted a numerical analysis of such a phenomenon using a full-size, anthropometric model of a human being, considering its biomechanics (Fig. 1). A coupled analysis was carried out using two software for numerical simulations: MADYMO (a multibody biomechanical human model) and LS-Dyna (a discrete model of the operator's cabin load-bearing structure with the seat). The human model used during the analysis is based on a dummy used to test the safety of passengers during accidents and emergencies in aircraft, where the vertical forces affect the human body the most.

The construction of the dummy is adapted to transfer such loads, and the obtained results are similar to the response of the human body and repeatable, which was the main reason for the selection of this type of model. This is a 50th-percentile male dummy from the Hybrid III family. It is marked with the abbreviation FAA meaning the Federal Aviation Administration, a transportation agency of the U.S. Government that regulates all aspects of civil aviation [3]. The described dummy was created for the purpose of testing the safety of passengers and airline seats.

As a result of the performed analyses, the injuries that the operator may suffer depending on the velocity at which the machine is thrown upwards were determined [4]. These studies have enabled the operator's safety to be assessed in a wide variety of accident situations. However, this method is not free from disadvantages. Calculations of a full human model with a seat and cabin are complicated and time-consuming, and the software used for numerical simulation is expensive and requires specific knowledge in this area. Therefore, the authors developed a simplified (one-dimensional with four degrees of freedom) biomechanical human model (SBHM) that allows determining the dynamic response to dynamic loads with a large amplitude of kinematic excitations. The authors assumed that the developed research method could be used more widely for testing the safety of operators and did not force the use of dedicated commercial software.

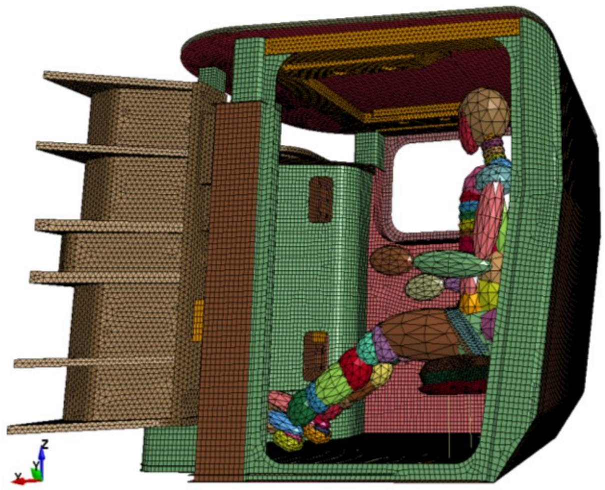

Fig.1. Full-size dummy model with the cab and operators seat

2. BIOMECHANICAL HUMAN MODEL USED IN THE LITERATURE

In the literature, there are many simple dynamic models currently used to study the ergonomics of machine operators and vehicle passengers. However, they are adapted to the analysis of vibrations (with accelerations up to 5 m/s2 and small amplitudes excitations), which do not threaten the lives of operators [5]. In some literature, scientists attempt to modify models of this type to adjust them to much larger loads. Unfortunately, the introduced modifications adapt them only to the one type and value of loads [6]. The introduction of any modifications of the initial boundary conditions in the analyses using models of this type causes the results obtained with their use to differ significantly from the dynamic response obtained using full-size models of the human body. The authors decided to elaborate on such a one-dimensional model in which the applied characteristics defining stiffness and damping will allow to obtain a dynamic response similar to those obtained using a full-size dummy model for a wider range of initial boundary conditions.

In the first stage of the model development, the level of detail of the model was established. It should have enough elements in order to determine the key injuries for the health and life of the operator while maintaining a simple structure with a relatively simple description of the characteristics. While analysing accidents involving machine operators, the authors determined that the effects of spinal injuries, especially in the cervical and lumbar section, as well as head injuries, are most tragic. For this reason, a model with four degrees of freedom was chosen, in which the following elements of the human body can be distinguished: head with neck, body divided into thoracic and lumbar parts, as well as thighs with a sacral part of the spinal cord. More degrees of freedom would significantly complicate the elaboration of the model by introducing too many variables, while a smaller number would make it impossible to obtain the most important information about injuries due to insufficient accuracy.

Due to the above-mentioned aspects, the further analysis included two models with four degrees of freedom available in the literature, which have been proven for years in the study of operator ergonomics [7]. These are models developed by Boileau et al. [8] and Wan and Schimmels [9]. In the literature, you can find many similar models of the human body with four degrees of freedom as those of Abbas [10], Zhang [11], Liu [12], Singh and Wereley [13] or Srdjevic and Cveticanin [14], but all of them are only extensions and modifications of previously mentioned models, which is why the authors focused only on the two basic ones.

