Estimation of spine injury risk as a function of bulletproof vest mass in case of Under Body Blast load

Artur Iluk

Abstract Currently, the majority of Under Body Blast (UBB) test of vehicles is carried out according to STANAG 4569 with the use of 50th percentile male Anthropomorphic Test Device (ATD) Hybrid III and Dynamic Response Index (DRIz) criterion based on the acceleration profile. In practice, the soldiers often wear Personal Protection Equipment (PPE) increasing their weight, such as massive bulletproof vests. In the paper, the increase of the spine injury risk as a function of the actual occupant mass and the additional load of the torso was estimated for three types of the blast-attenuating seats. Modification of the DRIz criterion values with respect to the occupant mass and additional inertial loading of the torso was proposed. Influence of PPE inertia was also investigated with the use of detailed numerical model of the ATD and blast-attenuating seat.

Keywords blast attenuating seat, spine injury, Personal Protection Equipment, Under Body Blast

I. INTRODUCTION

The Under Body Blast (UBB) case is one of the most dangerous kinds of blast load of the vehicle [1]. For modern military armored vehicles, the lower part of the vehicle body is designed to withstand the mechanical load of detonation up to a reasonable mass of the explosive by preserving the mechanical integrity of the body and avoiding an excessive deformation of the body structure. One of the most dangerous biomechanical risks for the crew is vertical acceleration of the seat [2].

Risk of spine injury is assessed by experimental or numerical tests at various levels of complexity, from simple drop tower tests [3, 4] or sledge impact tests [5] to expensive full-scale vehicle blast tests [6]. To obtain repeatable results in these tests, the 50th percentile Anthropomorphic Test Devices (ATD) equipped with acceleration and force sensors are used. According to STANAG 4569, ATDs in order to resemble conditions of inertial loading of the spine wear the standard combat wear and boots, including the Personal Protective Equipment (PPE), if the occupant uses it in normal operational condition [7].

Fig. 1. Soldier wearing Improved Outer Tactical Vest

The military-grade bulletproof vest can weigh 16-18kg, which is significant in comparison to the mass of the upper part of the human body. The total mass of the upper body PPE can reach 30kg [8]. As a result, the inertial loading of the spine can increase in the case of vertical acceleration load. Depending on the type of damping system used in the seat, deviation of the occupant mass from an average 50th percentile male can change the risk of the spine injury.

The Dynamic Response Index (DRIz) model [9] describing the dynamics of the human body was developed based on pilots in the U.S. Army. Similarly, the threshold criterion was set to approximately the 50th percentile male. According to the NATO Standardization Agreement STANAG 4569, the DRIz model is used to assess the risk of spine injury in an Under Body Blast event. Tests were conducted with the use of a 50th percentile Hybrid III Anthropomorphic Test Device. Unfortunately, the additional inertial load of the torso with PPE during the UBB test is changing the dynamic behavior of the body defined by the standard DRIz model developed for pilots. The presence of PPE changes the natural frequency of vibration and compression of the spine, which are the basis of this model.

The primary aim of this study is to propose a modification of the DRIz model parameters and criteria for evaluation of the risk of a spine injury for tests with the use of PPE. The influence of the occupant mass other than the standard 50th percentile ATD was also investigated. The secondary goal is the trial of evaluation of the spine injury risk for various strategies of a damping applied in a blast attenuating seat.

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II. ANALYTICAL MODEL

The investigation of the spine dynamic load in experimental tests with the use of ATD or PMHS and additional inertial torso load is limited by available masses of the body. The influence of the additional inertial loading of the torso can be checked at the preliminary stage with the use of a simplified analytical model, which is able to capture the main phenomena during vertical loading of the spine and reveal the trends in the load variation. The analytical results can then be verified by more detailed numerical models.

In the DRIz model, the mass of the occupant is not defined explicitly; only the ratio of mass to stiffness is specified in the form of natural frequency of vibration. Most of the systems that protect the spine from the effects of the explosion are based on the damping devices, limiting the maximum force exerted on the human body. For the lower body mass, the same attenuating force triggers greater acceleration and therefore the values obtained from the model DRIz can be higher. This means the seats, which have passed the test with a 50th percentile person, probably do not offer the same level of protection for the 5th percentile occupant.

The additional problem is the fact that the value of the DRIz criterion is effectively based on predetermined shortening of the spine. The limit value 17.7 corresponds with the 62mm spine compression. For the smaller occupant with a shorter spine, the compression by the same distance causes greater average strain of the spine.

The answer to both questions noted above in the context of the DRIz model requires consideration of the spine as a mechanical system with a certain stiffness and damping. The internal structure of the human spine is complex. However, the DRIz model treats it as a simple single mass system with linear spring and damper. To assess the influence of the occupant weight and additional load of the torso, an analytical model was designed on the basis of the DRIz model.

The risk assessment is based on the following assumptions:

- mass of the part of the body loading the spine is proportional to the total body mass,
- spine injury starts at the same averaged strain (ε_{max}=const),
- averaged cross section area of the spine is proportional to the body mass,
- average stiffness of the spine material is constant (E=const),
- change in the risk of spine injury is assessed by the change of the average strain.

The assumptions are based on adaptation of the mechanical structure of the bone of mammals to the mass of the body [10]. The bone density and strength depends on the height and weight of the body. Except for very low and high Body Mass Index (BMI), not common for soldiers, the global strength of the spine is adapting to the torso mass [11]. The change in strength of the human bones is mainly due to increased bone cross section area and not due to a change in volumetric bone density [12].

