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## THE USE OF BIOMECHANICAL INDEX TO ESTIMATE SOLDIER'S LEVEL OF THREAT

**Abstract:** The aim of the article was to characterize the biomechanical indicators for assessing the severity of the crew of special vehicles. Defined parameters affecting obtainable value of indicator, their the method of determining and interpretation. In addition, the author developed a original computer program to determine the biomechanical indicators. The examples of the results of the indicators obtained on the basis of experimental studies are presented as well.

### 1. Introduction

An explosion of land mine under a military vehicle has a great influence on the vehicle itself but also, and first of all, on the people inside it. All factors like temperature, pressure or acceleration have a measurable impact on a person's physical and mental health. A branch of science dealing with mechanical overload on a human body is called biomechanics. Each part of the body, any organ reacts in a different way to a given overload. To understand the threats biomechanical index has been elaborated for their estimation [2, 3].

The scale of crew's danger in a moment of explosion depends on the distance from the source of explosion as well as the direction of the shock wave. A proper vehicle construction is able to cushion some of the overloads or at best level them completely. To parts of the body most prone to injury we include a head, a spine, lower limbs and internal organs. The explosion is connected with many factors which influence the body in many various ways [2, 3].

### 2. Head Injury Criterion

A head is the most injury-prone part of a body. It often happens that passengers of military vehicles experience serious injuries, lameness or even death. Such injuries are common in car crashes that's why the parameter is often tested in crash-tests to evaluate the vehicle's safety [2].

Overload tolerance is individual for every person and depends on such factors like age, sex, health condition. The degree of injury is dependent on maximum parameter value but also the direction of acceleration and time [1,2].

To set a factor Head Injury Criterion the formula beneath is applied [2,3]:

$$HIC = \max \left[ (t_2 - t_1) \left( \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right)^{2,5} \right] \quad (1)$$

where:

$a(t)$  - acceleration of the center of mass of the head [ $m/s^2$ ],

$g$  - gravity acceleration [ $m/s^2$ ],

$(t_2 - t_1)$  - interval of maximum acceleration [s].

For the factor HIC36 critical value was taken 1000. The research is done within 36 ms. Exceeding the value can result in serious head injuries or even a loss of life. The value was used regardless of sex, age, or weight of a person. The latest research suggests lowering critical value HIC 15 to 700 (examined max within 15 ms) as a barrier between the lack of injuries and the appearance of medium injuries. The value would be right for men, women and children over the 6<sup>th</sup> year of age. For 3 year old children the value would be 570 and for babies/infants 390. The values were examined due to a fact that the factor is also used to check car safety, airbags or in designing extreme sport helmets. Head Injury Criterion is the basic criterion used in designing soldier's helmet too [2, 3, 1].

### 3. Neck Injury Criterion

The mechanism which reduces overload affecting head is neck spinal column. In the moment of acceleration the head moves backwards. The move gives a beginning to forces affecting cervical vertebrae which results in injuries. Very often along with head injuries, the spine is endangered too. Biomechanical factor describing the relation of acceleration impact and speed over the probability of injury is called Neck Injury Criterion [2, 3].

$$NIC = 0,2a_{rel} + v_{rel}^2 \quad (2)$$

where:

$a_{rel}$  - the relative acceleration between the first thoracic vertebra (T1), and the first cervical vertebra (C1) [ $m/s^2$ ],

$v_{rel}$  - the relative velocity between the first thoracic vertebra (T1), and the first cervical vertebra (C1) [ $m/s$ ],

0,2 – constant that specifies the length of the cervical spine.

The critical value index is assumed NIC 50 -15  $m^2/s^2$ . After exceeding the value there is a change in the natural shape of spinal column what in consequence results in breakage of vertebra and other and other serious injuries. All spine injuries lead mostly to lameness and death at worst [2, 3].

The acceleration exerted on the spine turns into certain squeezing and stretching forces as well as bending moments affecting the cervical part of the spine. There is a criterion including the parameters called  $N_{ij}$ . Beneath the formula is presented [2, 1, 8]:

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (3)$$

where:

$F_z$  – compression force [N],

$M_y$  – extension or flexion bending moment [Nm],

$F_{int}$  – critical value for extension or flexion [N],

$M_{int}$  – critical value for extension [Nm].