Boileau and Rakheja proposed a human model with constant and linear characteristics (Fig. 2). It is a model of a human sitting on a seat with his feet supported and his hands held in a car driving position. It is supposed to enable proper distribution of loads from the vehicle and the seat to the head. It was established that the four degrees of freedom of the model are enough to obtain the data necessary to determine the impact on the behaviour of key parts of the human body. The parameters of the model were selected based on published results of studies on people subjected to low-frequency loads [15], with the limitations identified based on the analysis of anthropometric and biomechanical data available for the human body. The model was tested and, on this basis, it was found that its dynamic response is comparable to the response of the human body under dynamic excitations with acceleration values not exceeding 4 m/s2. The proposed driver model consists of four elements with a mass, connected by elastic elements with linear stiffness and damping characteristics. This assumption is consistent with the generally accepted idea that in the first approximation, the non-linearity of the human body can be neglected when the vibration load is not excessive. The four weights represent the following four parts of the body: head and neck (m1), chest with upper torso (m2), lower torso (m3) and thighs and pelvis with seat (m4). The weight of the lower legs with feet is not included in the model, because its share in the dynamic response is negligible and does not affect the results in terms of loads and displacements of the upper part of the biomechanical model of the human body. This is due to the support of the feet and the fact that the mentioned elements of the model are outside the seat and do not constitute a load for it. This assumption is also justified by Fairley [16], who proved that the share of the legs in transferring the vertical forces of the cushioned seat is relatively insignificant, as both the legs and the seat are subjected to the same kinematic inputs. Hands and further arms are supported on the steering wheel and are also not included in the model, assuming that their mass has a negligible contribution to the obtained dynamic response of the whole body. The inertia of the four main body segments in the model is determined based on anthropometric data identified by Pheasant [17]. On this basis, the proportion of total body weight estimated for different body segments is 8.4% for the head and neck, 36.6% for the chest and upper body, 13.4% for the lower body and 20% for the thighs and pelvis. For a seated driver with an average body weight of 75.4 kg, it is assumed that 73.6% of the weight is supported by the seat, so it is approximately 55.5 kg of total body weight. The following segments are connected by elements with the following stiffness and damping coefficients: pelvis and thighs are represented by k1 and c1, lumbar region by k2, c2, thoracic region by k3, c3, and cervical spine by k4, c4. The development of a human body model involves the identification of these parameters. The biomechanical properties of the spine, thorax, and upper body are relatively unknown and vary widely. In a study conducted on corpses, Kazarian [18] determined the stiffness for

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the lumbar spine in the range of 100–300 kN/m and for the thoracic spine in the range of 150–200 kN/m. Mertens [19] proposed a model of the human body using damping coefficients in the range of 500–4000 Ns/m. Although the reported data represents high variability, the identified ranges can be used as effective limit values for optimising the models.

