MODELING BIOMECHANICAL INTERACTION HUMAN - SMALL ARMS

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Abstract
Presented is a complex mathematical model biomechanical interaction human - hand weapon. With this model it is possible to carry out calculations for two typical shooting positions - shooting standing and kneeling shooting. The calculations are made for shooting with ammunition calibre 5.56 mm. For this type of ammunition is provided a recoil force which acts as the external loading of the virtual model of a man. Mathematical model of biomechanical systems man - Hand Gun permit a deflection weapon during firing and misalignment caused when shooting bursts.

Keywords: Hand weapon, human, interaction, model, biomechanical.

1 Introduction

One type of interaction in the system of human-firearm is physical interaction. Creating a biomechanical model of the system is possible to measure the impact of small arms on the properties of the effectiveness of shooting in a variety of tactical situations. The complexity of this issue is to create a model of the human body that would faithfully represent biological, anthropological and physical properties of man. Another problem is that these characteristics are in fact strictly individual, virtually do not two same people [3], [4], [6].

2 Virtual human model - small arms

Virtual models of mechanical systems man - Hand Gun was created in the Windows MSC.ADAMS. ADAMS/Solver^{TM}. ADAMS/Solver^{TM} a program module is used to solve static, kinematic and dynamic equations of motion. ADAMS/Solver^{TM} working with equations that are automatically generated based on user-created model at the stage of pre-processing functions. In this process the user creates by using the pre-processor model, which represents the mechanical system. Solver automatically creates a system of differential and algebraic equations. The actual process of simulation must be actively managed by the user, because during the analysis may be problems with convergence task.

2.1 The philosophy of mathematical solutions

By creating a model we define the first step of the dynamic differential equations for each degree of freedom of movement, which has not been taken idealized geometric relationships that bind power and acceleration.

In the second step, we create kinematic differential equation expressing the dependence of the speed and position coordinates for all degrees of freedom of all bodies and the algebraic equation for each prescribed movement - scalar kinematic holonomic, no holonomic and for each component of force.

The system seeks solving the system of equations in the form of a column vector of unknown parameters.
Systems of equations:
Dynamic Differential Equations:

$$\mathbf{M}(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}},\mathbf{f},t)=0 \tag{1}$$

Kinematic differential equations:

$$\dot{\mathbf{q}}-\mathbf{q}=0 \tag{2}$$

Binding algebraic equations:

$$\mathbf{\Phi}(\mathbf{q},\mathbf{f},t)=0 \tag{3}$$

where $\mathbf{q}$ is the arithmetic vector of generalized coordinates, $\dot{\mathbf{q}}$ is the vector arithmetic generalized velocities, $\ddot{\mathbf{q}}$ is a generalized acceleration vector arithmetic, $\mathbf{f}$ is vector arithmetic generalized binding and external forces, t is time.

A method for solving these equations is based on a prediction-correction process solution. Solution ongoing in state space while the system is transformed into a system of n equations with $2n$ unknowns,

$$\mathbf{G}(v,\dot{v},t)=0 \tag{4}$$

where *v* is a vector of state space variables.

2.2 Description of the model

The basic element of the virtual model of the human body is a system of bodies that represent the skeleton of the body. Full body model consists of 19 parts:

- head
- neck
- upper torso
- middle of the fuselage
- lower torso
- scoop + clavicle (left / right)
- upper arm (left / right)
- underside of the arm (left / right)
- hand (left / right)
- upper leg (left / right)
- lower leg (left / right)
- foot (left / right)

In Fig. 1 shows the human skeleton model with color-coded parts.