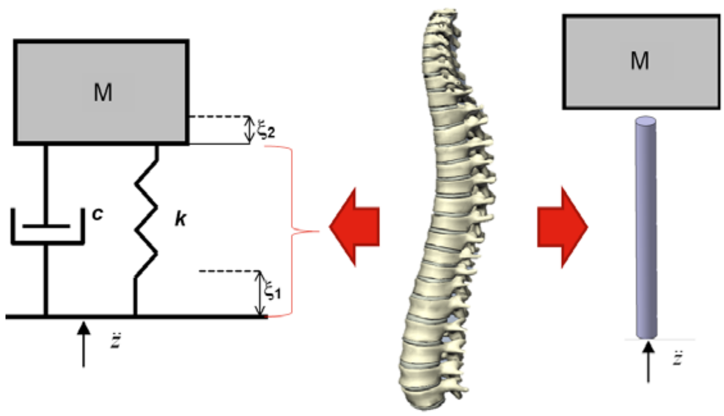

Fig. 2. Parametric model of the spine.
Physical parameters: *A* – cross section area,
E – Young modulus, *l* – length, ε_{max} – max strain

The given assumptions allow replacing the complex structure of the spine with a simple, homogeneous column of length *l*, a constant cross-section *A* proportional to the body mass. The column is loaded by mass proportional to body mass *M*, representing the upper part of the body (Fig. 2). The material of the vertebral column is linear-elastic with the Young's modulus *E*; maximum allowed value of the strain ε_{max} is also constant.

The analytical model does not describe directly the occupants with the different masses, but only compares their mechanical parameters. The reference values corresponding to the 50th percentile male are designated below by subscript 0, and values describing the size of the spine of an individual with different mass by subscript 1.

The parameters of the spine of an occupant having different dimensions and mass are defined as a function of the parameters of the standard 50th percentile one.

The ratio of the average axial stresses σ in the spines for static conditions is:

$$\frac{\sigma_1}{\sigma_0}=\frac{M_1 g l_1}{EA_1}\frac{EA_0}{M_0 g l_0}=\frac{l_1}{l_0}. \tag{1}$$

According to the initial assumption, the cross section area *A* is proportional to the mass *M*, therefore the ratio of stresses do not depend on this parameter. The ratio of the axial stiffness *k* of the spines is determined from the formula:

$$\frac{k_1}{k_0}=\frac{M_1 g}{\sigma_1}\frac{\sigma_0}{M_0 g}=\frac{M_1 l_0}{\sigma_0 l_1}\frac{\sigma_0}{M_0}=\frac{M_1 l_0}{M_0 l_1}. \tag{2}$$

The ratio of the acceptable shortenings of the spine is equal to:

$$\frac{\delta_{\max_1}}{\delta_{\max_0}}=\frac{l_1\varepsilon_{\max}}{l_0\varepsilon_{\max}}=\frac{l_1}{l_0}. \tag{3}$$

Consider the three blast-attenuation control strategies:

1. Constant damping force adjusted for the 50th percentile occupant, corresponding to the seats with the fixed damping force.
2. Constant damping force proportional to the real mass of occupant *M*, corresponding to the seats manually adjusted to the occupant weight.
3. Constant damping force proportional to the measured total mass of the occupant with additional mass of the vest *m*, corresponding to the seat with damping force automatically adjusted to the occupant weight.

For all cases, the damping force is independent of the relative velocity or position of the seat base and the seat is constant. In the first case, the spine is always loaded with compressive axial force *F* with a constant value, independent of body mass and the mass of personal protective equipment. The value of the force F_0 is set optimally for the average 50th percentile occupant:

$$F_1=F_0=\mathrm{const}. \tag{4}$$

Shortening of the spine δ is equal to

$$\delta_1=\delta_0\frac{M_0 l_1}{M_1 l_0}. \tag{5}$$

The parameter *R* is introduced to describe the ratio of shortening of the spine δ to the maximum acceptable shortening $\delta_{\max}$:

$$R=\frac{\delta}{\delta_{\max}}. \tag{6}$$

It is assumed that the larger values of this parameter correspond to the increased risk of the spine injury. The relative change of the averaged strain for an occupant with a non-standard mass M_1 is equal to

$$\frac{R_1}{R_0}=\frac{\delta_1\delta_{\max_0}}{\delta_{\max_1}\delta_0}=\frac{M_0 l_1}{M_1 l_0}\frac{l_0}{l_1}=\frac{M_0}{M_1}. \tag{7}$$

For the second case, when the force *F* acting on a body is proportional to the real mass of the body,

$$F_1=F_0\frac{M_1}{M_0}. \tag{8}$$

From equations (2) and (8), shortening of the spine δ is equal to

$$\frac{\delta_1}{\delta_0}=\frac{F_1 k_0}{F_0 k_1}=\frac{M_1 k_0}{M_0 k_1}=\frac{l_0}{l_1}, \tag{9}$$

$$\delta_1=\delta_0\frac{l_1}{l_0}. \tag{10}$$

From equations (3), (6) and (9), the relative change of strain in this case is equal to

$$\frac{R_1}{R_0}=\frac{\delta_1\delta_{\max_0}}{\delta_{\max_1}\delta_0}=\frac{l_1}{l_0}\frac{l_0}{l_1}=1. \tag{11}$$