The parameter in the formula depends on type of overload. The force in the axle can squeeze vertebra or cause their stretching. Critical value of axle force is independent on the direction of its action. A slightly different situation occurs during bending moments. For  $N_{ij}$  criterion, index border value equals 1.0. Exceeding the value means 15% probability that serious injuries will occur. The probability rises proportionally to the rise of index value. The most common injuries of cervical part are breakage, grinding or twisting [2, 1, 8].

*Table 1. Critical value of parameters for  $N_{ij}$  criterion [2, 8]*

Human body type	Compression force [N]	Flexion force [N]	Bending moment to front [Nm]	Bending moment to back [Nm]
1 year -old baby	1465	1465	43	17
3 year-old toddler	2120	2120	68	27
6 year- old child	2800	2800	93	39
Woman	3370	3370	155	62
Average man	4500	4500	310	125
Big man	5440	5440	415	166

#### 4. Combined Thoracic Index

Thoracolumbar part of the spine like the cervical is prone to serious injuries evoked by explosion. At the highest level there are inner organs namely a heart or lungs, absolutely essential for life. The organs are protected by ribs which nonetheless under pressure of shock wave bend or even break leading finally to their complete damage. Too big chest indentation results in crushing the inner organs. Moreover the organs are hurt by bits of breaking ribs. High pressure can lead to disturbance of natural heart electromechanical impulses that stimulate its action (Fig. 1). There is a danger of arrhythmia, atrial fibrillation or heart attack [8].

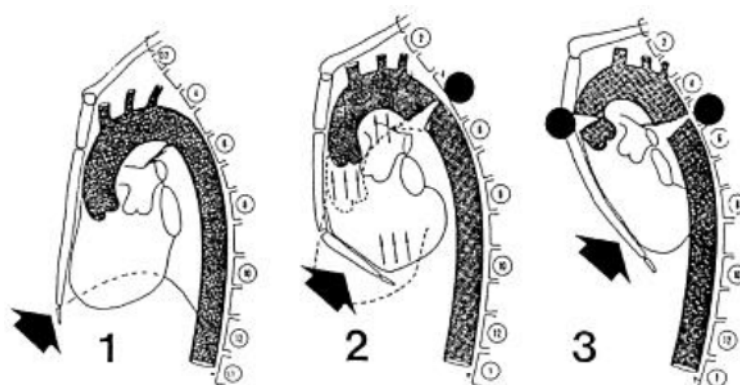


Fig. 1. The consequences of excessive chest pressure load [8]

$$CTI = \frac{A_{max}}{A_{int}} + \frac{D_{max}}{D_{int}} \quad (4)$$

where:

$A_{max}$  - the maximum value of the acceleration acting on the chest [ $m/s^2$ ],

$D_{max}$  - the maximum deflection of the chest [mm],

$A_{int}$  - maximum allowable values of the acceleration acting on the chest [ $m/s^2$ ],

$D_{int}$  - maximum allowable deflection of the chest [mm].

CTI index value should not exceed 1.0. Each man is different in height, weight, age and sex. It applies to inner organs too which are able to cushion the explosion overload on the chest [1].

Table 2. The critical values of the parameters for the criterion CTI [3]

Human body type	Large Male	Mid - sized Male	Female	6 year- old child	3 year – old toddler	1 year - old baby
$D_{int}$	114	103	84	64	57	50
$A_{int}$	83	90	90	90	74	57

## 5. Dynamic Response Index

Another biomechanical index connected with thoracolumbar part of spine is Dynamic Response Index (DRI). This criterion can help to estimate spine compression as a result of charge explosion under a multi-purpose vehicle. The index was borrowed from the aircraft industry where it is used for pilot seats' examination. The criterion is nothing but an analysis of simple mechanical set with one latitude (Fig. 2). The set does not correspond with the human body and its dynamic reaction to sudden overload in the direction of an axle (hence the index is often defined as DRI) [2, 3].