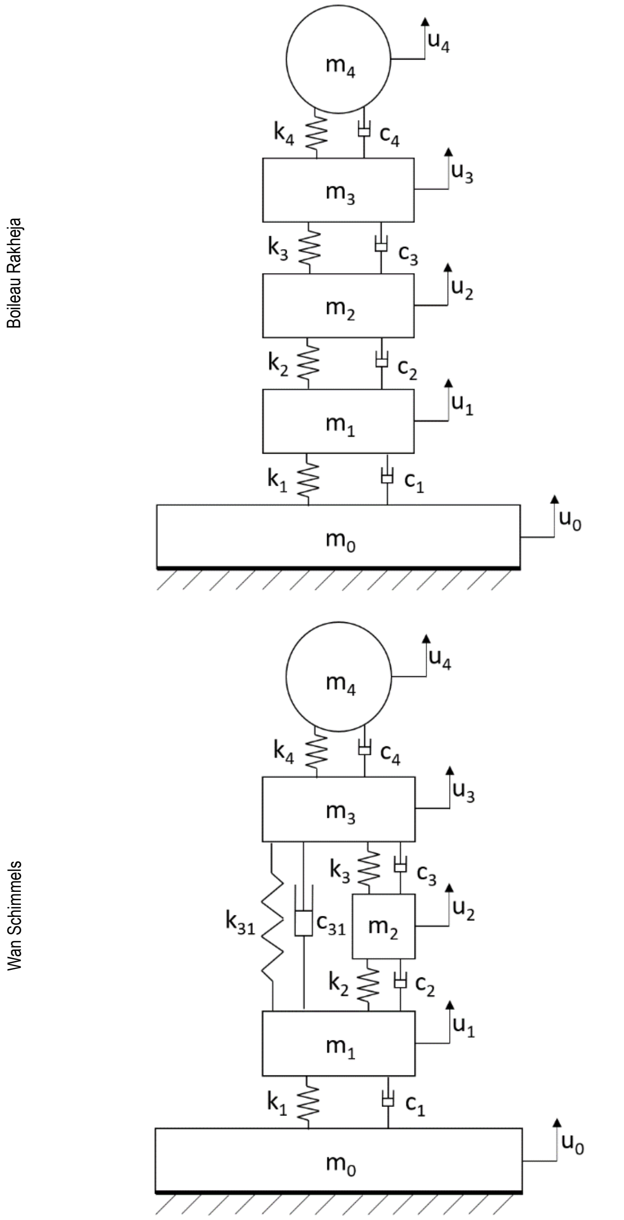

Fig.2. BR and WS models. BR, Boileau-Rakheja; WS, Wan-Schimmels

Finally, for the elements of the analysed model, the following characteristics were adopted by Boileau and Rakheja [20]:

m_1 = 12.78 kg,	k_1 = 90 kN/m,	c_1 = 2,064 Ns/m.
m_2 = 8.62 kg,	k_2 = 162.8 kN/m,	c_2 = 4,585 Ns/m,
m_3 = 28.49 kg,	k_3 = 183 kN/m,	c_3 = 4,750 Ns/m,
m_4 = 5.31 kg,	k_4 = 310 kN/m,	c_4 = 400 Ns/m.

This approach made it possible to develop a generalised and unique model of the seated vehicle drivers, based on which the dynamic behaviour of the human body can be estimated.

The Wan-Schimmels (WS) model, similar to the Boileau-Rakheja (BR) model discussed above, is composed of four separate mass segments. The difference is the number of connections – the segments are connected with each other by five pairs of springs and dampers, and the total weight of the model is 60.67 kg. The stiffness and damping properties of the thighs and pelvis are (k1) and (c1), the lower torso is (k2) and (c2), the upper torso is (k3, k31) and (c3, c31), and the head is (k4) and (c4). The values of masses, stiffnesses and dampings determined in this model are as follows:

m_1 = 36 kg,	k_1 = 49.34 kN/m,	c_1 = 2,475 Ns/m.
m_2 = 5.5 kg,	k_2 = 20 kN/m,	c_2 = 330 Ns/m,
m_3 = 15 kg,	k_3 = 10 kN/m,	c_3 = 200 Ns/m,
	k_{31} = 192 kN/m,	c_{31} = 909,1 Ns/m
m_4 = 4.17 kg,	k_4 = 134.4 kN/m,	c_4 = 250 Ns/m.

The four weights represent the following body segments: head and neck (m4), upper torso (m3), lower torso (m2) and thighs and pelvis (m1). The arms and legs are connected to the upper torso and thigh respectively.

The WS model is also limited to acceleration in the range around 4 to 5 m/s2.

2.1. Literature models comparison

The models discussed above have been subjected to loads that may be experienced by machine operators during accidents in mines related to the uplift of the floor. These results were then compared with the results obtained after analysing a full-size human model in the MADYMO program (Hybrid III). All models were analysed with the velocity of the upthrow of 10 m/s and then suddenly stopped, which was followed by a rebound and free fall [21]. This simulates the event of throwing the machine up and then impacting the roof of mine gallery [22]. An additional degree of freedom has been added to the biomechanical models in the form of the operator's seat, along with the stiffness and damping of its base. A comparison of the dynamic response for the dummy from MADYMO and the models presented in Fig. 2 for velocities 5 m/s and 10 m/s are shown on charts in Figs. 3 and 4.

The results obtained from both one-dimensional models described in the literature were similar and at the same time, both significantly differed from the results obtained using a full-size human body dummy. This confirms the authors' assumption of these models regarding the limitation of kinematic excitation to which they may be subjected. In the performed analysis, the loads significantly exceeded the limit, and permissible accelerations were specified in the range of up to 5 m/s2. This means that none of these models can be used directly to study this phenomenon causing accidents in mines without introducing the necessary modifications to them.

Finally, the Boileau-Rakhej model was adopted for further analysis due to the smaller number of parameters and thus characterized by a greater simplicity of description, which in turn facilitates the process of adapting the model to the given boundary conditions.