The strain of a non-standard occupant is equal to the strain of a 50th percentile one, but when the torso is loaded with an additional mass *m*, such as Personal Protection Equipment, this mass is taken into account by the control force. In the case where the force F acting on the body is proportional to the sum of the mass body M and the additional mass m

$$F_1 = F_0 \frac{(M_1 + m)}{M_0} \quad (12)$$

From equations (2) and (12), shortening the spine δ is equal to

$$\frac{\delta_1}{\delta_0} = \frac{F_1 k_0}{F_0 k_1} = \frac{(M_1 + m) l_1}{M_1 l_0}, \quad (13)$$

$$\delta_1 = \delta_0 \frac{(M_1 + m) l_1}{M_1 l_0} \quad (14)$$

From equations (3), (6) and (13), the relative change of strain in this case is equal to

$$\frac{R_1}{R_0} = \frac{\delta_1 \delta_{\max_0}}{\delta_{\max_1} \delta_0} = \frac{(M_1 + m) l_1}{M_1 l_0} \frac{l_0}{l_1} = \frac{(M_1 + m)}{M_1} \quad (15)$$

Figure 3 shows the relative change of strain in the spine R_1/R_0 as a function of the occupant mass. The ratio is calculated in relation to the 50th percentile ATD with no additional load and the seat damping system optimized for the mass of such an ATD. Because of lack of data about the military population, the calculations were carried out for full range of 5th to 95th percentile civilian occupants.

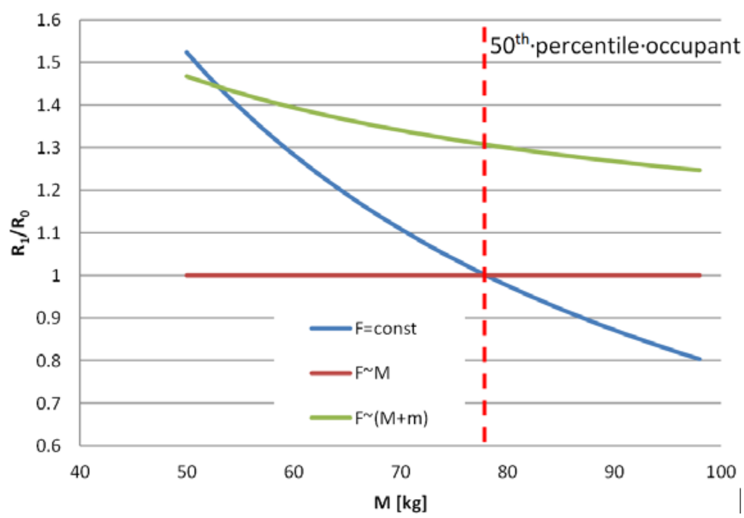

Fig. 3. Changing the strain in the spine compared to a standard 50th percentile occupant as a function of body mass M, for occupant wearing heavy PPE (m=20kg)
F = const – attenuating system with a constant accelerating force,
F ~ M – attenuating force proportional to the actual body mass,
F ~ (M+m) – attenuating force proportional to the total mass of the occupant and PPE.

The damping system manually adjusted for the actual mass of the occupant offers a constant level of the relative strain (Fig. 3, red line). For such seats, there is a risk connected with the incorrect setting of the damping force, especially in a situation when it is used by many people with different masses.

The blast attenuating seat with the fixed damping force optimized for the 50th percentile occupant increases the relative strain for 5th percentile occupants by 50%. In such a case it offers a safety level similar to the automatically adjusted seat and is not sensitive to the additional inertial loading of the body (Fig. 3, blue line). For heavy occupants these seats are theoretically more safe, but there is a risk of excessive stroke of the damping system and bottoming out.

The most interesting is the damping system that adjusts automatically for the measured weight of the occupant (Fig. 3, green line). Because the additional mass of the vest is included in the measured occupant mass, actually the system is adjusting for an occupant heavier than the actual one. As a result, the relative change of the strain is higher than for the fixed force seat in the whole range of occupant masses.

In Figure 4 the effect of the additional torso load m on the relative strain in the spine for the automatically adjusting damping system is shown. A heavier bulletproof vest always increases the compression of the spine, but the greatest increase occurs for the light occupants.

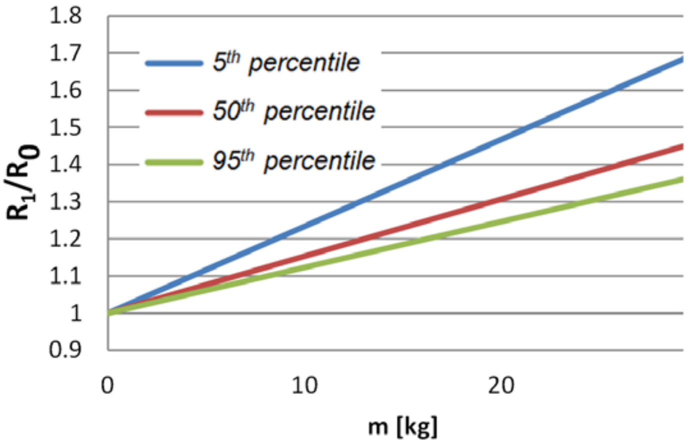

Figure 4. Influence of PPE mass on the relative change of strain in spine for the damping force proportional to the sum of the mass body mass *M* and an additional mass *m*

These calculations were made for static forces. In the case of dynamic loads, the changes of mass and stiffness influence the oscillation period of the mass-spring system used in the DRIz model. The modified frequency of vibration of the whole system ω_1 is equal to:

$$\omega_1 = \omega_0 \sqrt{\frac{M_1 l_0}{(M_1 + m) l_1}} \, . \qquad (16)$$

When assessing the safety of occupants with masses different than the average one, to determine the response model vertical acceleration profile obtained during the tests, it is proposed to use the modified natural frequency ω. In Figure 5 the influence of the additional torso load on the vibration frequency of occupants with different masses is presented.