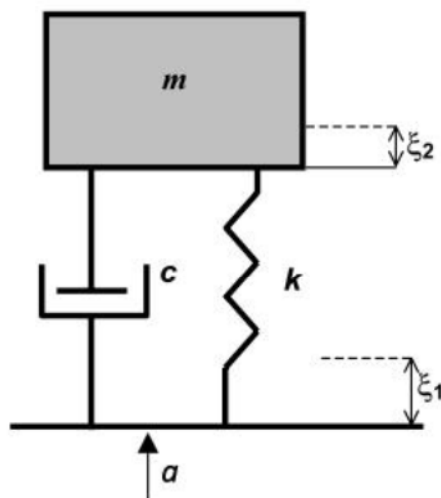


Fig. 2. Model DRIZ [1,2]

Using simple dynamic mechanical systems dependence, the following equation of motion for this model is [2, 3]:

$$a(t) = \frac{d^2\delta}{dt^2} + 2\varphi\omega_n \frac{d\delta}{dt} + (\omega_n)^2\delta \quad (5)$$

where:

$a(t)$  – is the acceleration in the vertical direction measured at the position of initiation;

$\delta$  – is the relative displacement of the system with,

$$\delta = \xi_1 - \xi_2 \quad , \delta > 0 \quad (6)$$

$\varphi$  – is the dumping coefficient,

$$\varphi = \frac{c}{2 \cdot m \cdot \omega_n} \quad (7)$$

$\omega_n$  – is the natural frequency with,

$$\omega_n = \sqrt{\frac{k}{m}} \quad (8)$$

The Dynamic Response Index is calculated by the maximum relative displacement  $\delta_{max}$ , natural frequency  $\omega_n$  and the gravity acceleration  $g$  [1,2].

$$DRI = \frac{\omega_n^2 \cdot \delta_{max}}{g} \quad (9)$$

where:

$\omega_n$  - 52,9 rad/s = 8,4 Hz,

$\varphi$  - 0,224.

The above parameter values were assigned in the aircraft industry research. Border value of DRI index equals 17.7. Exceeding the value according to AIS scale means 10 % probability of serious spine injuries. DRI index analysis enables technical development of military vehicle's seats [2, 3].

## 6. Tibia Index

Reactions acting in the vertical axle create a great danger for lower limbs. In the time of explosion under a military vehicle feet are located on the bottom. As a result of local explosion the floor of the vehicle gets distorted and the same forces affect directly the lower limbs. The most prone to injury is tibia. To estimate danger we apply Tibia Index [3, 1].

$$TI = \frac{F_z}{(F_z)_{int}} + \frac{M_g}{(M_g)_{int}} \quad (10)$$

where:

$F_z$  – axial compression force [kN],

$M_g$  – resultant bending moment [Nm],

$(F_z)_{int}$  – critical axial compression force [kN],

$(M_g)_{int}$  – critical bending moment [Nm].

Table 3. The critical values of the parameters for the criterion TI [1]

Human body type	Large female	Mid – sized female	Male
$(M_g)_{int}$	307	225	115
$(F_z)_{int}$	44,2	35,9	22,9

## 7. Traumatic Brain Injury

Biomechanical index which estimates the level of brain injury is Traumatic Brain Injury (TBI). The injuries which seem to be harmless in the very first moment often end in serious complications leading to disability or death. The injury is caused by a rapid and strong head impact into an object. Brain injury is caused by acceleration parameter affecting the brain along with making it move in a braincase (brain ricochet or brain injuries caused by broken skull bones). Biomechanical index TBI, unlike the other indexes, is not defined by a formula. The essential thing is the right recognition of brain injuries as a result of accidents. That's why the symptoms connected with TBI index can be divided into: light, mild and hard [7, 6].

## 8. Chest Wall Velocity Predictor

Another index referring to inner organs placed in the thoracolumbar part of the spine is Chest Wall Velocity Predictor (CWVP). Like in the DRI case, chest is perceived as a simple dynamic and mechanical structure (Fig. 3).

The essential parameter is the pressure affecting the rib cage. While the chest sinks deeper into the body, the internal organs such as a heart and lungs and ribs are crushed. The structure of the chest is able to cushion the pressure by acting like a spring. A measurable affect onto the parameter's harmfulness is the direction and time of action [2, 3, 5].