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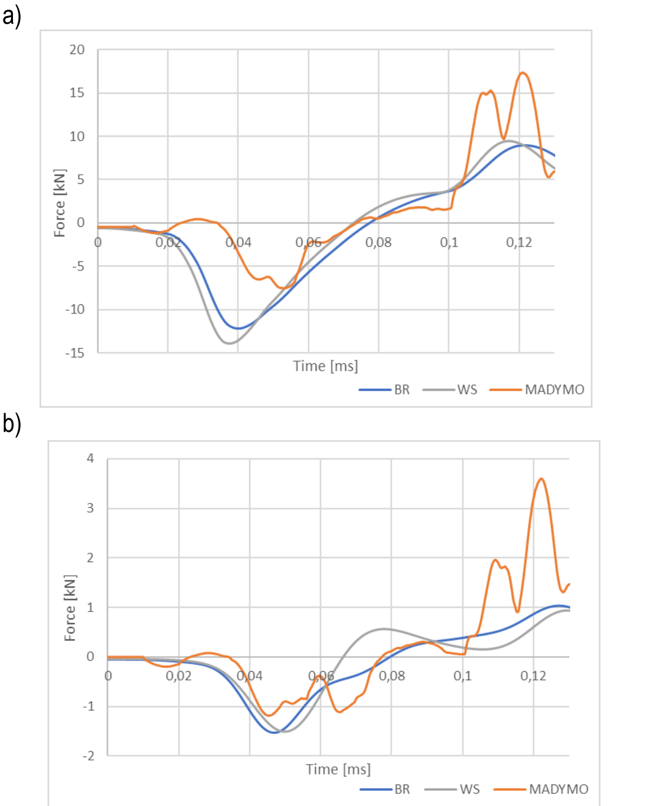

Fig. 3. Comparison of forces acting on a lumbar spine of the human model; BR model, WS model, MADYMO – MADYMO Hybrid III dummy (a – lumbar spine, b – cervical spine; velocity 5 m/s). BR, Boileau-Rakheja; WS, Wan-Schimmels

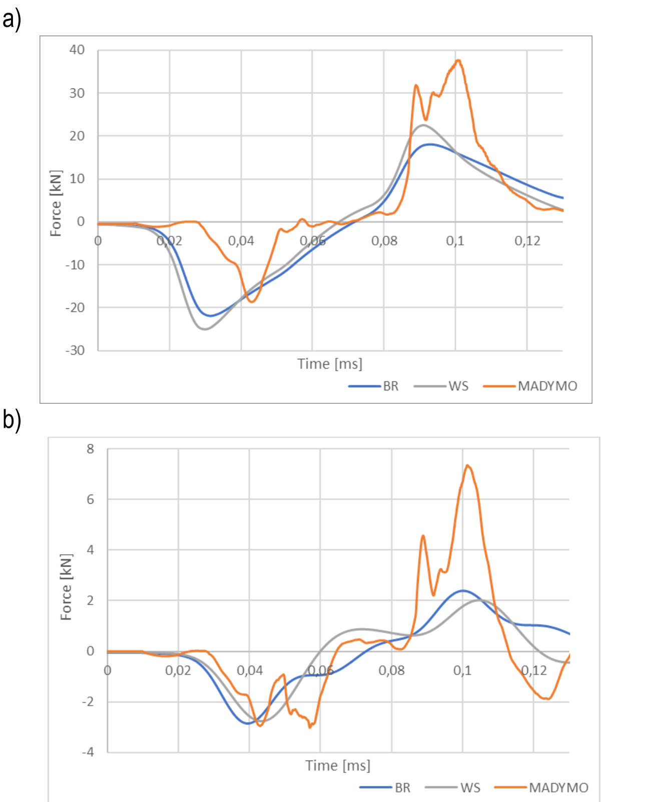

Fig. 4. Comparison of forces acting on a cervical spine of the human model; BR model, WS model, MADYMO – MADYMO Hybrid III dummy (a – lumbar spine, b – cervical spine; velocity 10 m/s). BR, Boileau-Rakheja; WS, Wan-Schimmels

3. SIMPLIFIED BIOMECHANICAL HUMAN MODEL

The one-dimensional model of a seated human was developed, whose dynamic response to the imposed excitation is similar to a full-size dummy seated on the operator's seat (Fig. 5).