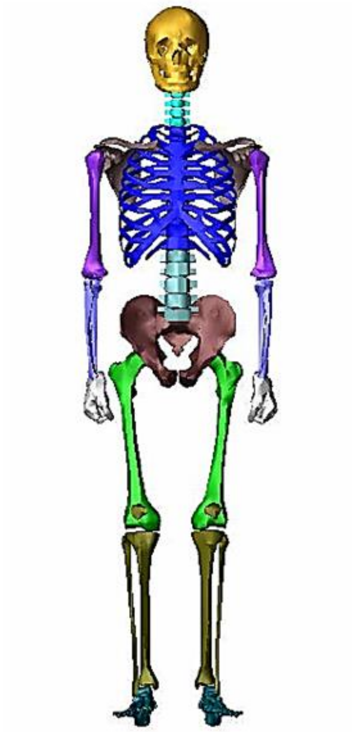

***Fig. 1** Model skeleton body*

Each body segment is represented by the corresponding graphical representation of the individual bones of the body parts involved. Mass moments of inertia, center of gravity position and dimensions of these bodies are calculated based on data from anthropometric database [5]. Similarly, the location of the individual segments is calculated based on this data.

Muscular system is the part of the human body, which provides the movement. Similarly, in the case when a virtual model must be taken care to ensure that the parts moving relative to each. A guiding principle of the muscular system, the individual muscle tension always acts only. Never pressure. For virtual muscles can operate is first necessary to prescribe a time history of shortening them and of expanding. This ensures that, in a first step the rules imposed by moving various parts of the skeleton and perform the inverse dynamic analysis. During this analysis, they experience a change in the lengths of all muscles. Subsequently, these recorded changes in the regulations as individual muscles timing of the desired length of the muscle. Every muscle comes with a PD controller whose task is to regulate the amount of force a muscle acts so that the final length of the muscle was responsible as possible, as accurately prescribed value.

The formulation of this regulation is:

$$F_l = \begin{Bmatrix} F_{max} & F_l \geq F_{max} \\ P(L_d - L_a) + D(\dot{L}_d - \dot{L}_a) & F_l < F_{max} \\ 0 & L_d \geq L_a \end{Bmatrix}, \tag{5}$$

where L_d is the desired length of the muscle, L_a is the actual muscle length, $\dot{L}_d$, the rate of change in muscle length, $\dot{L}_a$ the current rate of change in muscle length, P is the proportional gain, D is the derivative gain of the controller, and F_{max} is the maximum force that can the muscle inferred. F_{max} is substantially physiological range indicated for different muscle:

$$F_{max} = pCSA \cdot M_s \tag{6}$$

where $pCSA$ is the cross sectional area of the muscle, and t M_s is the maximum stress that is able to transmit a muscle.

In the case of interaction simulation model of a man - Small Arms prescribed "movement" represent the posture and weapons in a stable position. Each segment is prescribed constant position and direction in all three directions. The regulation of muscle activity then try to draw such strength in individual muscles, which will ensure that a stable position.

During analyzes were considered and compared two basic positions during shooting: shooting in standing position (Fig. 2) and shooting in a kneeling position (Fig. 3).