TABLE I

The summary of the frequency of vibration of the system ω [rad/s] as a function of PPE mass m [kg]

m	5th percentile	50th percentile	95th percentile
0	56.6	52.9	51.0
10	51.6	49.8	48.5
20	47.7	47.2	46.4
30	44.6	44.9	44.6

The increase of additional torso load *m* reduces the frequency of vibration of the system and delays the dynamic response of the spine. In Table I the frequencies for the three sizes of the ATD are shown.

The additional mass of 20kg loading the torso of the 50th percentile ATD reduces the natural frequencies from 52.9 to 47.2 rad/s. Assuming that the deflection limit is not changed and is 62mm (the same spine), the maximum compression of the spine for DRIz values equals 14.1. In fact, the significant PPE weight will cause a precompression of the spine and further reduction of the safe range of the spine compression, but this effect is neglected in the present study.

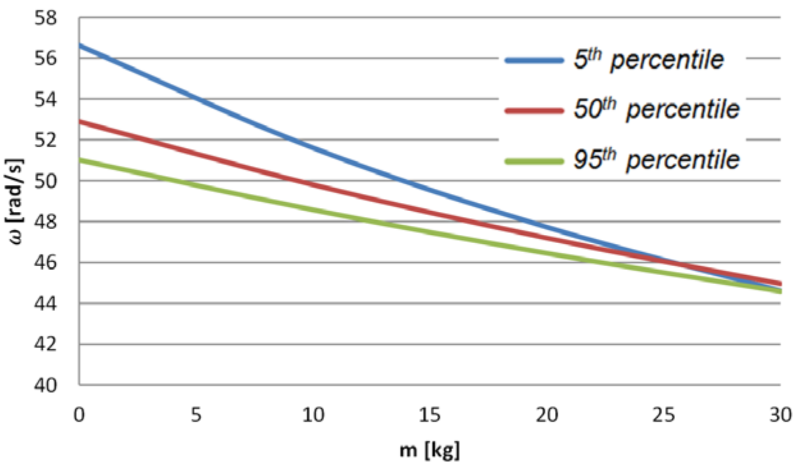

Figure 5. Influence of an additional torso load with the mass m on the vibration frequency ω for occupants of different sizes.

The presented analytical model allows determining the safe DRIz values for occupants with masses different than the average and additional inertial loading of the body. The DRIz parameter values at which the average axial strain of the spine reaches values equivalent for the ATD without additional load are presented in Figure 6 and Table II. The DRIz model is validated only for 50th percentile occupants. The limit value 17.7 for occupants with different masses is a result of the assumption of the presented model, mainly the assumed adaptation of the mechanical structure of the bone to the mass of the body. These assumptions lead to identical relative strain of the spine for the occupant with different masses without PPE.

TABLE II
Summary of acceptable values of DRIz
with different masses m of PPE

m [kg]	5th percentile	50th percentile	95th percentile
0	17.7	17.7	17.7
10	14.9	15.7	16.1
20	12.7	14.1	14.7
30	11.0	12.7	13.5

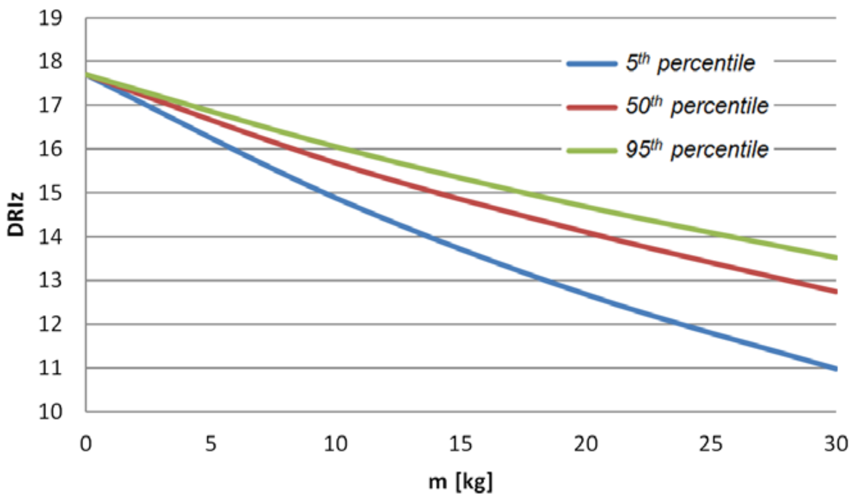

Figure 6. DRIz parameter values reached at maximum allowable compression of the spine as a function of the mass *m* of PPE.

The allowable compression of the spine decreases rapidly with the increase of additional mass loading of the body. In a situation where a person sits on the seat that meets the DRIz criterion and wears a heavy bulletproof vest, the risk of the spine injury increases.