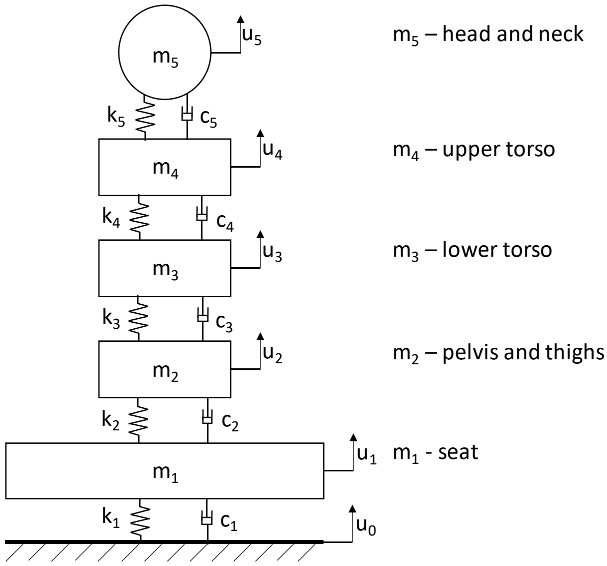

Fig. 5. Applied, SBHM of the operator positioned on the seat, with 5 degrees of freedom SBHM, simplified biomechanical human model

It is a 5-degree-of-freedom model that can be analysed with any software capable of solving inhomogeneous non-linear second-order differential equations. The model is described by the differential equations of motion shown below:

$$m_1\ddot{u}_1 + c_1(\dot{u}_1 - \dot{u}_0) + k_1(u_1 - u_0) - c_2(\dot{u}_2 - \dot{u}_1) - k_2(u_2 - u_1) = 0$$

$$m_2\ddot{u}_2 + c_2(\dot{u}_2 - \dot{u}_1) + k_2(u_2 - u_1) - c_3(\dot{u}_3 - \dot{u}_2) - k_3(u_3 - u_2) = 0$$

$$m_3\ddot{u}_3 + c_3(\dot{u}_3 - \dot{u}_2) + k_3(u_3 - u_2) - c_4(\dot{u}_4 - \dot{u}_3) - k_4(u_4 - u_3) = 0$$

$$m_4\ddot{u}_4 + c_4(\dot{u}_4 - \dot{u}_3) + k_4(u_4 - u_3) - c_5(\dot{u}_5 - \dot{u}_4) - k_5(u_5 - u_4) = 0$$

$$m_5\ddot{u}_5 + c_5(\dot{u}_5 - \dot{u}_4) + k_5(u_5 - u_4) = 0 \qquad (1)$$

where: *mn* – mass of following segments; *un* – time-variable displacements; *kn* – stiffness as a non-linear deflection function; *cn* – damping.

The dynamic model was built in Matlab Simulnk R2022b. The model is shown in Fig. 6. As part of the tests performed, the dynamic responses of the system to the given excitation were analysed. In the model, elements of the integrator type were used twice to integrate the acceleration signal of a given term, to the velocity and, in the second step, to the displacement. These blocks are marked in yellow on the model. The blocks marked in orange describe the dependence of the segment stiffness on the

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value of the displacement difference between individual segments (deflection). The Ki(Ui) relationship diagrams are shown in Figs. 6–10. Damping values adopted following literature data [8] are marked in green, and mass elements used in the model are marked in light blue. The model uses blocks from groups: Math Operations, Continuous, Lookup Tables, Sources and Sinks.

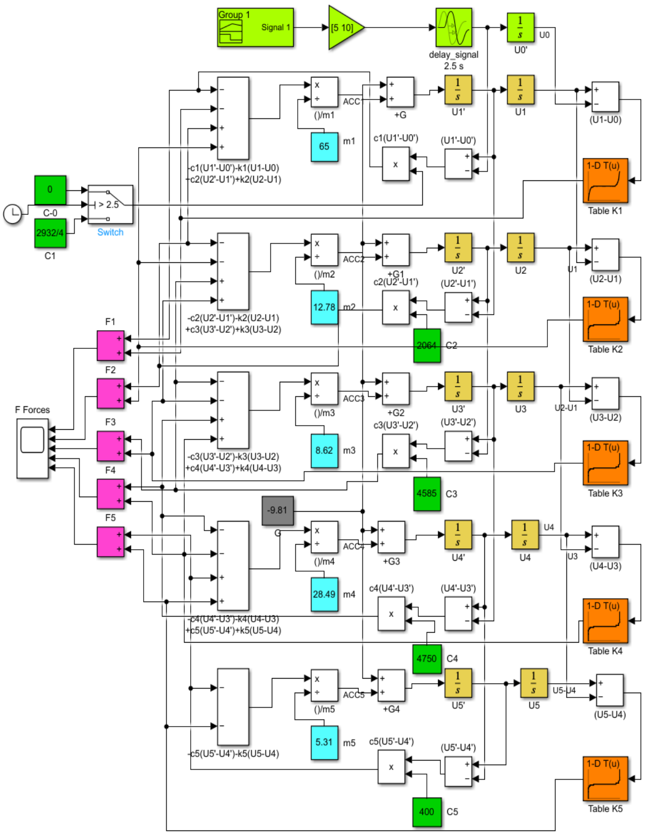

Fig. 5. Diagram of the developed SBHM in MATLAB Simulink. SBHM, simplified biomechanical human model