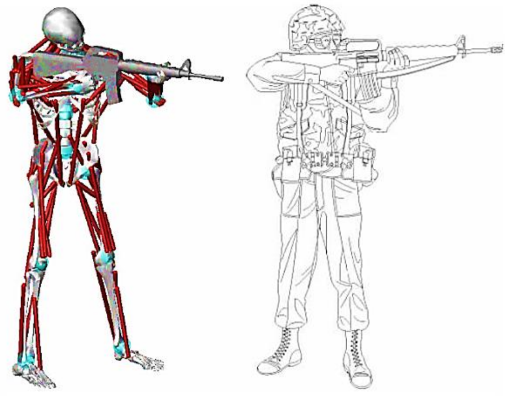

Fig. 2 *Shooting standing*

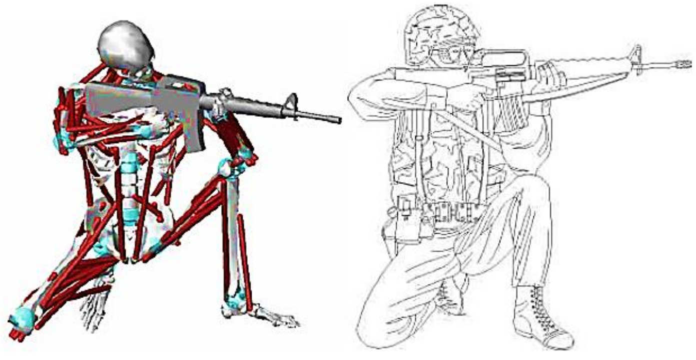

Fig. 3 *Shooting kneeling*

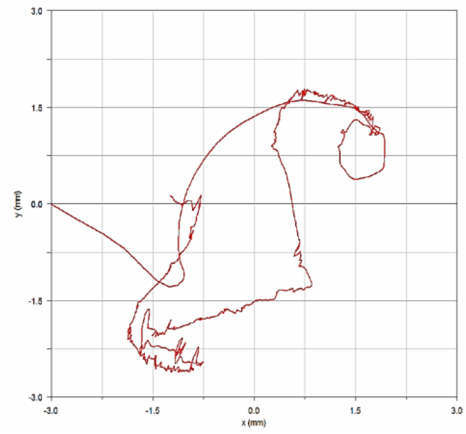

Fig. 4 *The movements muzzle in the shooting standing*

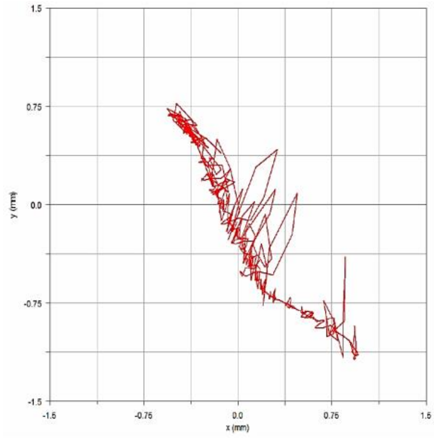

Fig. 5 *The movements muzzle in the shooting kneeling*

Generally, firing accuracy depends only on the properties themselves weaponry but also heavily on the characteristics of the actual shooter. It is known that the main cause of variance in the shooting at a stationary target is other than the natural dispersion of munitions and vibration of the actual system man -weapon. These vibrations are caused by flexible connections between different parts of the human body model and a flexible connection between man and weapon. As these flexible links has a degree of damping mechanical system man-weapon never gets into its initial position. This affects the accuracy of fire when firing bursts with small time intervals between shots. The effect of these non-rigid and damping to the materials for the accuracy of the model aiming adjustment is shown in Fig.4 for shooting in the standing position and Fig.5 for shooting in the kneeling position. Displayed are changes of position muzzle in the *x*-*y* plane. The data represent the results of simulations directed of adhere weapons (length simulations -10 s).

In Fig. 6 is a comparison of head movements to scale. The results show smaller amplitude of oscillation model for representing the shooter in kneeling. From a mechanical point of view when shooting in a kneeling body is in contact with the floor on three points, which increases stability. The left hand is supported on the left knee, which also increases the stability of adhere of a weapon, as the ready position is not maintained by the sole action of muscle groups.

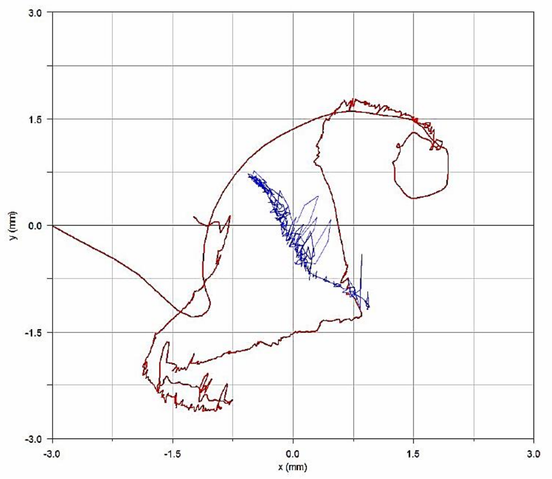

Fig. 6 *Comparison moving muzzle*

2.3 Recoil Dynamics - impulse of shoot

A shot of firearms does not act only on the projectile, but also on the weapon. Force applied to shoot at the weapon will create a stimulus that causes the movement of weapons.

The impulse from shoot is created by the force of the shot $F(t)_H$ at the time of the shot. And this impulse wills the effect of the shot gun.