The main purpose of the presented analytical model is the adaptation of the DRIz model parameters for evaluation of the test of the blast-attenuating seats, not only in conditions for which the DRIz criterion was validated (50th percentile occupant, no heavy PPE) but also with ATDs of different mass and wearing heavy bulletproof vests. In such tests, the proposed modification of frequency of vibration and suggested limit values can be used for the evaluation of the test results.

III. Numerical simulations

The influence of the inertia of the bulletproof vest on DRIz values was also checked numerically on the flexible ATD model in LS-Dyna in order to investigate the dynamic response of the occupant to a vertical acceleration pulse. The elasticity of the seat structure, cushion and occupant body were taken into consideration. The seat structure is based on a real blast attenuating seat equipped with 5-point safety belts without pretensioners. Before actual simulations, the model reached static equilibrium under gravity load to precompress the seat cushion. Afterwards, the safety belts were fit to the body without preload.

The axial force in the lumbar spine was compared for the occupant with and without the additional mass of 18kg on the torso simulating the bulletproof vest.

One of the most important factors in analysis of the spine injury risk is the load acceleration profile. The real data measured in blast experiments are very complex and vehicle-dependent. In order to analyze the response of the ATD spine, in the present study the synthetic load acceleration profile is proposed.

In available literature, the most common blast load profile is the triangular pulse [2, 4, 6]. The parameters defining this profile are:

- total velocity change,
- peak acceleration,
- time to peak acceleration,
- total time of the impulse.

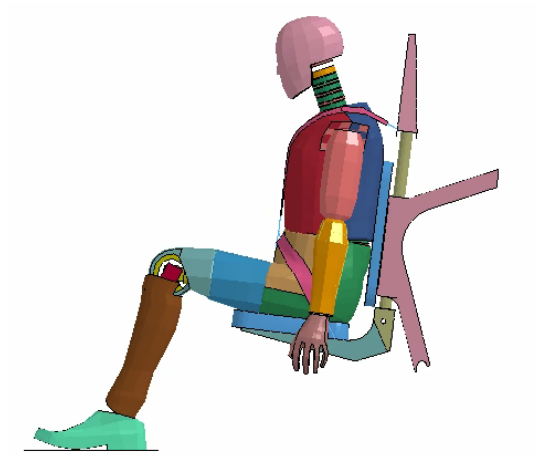

Fig. 7. Model of the Hybrid III and the blast attenuating seat equipped with the fixed force damping system and 5-point safety belts.

For triangular impulse shapes with equal times of acceleration increase and decrease, it is enough to define only two of the above parameters. Commonly used peak acceleration is in the range of 250-350g with total time of impulse 5-10ms [3-5]. The total change of velocity caused by the acceleration pulse is in the range of 7-12m/s [4, 7].

For spine injury assessment in case of an Under Body Blast event, the acceleration profiles are not describing the vehicle acceleration, but acceleration of the seat mounting point located on a side wall of the vehicle. The final vertical velocity of the vehicle is lower than peak vertical velocity of the seat mounting point.

The difference between these velocities is the result of the elasticity of the vehicle structure. After the initial stage of blast energy transfer, a part of the energy is stored as an elastic strain energy. At the end of blast energy transfer, when the vertical acceleration drops to zero, the elastic strain energy is restored. As a result, the seat mounting point is decelerated by a negative acceleration pulse. This effect is illustrated in Figure 8. A similar effect of the deceleration phase was reported by Ramalingam [1].

The negative acceleration pulse has potential influence on the spine compression process; thus it can stop the spine from compressing. In case of the blast-attenuating seat, the influence of the deceleration phase is even more significant in that it can decrease the required stroke of the seat. The seat stroke is used to equalize the vertical velocities of the vehicle and the occupant. The deceleration pulse reduces the final vertical velocity of the seat mounting point to the vertical velocity of the vehicle (Fig. 9).

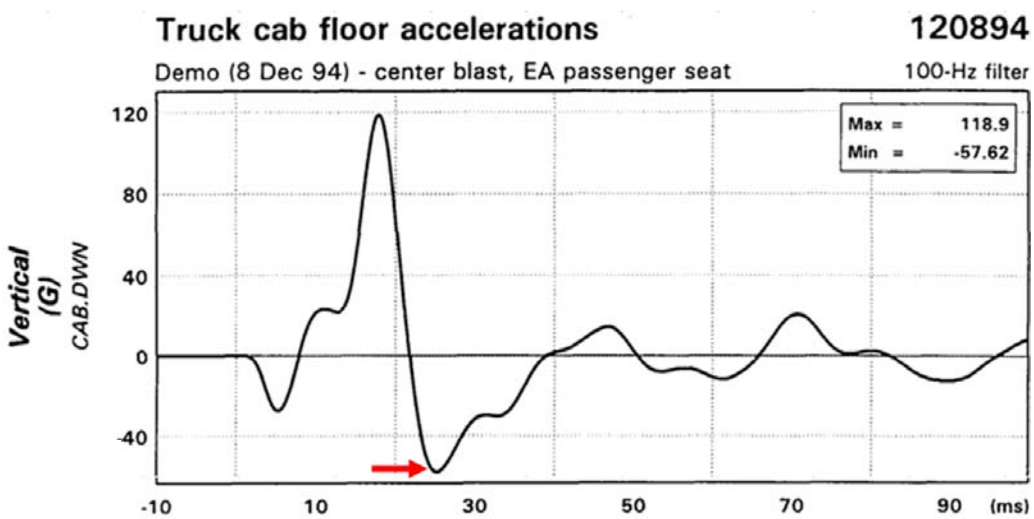

Fig. 8. Vertical accelerations of the truck cabin during UBB test [6]. The deceleration phase as a result of the elastic strain recovery marked by arrow.