The simulation was carried out for a period of 3.5 s. For the first 3 s, the only load acting is gravity, which helped to stabilize the system. Then, an excitation in the form of a time-varying displacement is introduced into the system. Kinematic excitation in the form of variability of displacements over time was obtained by integrating the course of velocity changes (excitation U0 – the excitation signal was marked with light green in the diagram). The dynamic response was analysed for two maximum values of the excitation velocity 5 m/s and 10 m/s (maximum value of the course), respectively. In the proposed model, the values of forces acting on individual elements in the model were determined (marked in magenta). The values obtained from the Matlab Simulink R2022b model were compared with the values obtained from analyses in the Abaqus and Madymo software.

The configuration parameters set in the simulation are as follows: simulations were performed with a constant integration step of 1.0 e–5/s. The method of direct integration of equations (solver based on Euler's equations) was used, i.e. the Euler integration method is used to compute the model state at the next time step as an explicit function of the current value of the state and the state derivatives. This solver requires fewer computations than a higher-order solver [23].

The stiffness parameters were selected empirically, by comparing and matching the results with the results obtained using a full-size numerical model of a human placed in the operator's seat (there was also a condition that in a certain range of deflections, the deviation checked by the least squares method from the linear model should meet the condition R > 0.9998.

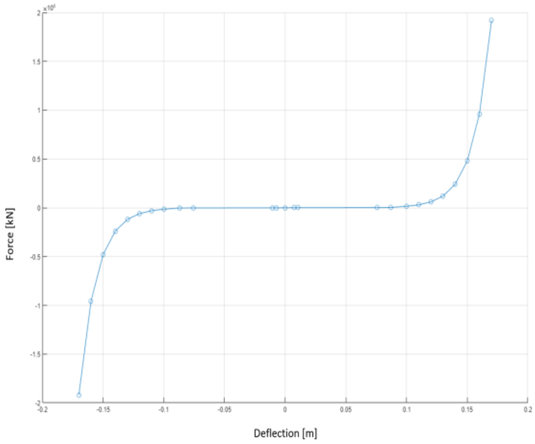

Fig. 6. Stiffness k1 of the seat base segment

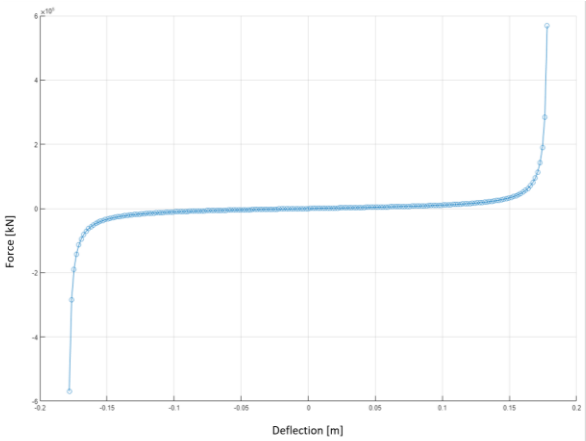

Fig. 7. Stiffness k2 of the thighs and sacral part of the spine with seat cushion segment