Shot impulse I_{Hk} can be set with sufficient accuracy on the basis of basic parameters of the ballistic (bullet weight, the weight of powder charge, initial velocity bullet).

$$I_{Hk} = \int_0^{t_u} F_H dt + \int_{t_u}^{t_k} F_H dt \tag{7}$$

At a time when projectile is in the barrel, it forms a weapon, projectile and powder filling a single set of materials. The forces from the combustion gases pressure acting on the projectile and the barrel are inner strength system. If the system does not operate any external force, momentum systems shall remain constant. E.g. if the momentum of the system at the beginning zero (system motion does not take place), it is so in any moment during the shooting. Thus, the following applies:

$$H_0 = m_z \dot{x}_{z0} + m_q \dot{x}_{q0} + m_\omega \dot{x}_{\omega 0} = H = m_z \dot{x}_z + m_q \dot{x}_q + m_\omega \dot{x}_\omega = const. \tag{8}$$

Where
H_0 - initial momentum of the system
m_z - mass of weapon
m_q - projectile weight
m_ω - weight powder charge
$\dot{x}_z$ - speed of weapons recoil
$\dot{x}_q$ – projectile velocity
$\dot{x}_\omega$ – combustion gases medium speed

Muzzle shot impulse is a vector on the axis of the barrel and towards the bottom chamber and it size is equal to the momentum of the projectile and the combustion gases at the time of exit projectile from the barrel.

If we consider the ammunition caliber 5.56 mm [2]:

- m_q = projectile weight 4.03 g

- Weight of the powder charge m_ω = 1.6 g
- Initial velocity projectile v_0 = 910 m / s

$$I_{Hu} = \left(0.00403 + \frac{1}{2} \cdot 0.0016\right) \cdot 910 = 4.3953\ kg.m.s^{-1} \tag{9}$$

By creating a virtual model of the shot can be determined timing of the force that will respond Muzzle shot impulse I_{Hu}. The model consists of a body which represents the mass of projectile and powder charge. This body has a speed limit, due to the acceleration during shooting. This rule has the shape of the transition curve between [0 s; 0 m s] and [0.000838 s; 910 m/s]. Consequently, it is possible to check the results of a simulation of the timing of the force that is needed to make this movement (Fig. 7).