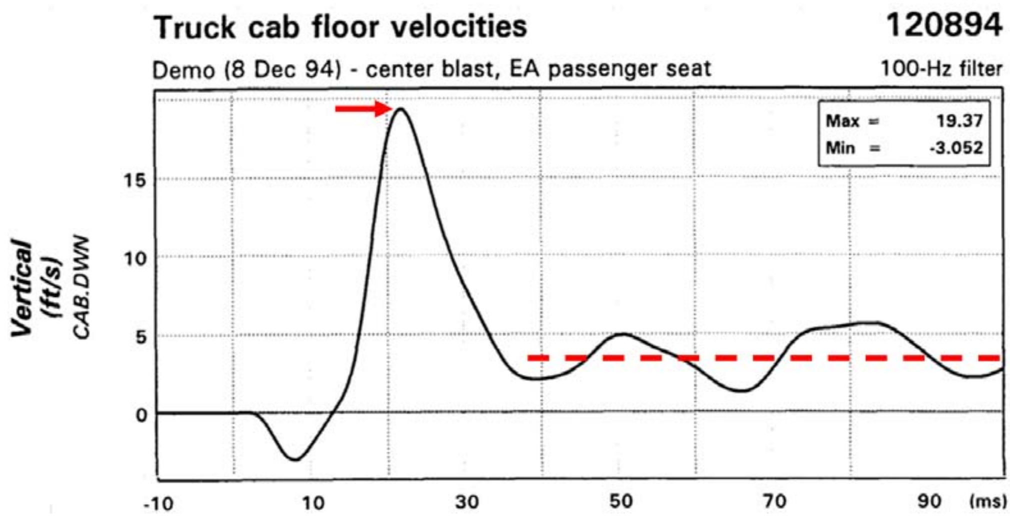

Fig. 9. Vertical velocity of the truck cabin during UBB test [6]. The peak velocity marked by arrow, average final velocity after deceleration phase marked by dashed line.

The simulation of the UBB carried out with the drop towers or sledge test stands characterizes the deceleration pulse in a similar way as part of the impact energy is stored in elastic structures of the stands [1, 3, 9]. However, the deceleration pulse is neglected in the acceleration pulse used for simulations.

In the present study, two types of the synthetic acceleration profile were used. The first contains the positive and negative pulses; in the second one, the deceleration pulse is neglected. Both profiles are applied to the seat mounting points and the footrest pad. The shape of the pulses is presented in Fig 10.

The positive phase uses the triangular acceleration pulse with the peak acceleration 300g and total time 5ms. After the positive phase, the negative acceleration is applied to the seat mounting point with the peak value arbitrarily set to half of the maximum positive acceleration value. The time to the minimum acceleration was set to preserve the jerk from the positive phase, while the final increase of acceleration to zero is twice slower. Such a profile is well correlated with the blast test data presented in Figure 8. The peak velocity change is equal to 7.35m/s, the final velocity change is lower due to negative acceleration phase and equal to 2.8m/s (Fig. 11). After 0.58s the vehicle hits the ground and the vertical velocity drops to zero. For the profile containing only the positive phase, the final velocity is equal to 7.35m/s.

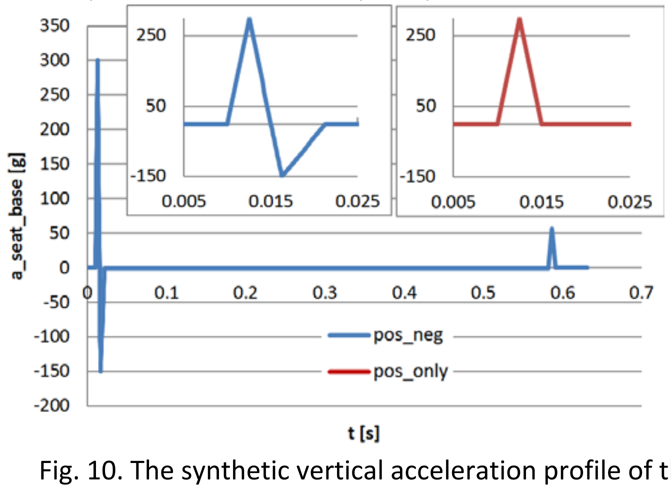

Fig. 10. The synthetic vertical acceleration profile of the seat mounting point used for numerical simulation. Magnified view of the initial positive and negative acceleration phase (blue) and only the positive acceleration phase (red).

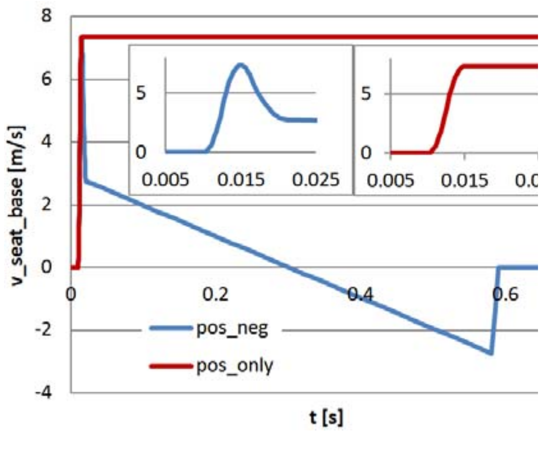

Fig. 11. The synthetic vertical velocity profile of the seat mounting point used for numerical simulation. Magnified view of both types of acceleration profiles.