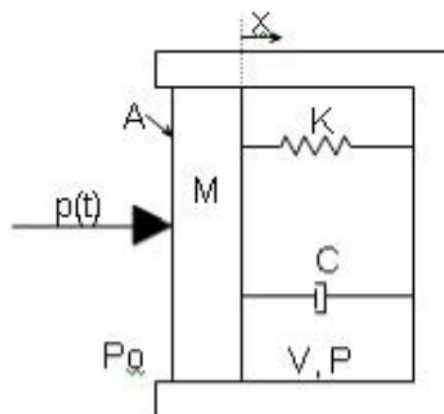


Fig. 3. Thorax Model [2]

The action of presented structure in fig. 3 can finalize in the formula beneath [3]:

$$M \cdot \frac{d^2x}{dt^2} + C \cdot \frac{dx}{dt} + K \cdot x = A \cdot \left[ p(t) + P_0 - \left( \frac{V}{V - A \cdot x} \right)^\gamma \cdot P_0 \right] \quad (11)$$

where:

A – effective area [m<sup>2</sup>],

M – effective mass [kg],

V – initial gaseous volume of the lungs [m<sup>3</sup>],

x - displacement [mm],

C – damping factor [Ns/m],

K – elasticity pressure [N/m],

P<sub>0</sub> – ambient pressure [Pa],

p(t) - overpressure [Pa],

γ – polytropic exponent for gas in lungs.

Most parameters are dependent on the type of human body. The values have been checked by Axelsson and put in a chart (4) for medium human (about 70 kg) [3]:

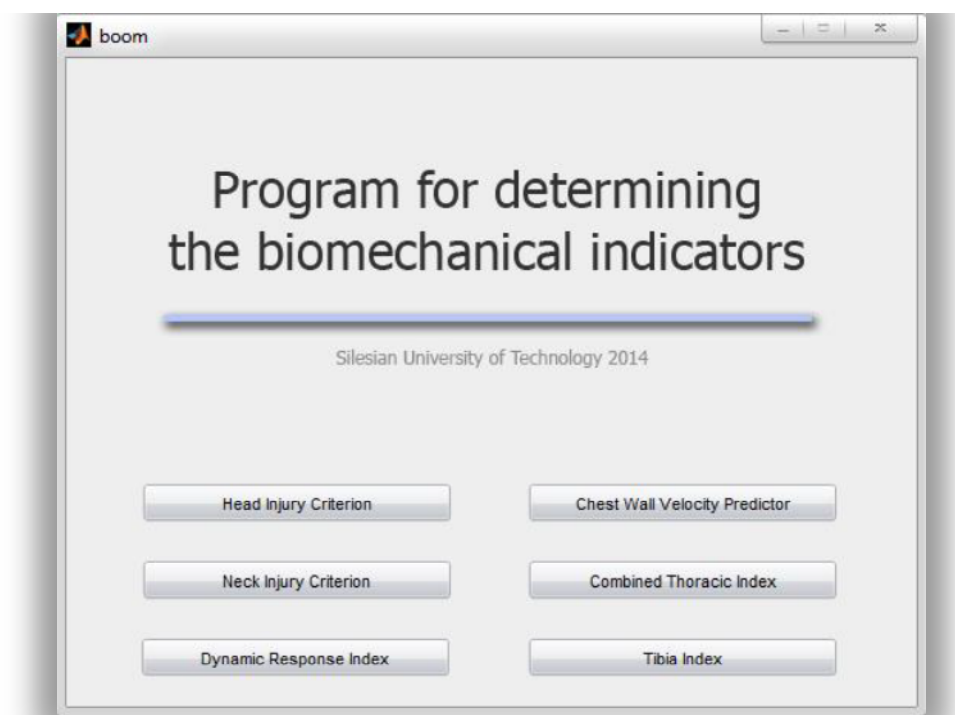
Table 4. The parameter values for a medium-sized man [3]

Parameter	Unit	Value
M	kg	2.03
C	Ns/m	696
K	N/m	989
A	m <sup>2</sup>	0,082
V	m <sup>3</sup>	0,00182
γ	-	1,2

Exceeding the values of 3.6 ms speed onto the chest given a risk of injuries. The higher the speed, the greater the injury [3, 5].

## 9. An original computer program for determining the biomechanical indicators

Within a project an authorial computer program was elaborated which is used to appoint selected biomechanical indexes to estimate the danger of the crew. Matlab program was used to carry out the task. The idea helps to perform complicated calculations and simulations. Moreover it is possible to design dedicated graphic interface (GUI) which enables to move around intuitively as well as to operate easily. The program allows to appoint indexes described before (Fig. 4).



*Fig. 4. Graphic User Interface*

The program allows to become familiar with basic information about the selected indicator, such as the formula and the critical value (Fig. 5).