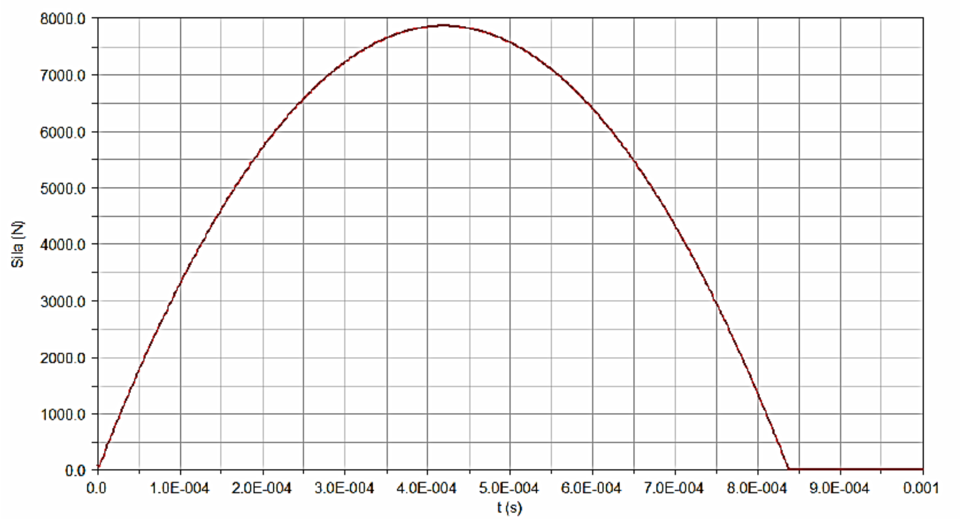

Fig. 7 *The force required for the movement of the projectile*

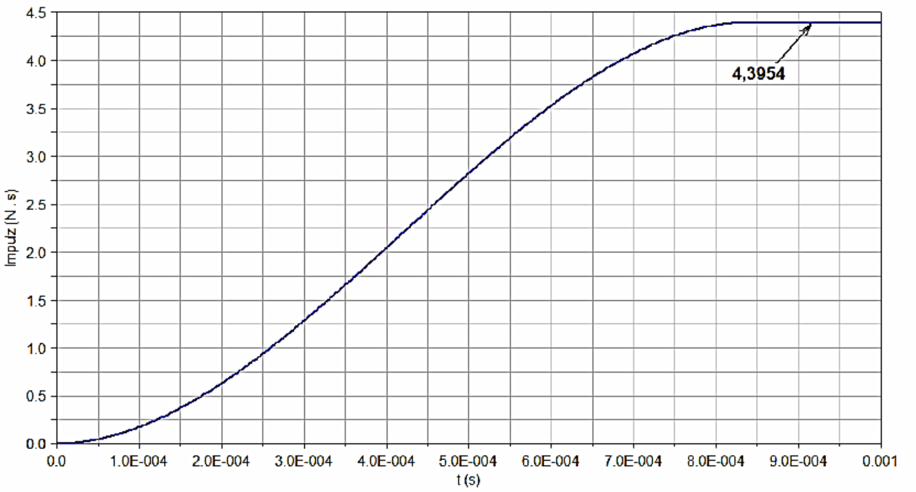

Fig. 8 *Shot impulse*

Integration these curve to trace the pulse (Fig.8). This curve substantially represents the area under the force curve. Final value observed by simulation is 4.3954 kg.ms^{-1}. This exactly corresponds to the calculated value.

3 Operation a handgun while shooting

Shot pulse effects not only on projectile, but also by the gun and causes their movement. This leads to a recoil (push arms backwards) and weapons-twist and therefore it especially effects on the direction of the exit fire and therefore effects on the accuracy of weapons. If investigating this so-called angle of muzzle mainly distinguishes shooting single shots, when our course of motion gun takes only until the exit fire from the muzzle of the barrel and firing bursts, when we take into consideration the movement of weapons caused several consecutive shots.

3.1 The movement of weapons during firing

The gun is loaded during firing (Fig. 9) by the force of the shot, by gravity and holding of weapons.

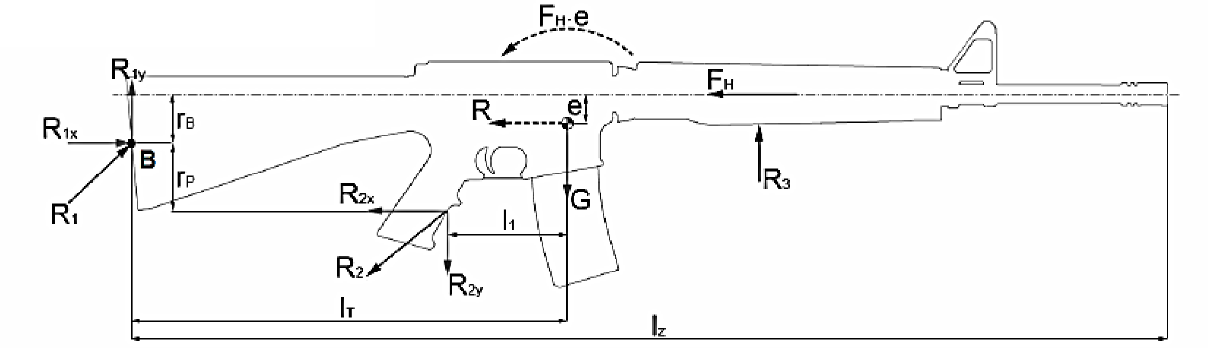

Fig. 9 *The forces on the gun*

Under the force of the shot thus it leads to displacement weapons back and to the rotation about the center of gravity. This prevents leaned butt against shoulder shooter holding a gun grip, or holding of weapons. Leaning arms on the shoulder shooter has elastic properties, and the force R increases during recoil due to muscle stiffness shoulders and torso.