The influence of the additional inertial loading of the torso has been checked with two methods. The first was the standard DRIz criterion used in blast tests according to STANAG 4569. As the second criterion, for both cases the value of the vertical force in the lumbar spine was compared. The response of the Hybrid III ATD spine for vertical load is not biofidelic [15], but for the qualitative assessment of the spine forces caused by inertia of the upper part of the body, it is acceptable.

The additional inertial loading of the torso with the mass of 18kg was simulated by increasing the density of the jacket of the ATD. Three scenarios have been investigated:

1. ATD without bulletproof vest and 10kN damping force in the blast attenuating seat;
2. ATD with the 18kg bulletproof vest and 10kN damping force in the blast attenuating seat;
3. ATD with the 18kg bulletproof vest and 13kN damping force in the blast attenuating seat.

All three models were loaded with both synthetic vertical acceleration profiles (Fig. 10). The damping force 10kN was optimized for real ATD mass [16], while 13kN damping force represents a blast-attenuating seat adjusted automatically to the measured total mass of the ATD and the bulletproof vest. The damping force realized by the seat damping system was independent of the relative velocity value and relative position of the seat parts connected to the occupant and the seat mounting points.

The results of the numerical simulations are shown in Figures 12 and 13 for 10-13kN nominal damping force, mass of the PPE 00kg (no PPE) and 18kg. Dashed lines represent values for models loaded with positive and negative phases of acceleration, while the continuous lines depict results for deceleration phase neglected (suffix no_dec).

Maximum DRIz value (Fig. 12) depends mainly on total change of velocity. For all cases without deceleration phase with higher total change of velocity, DRIz values are much higher. In Figure 13 the vertical contact forces measured between the ATD and seat pan cushion are shown. For all cases with the full acceleration profile (positive and negative phase), after initial peak force the contact force accelerating the occupant's body drops to zero and DRIz reaches value 10. When the negative phase is neglected, there is a second pulse of accelerating force which increases DRIz up to 15-17. In case of 10kN damper and only the positive acceleration phase with PPE, (Fig. 13, 10kN_18kg_no_dec), the available stroke of the seat was insufficient and at 76ms the force reached 24.2kN.

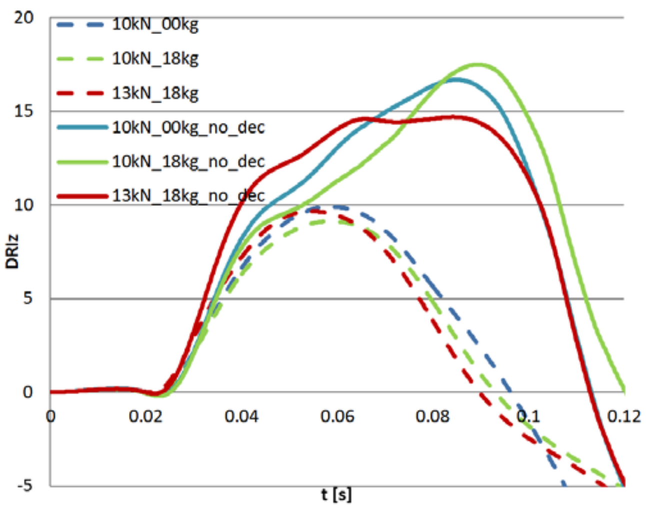

Fig. 12. DRIz profiles for all models.

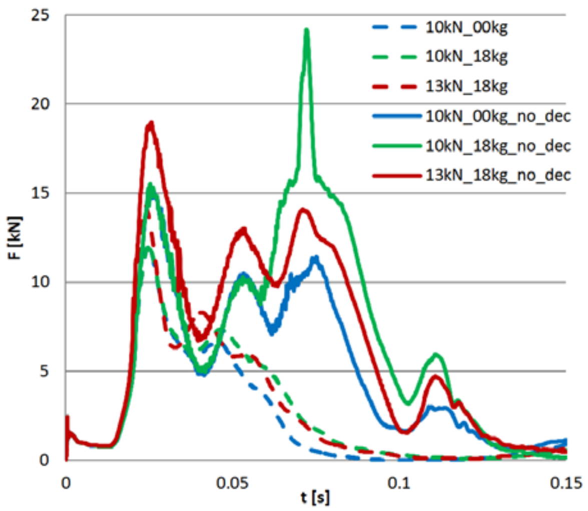

Fig. 13. Vertical contact force on the seat.

The values of maximum DRIz and the peak accelerating forces are presented in Table III. Additionally, the peak values of the inertial forces due to the PPE acceleration are listed. These forces were calculated as average acceleration of the ATD jacket multiplied by its mass. The time between initial acceleration pulse of the body and peak inertial load of PPE is about 25ms for cases with deceleration phase and up to 50ms for more severe cases without deceleration phase.