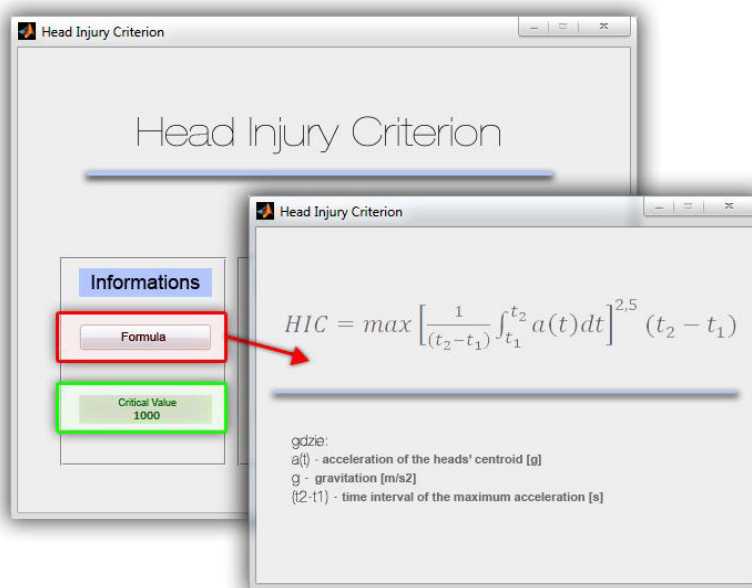


Fig. 5. Window containing the formula for calculating the sample rate of HIC indicator

It is possible to perform calculations using the downloaded file measurement data obtained during the tests. The result appears on the right side of the window and the corresponding color indicates a possible critical value is exceeded. Moreover, the results are displayed as a graph of the resulting value changes over time and saved to a separate file so that it is possible to analyze them next (Fig. 6).

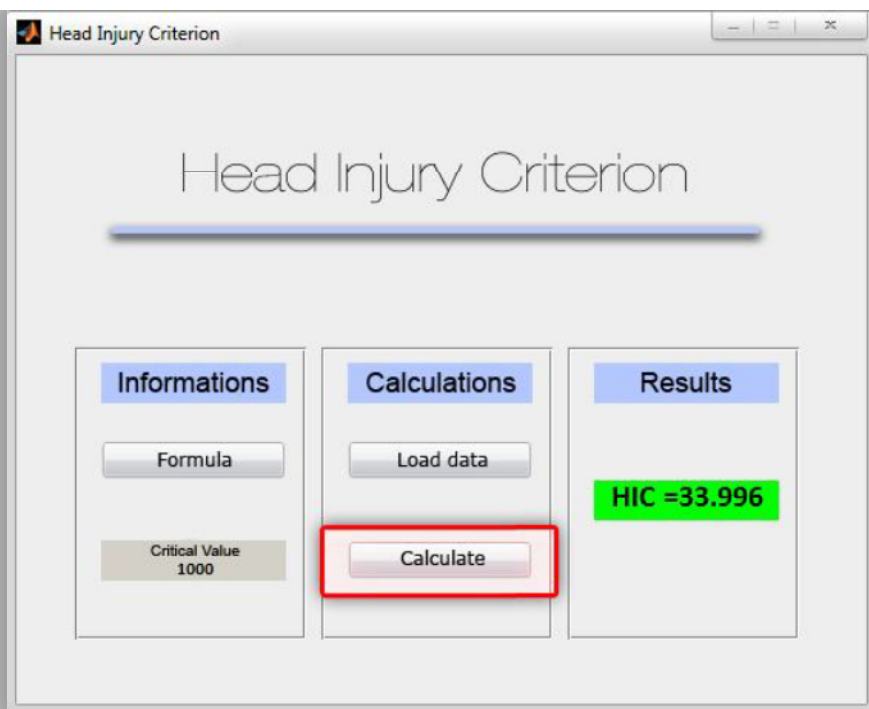


Fig. 6. Window program after completing the calculation

## 10. Conclusion

Biomechanics is an interdisciplinary science dealing with the examination of living organisms and their behavior influenced by external forces. It can be applied to many branches of science such as medicine, sport or even military. By means of biomechanical indexes it is possible to estimate the level of danger resulting from exceeding of critical values to organism. For many years they have been applied in car industry e.g. Crash tests through which the car's safety is examined. Nowadays biomechanical index is a part of technological development in military vehicles or as a means of soldiers' personal security used by modern armies.

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