In terms of the angle of jump is decisive moment F_H.e. Force F_H is given by ballistics of the cartridge, and therefore minimizing this moment is primarily a question of minimizing the distance e. Impact on reducing the angle of jump are also moments inferred shooter while holding guns. It is a question particularly of the form of the arms, its gun stock and gun possession.

The body is the basis shooter that captures the pulse of shot. Resistance base against the movement of arms is different. Due to the quality of supports guns are there may be two extreme cases ranged weapons:

a) A gun is held open, then if the force FH does not pass center of gravity, takes to turn around the center of gravity weapons

b) A gun is firmly supported at point B and there is a rotation around this point.

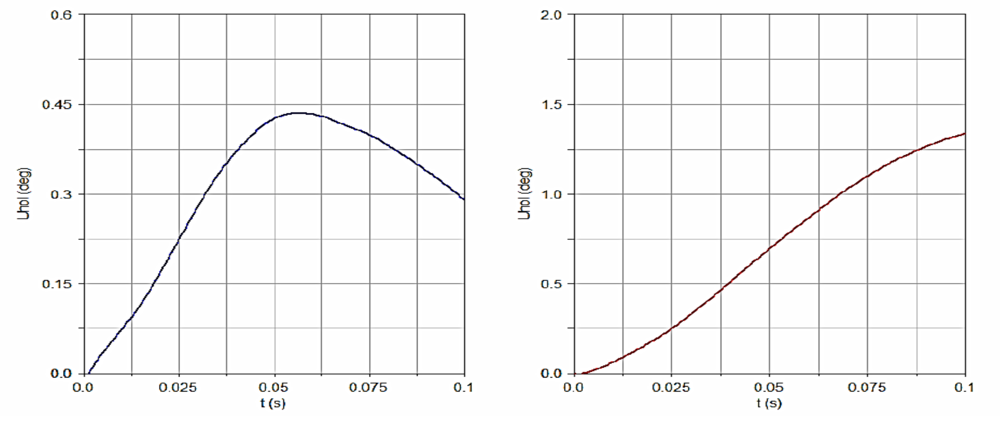

Fig. 10 *Angular rotation of the arms in the vertical and horizontal direction - one shot-standing*

The fact lies somewhere between those two extremes, closer to the first case, as to the time when projectile is on muzzle the barrel resistance size in comparing with the strength of the shot is much smaller. Recoil at this time is also very low and resistance shooter shoulder at this time practically will not increase.

Possession of assault weapons is important for continuous fire and application support in turn has significance for accurate and easy targeting. Too rigid abutment may however, caused the response will show support before living projectile from the barrel.

Fig.10 is shown waveforms of angular rotation arms in vertical and horizontal directions for one shot in the standing position.

Fig.11 is shown of angular rotation arms in vertical and horizontal direction for one shot when kneeling.

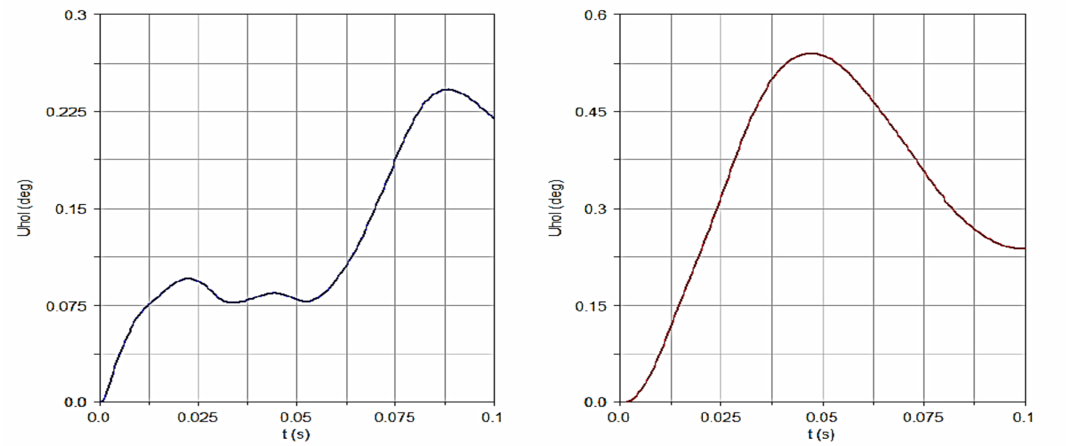

Fig. 11 *Angular rotation of the arms in the vertical and horizontal direction - one shot-kneeling*