TABLE III
The summary of the numerical simulation results

Model no.	Damping force [kN]	Mass of PPE [kg]	Deceleration phase	max. DRIz	accelerating force, I peak [kN]	accelerating force, II peak [kN]	peak PPE inertia forces [kN]
1	10	0	yes	9.9	11.9	8.3	-

2	10	18	yes	9.1	12.0	8.4	2.1 at 50ms
3	13	18	yes	9.7	14.3	8.3	2.3 at 51ms
4	10	0	no	16.7	15.3	12.3	-
5	10	18	no	17.5	115.5	24.2	4.3 at 76ms
6	13	18	no	14.7	19.0	15.3	3.5 at 58ms

IV. DISCUSSION

The DRIz criterion was developed for the 50th percentile occupant without additional inertial loading of the torso. This criterion was adopted by STANAG 4569 recommendation for the blast tests with PPE, if the occupant uses it in normal operational conditions, therefore in fact in conditions not validated for the original DRIz criterion.

The analytical model predicts the higher average strain in the spine in case of additional inertial loading of the torso. For occupants lighter than average, the risk connected with the increased spine compression is higher than for a person with average mass. Additional risk is connected with the blast-attenuating seats with the damping force automatically adjusting to the mass of the occupant. In case of soldiers wearing heavy Personal Protection Equipment on the upper body, it can cause the improper adjustment of the damping system for the heavier occupant.

Since the model is very simply, its main limitation is neglecting the internal structure of the spine. It assumed the concentration of the whole mass of the upper body at one point and a homogenous strain state in the spine structure. The real upper body under impulsive vertical load is compressed in the lower region at the beginning of the loading, and then the strain is propagated upwards with limited velocity. For very short acceleration pulses, the strain wave before the end of the pulse may not be able to reach the shoulders, where PPE is supported on the body. In such a case, the effect of additional inertial loading of the torso will have little influence on the total spine compression. The lower DRIz criterion values should be treated as a worst case scenario, when the peak PPE inertial force acts simultaneously with the peak vertical seat pan force. The analytical model is not able to predict the timing of both force pulses. The more detailed numerical model provides more information, but depends on the specific structure of the blast-attenuating seat.

In the numerical simulations, the peak PPE inertia forces occurred at 50-70ms (Table III), while the first seat accelerating force pulses (Fig. 13) ends at 30ms. For models with a deceleration phase, there is no significant second force pulse, and there is no increase of DRIz values for models with PPE (Table III, models 1 and 2). For more severe loads with no deceleration phase (higher velocity change), the second seat acceleration pulse is coincident with the PPE inertial force (t=50-70ms) and results in increased DRIz value (Table III, models 4 and 5). The influence of PPE inertia on the spine load is significant only in cases when the body acceleration pulse is relatively long, with length of pulse greater than about 40ms, as a result of 25-50ms delay between the initial acceleration pulse and the inertial reaction of the PPE. This time depends on the stiffness of the body and should be checked with a more biofidelic body model.

The results for load acceleration profiles with an identical first pulse shape (the same peak velocity change) but with or without a deceleration pulse (different final velocity change) reveal that the most significant parameter of the load profile for the DRIz model is the final velocity change. The DRIz model is not able to capture the risk of high-rate acceleration pulses. The work of Yoganandan et al. [17] suggests localization of the injuries on the impacted end of the spine for high-rate impacts, which cannot be captured by the DRIz model as a consequence of assumption of a homogenous strain in the spine. As discussed in [16], according to the DRIz model, a spine will survive extremely high acceleration in the short period which is in contradiction to the experiments [18].

The difference in these velocity changes is related to the presence of the deceleration phase discussed above. For vehicles with a stiff structure including the stiffness of the seat, the amount of energy stored after the blast wave impact as elastic strain is less significant, and the final velocity change is similar to the peak velocity change. For the purposes of simulation of the blast-attenuating seat performance, the presented synthetic acceleration profile can be used with the deceleration phase matching the elasticity of the vehicle.

V. CONCLUSIONS

The influence of Personal Protective Equipment in the loading of the spine in an Under Body Blast event was investigated for the various damping force control strategies. The analysis carried out with a simple analytical model based on DRIz criterion showed potentially increased risk for lighter occupants and blast-attenuating seats adjusting automatically to the weight of the body. The results suggest that a UBB test with the self-adjusting seats should be carried out with an ATD wearing PPE. For such a case, decreasing the DRIz limit and natural frequency of vibration of the body to the proposed values can be considered.

More detailed analyses were performed with the use of a finite element method. The flexible model of the Hybrid III ATD, the seat with damping system and 5-point safety belts were used. Two synthetic acceleration profiles of the seat base were proposed: one with typical triangular acceleration pulse and another with an additional deceleration pulse resembling that observed in tests, i.e. the recovery of elastic strain stored in the vehicle structure.

The numerical simulations, carried out with the use of the proposed acceleration profiles, show the limited influence of PPE on the values of DRIz criterion. However, the inertial forces of PPE significantly influence the seat-body interface peak force for the body acceleration pulses longer than about 40ms. The influence of PPE on the spine injury risk depends on the coincidence in time of two peaks of force: one caused by the inertia of PPE and the second produced by the interaction of the seat structure and the body.

The comparison of results for two proposed synthetic vertical acceleration pulses presented in figure 10 shows great influence of the deceleration phase on the global response of the body. It emphasizes the necessity of standardization of the vertical acceleration profiles used for simulations and tests of the blast attenuating seats.

VI. References

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