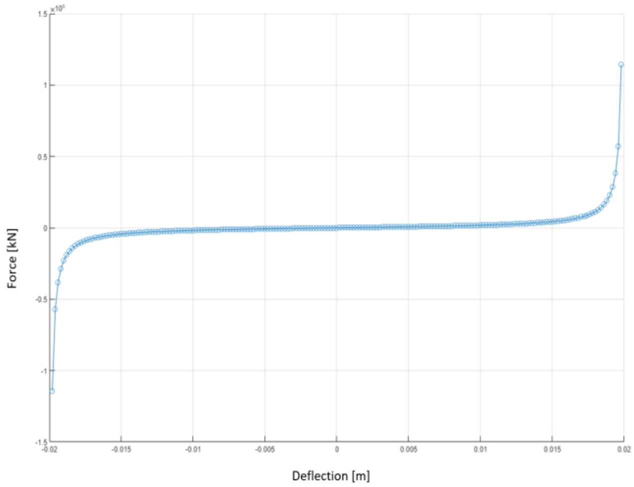

Fig. 8. Stiffness k3 of the lower torso segment

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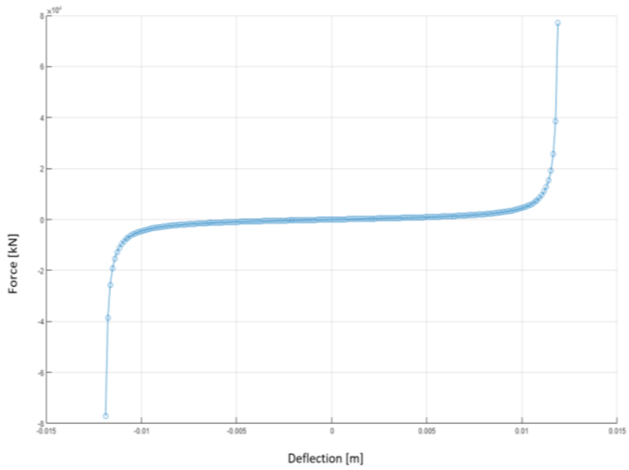


Fig. 9. Stiffness k4 of the upper torso segment

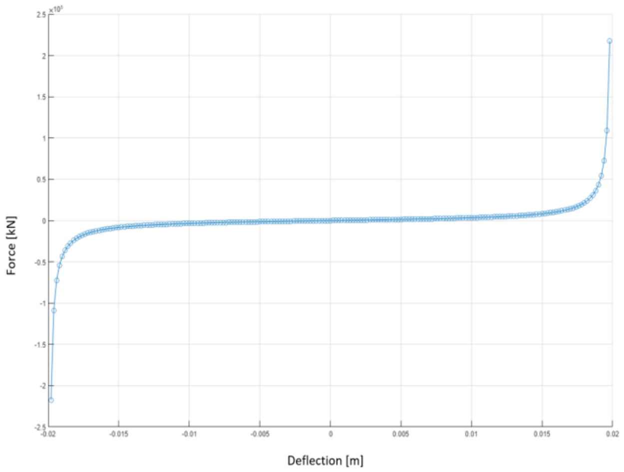


Fig.10. Stiffness k5 of the cervical spine segment

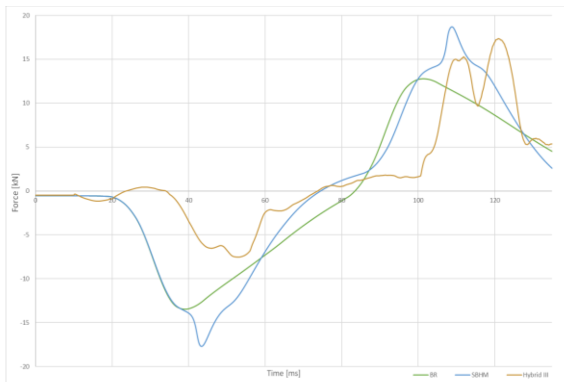
4. MODEL COMPARISON

To develop a one-dimensional biomechanical model of a seated operator, the authors used a model with four degrees of freedom developed to assess the ergonomics of machines and vehicles [8]. The linear models used so far in ergonomics studies have been developed based on experimental studies involving people, subjected to dynamic inputs, with small ranges of displacement (vibrations) safe for the health of the subjects. The existing models, due to linear characteristics, do not allow obtaining the correct results for excitations with large displacement amplitudes occurring simultaneously with high velocities, which occur in accident situations involving mining machine operators [21,22].

The authors introduced significant changes to the existing models consisting of describing the characteristics with non-linear functions and thus obtained a dynamic response in a one-dimensional model, similar to the results obtained in analyses using commercial solutions based on full-size dummies. Satisfactory results were obtained primarily for high velocities of the occurring phenomena. Characteristics that allowed the use of simple one-dimensional biomechanical models with four degrees of freedom to analyse impact dynamic loads were developed. To verify the correctness of the developed model, the obtained results (forces acting in individual segments) for various excitation velocities were compared with the results obtained for the Hybrid III (MADYMO) dummy. The developed biomechanical model allows us to determine the values of loads acting in several individual parts of the spine and to analyse the effects of the accident situation. It also allows for the deliberate development of structural elements to reduce the loads acting on the operator without the need to use commercial solutions in the form of, for example, the Hybrid III dummy. Requirements for structures protecting operators in terms of assessment of work ergonomics with loads related to vibrations arising during normal operation of machines can also be successfully analysed using the developed biomechanical model. In the linear part (at small ranges of deflection changes), the characteristics describing the stiffness of individual model elements were developed based on experimental studies on people, subjected to low dynamic excitations (vibrations safe for the health of the subjects). The authors showed that in the case of large deflections, the results obtained from the models described in section 2 of the paper are not correct, especially for the loads to which machine operators are subjected during an accident situation.

The modification of the linear characteristics in the models, introduced by the authors, allowed us to obtain quantitatively and qualitatively similar results to those obtained with the use of full-size dummies, as well as for large kinematic excitation. A method for determining the characteristics was developed, which allows the model to be adapted to the analysis of different loads in terms of duration and intensity. The results for different excitation velocities for SBHM, Hybrid III and Boileu-Rakheja original models were compared to verify the correctness of the developed characteristics, (Figs. 11 and 12).

a)



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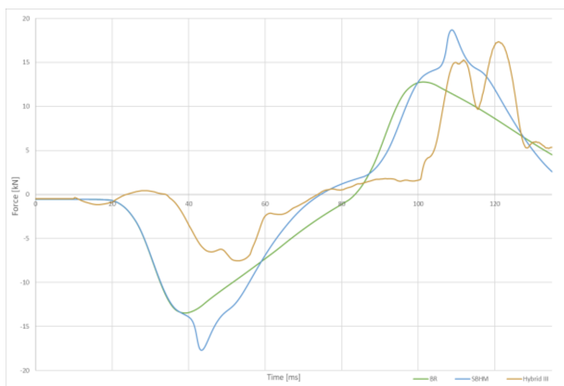

Fig. 11. Results comparison of full-size dummy (Hybrid III) and elaborated model SBHM; a – lumbar spine, b – cervical spine; velocity 5 m/s. SBHM, simplified biomechanical human model

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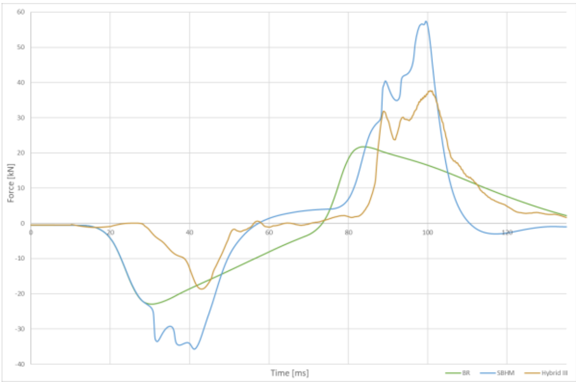
a)



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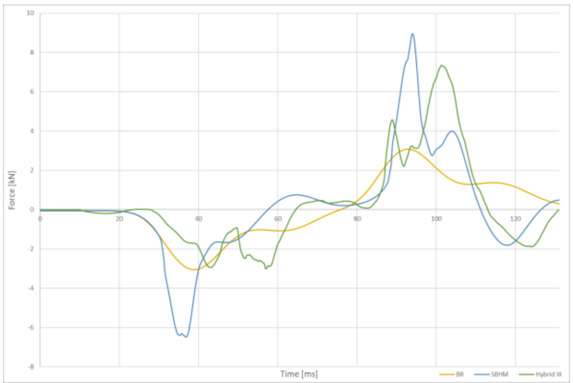

Fig. 12. Results comparison of full-size dummy (Hybrid III) and elaborated model SBHM; a – lumbar spine, b – cervical spine; velocity 10 m/s. SBHM, simplified biomechanical human model

5. CONCLUSIONS

The authors performed a comparison of the results obtained from two models, for the analysis of which the same initial boundary conditions were adopted. One of them is a full-size model of the operator with the seat and cabin, while the other is a proprietary one-dimensional model (the 5th degree of freedom is related to the movement of the seat).

1. A model has been developed in a way that allows the analysis of accident situations in mines, which have not been taken into account in safety studies so far.
2. A one-dimensional model of the human body (SBHM) based on the BR model was introduced, enabling a relatively simple and quick analysis of the loads acting on the human body, which can replace the full-size model in the initial analysis.
3. The characteristics that allow the multi-mass model with 5 degrees of freedom to be used for this analysis of impact phenomena were developed based on the author's method.

The developed characteristics implemented in a simple human model can also be used to analyse other phenomena related to the everyday operation, not only to assess the safety of mining machine operators. Safety assessment methods, so far limited to assessing the effects of rollover of the machine ROPS and assessing the effects of events related to falling objects FOPS [1] (these studies do not determine operator injuries, describe only the deformations of the cabin load-bearing structure and analyse the protected space) can now be supplemented with additional test methods and assessment criteria based on the biomechanics of the human body.

The direction for further research is the implementation of the model in studies on energy-absorbing elements, which will mitigate injuries resulting from accidents caused by vertical loads.

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