When shooter is kneeling there is less rotation of arms as in the case of fire in the standing position. This is logical due to the fact that the stiffness of a stationary the shooter is less than kneeling, as well as by kneeling position ensures better human contact pad. Likewise, it is stronger leaned weapon when shooting in a kneeling position

3.2 The movement of weapons at bursts firing

After the first shot goes weapon in its movement and gradually increasing resistance, which hinder movement. In case it is a shooting burst (3, 5 and 30 shots - cadence 600 shots / min.) gun before more shots not manage to return to its starting position. Deflection weapons when firing bursts can be determined as the sum of deviations of successive shots.

After the second shot, the recoil force trying to push the gun even more to shoulder shooter, but since the previous shot shoulder shooter is moved to its initial position under the influence of its former rigidity and deformation applied to the weapon more force than was the case during the first shot. This increased reaction causes a faster return weapon to the original position.

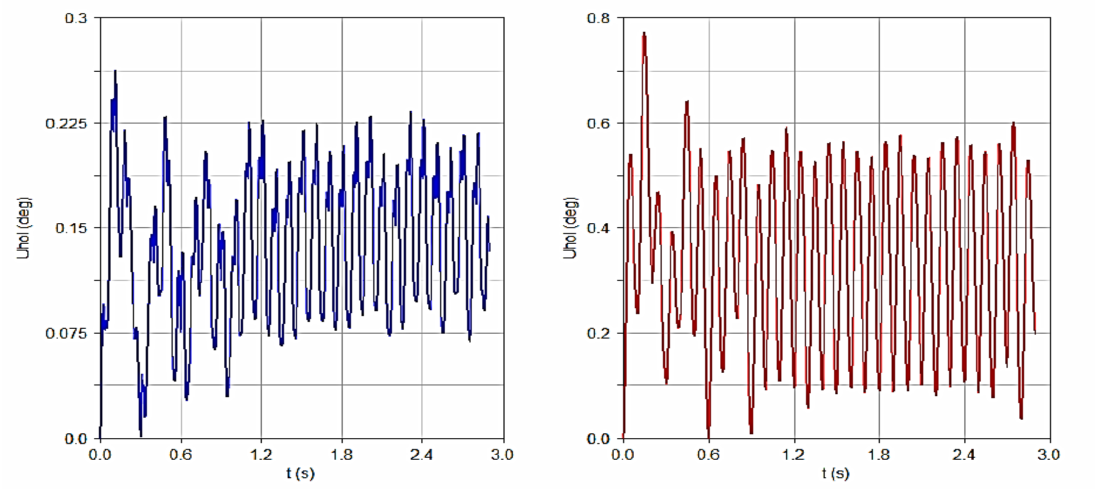

Fig. 12 *Angular rotation of the arms in the vertical and horizontal direction - 30 shots- kneeling*

After about the first 5-6 shots effect occurs when the difference between individual responses to the minimum and the shot gun is rotated the same every time. This phenomenon manifests itself strongly in the shooting in a kneeling position (Fig.12).

This behavior is affected by the overall stiffness of the system shooter - weapon of the ensuing natural frequency of the system. Obviously, the rate of fire affects the resulting motion of the weapon, as it directly affects the frequency of the excitation, the weapons and the ensuing natural frequency of the system. Obviously, the rate of fire effects on the resulting motion of the weapon, as it directly effects on the frequency of the excitation.

3.3 Effect of changes in model parameters on the movement of weapons

The parameters, those affect the overall behavior of the weapon system are subject of a degree of randomness. Method Design of Experiment (DOE) is possible to examine the impact of changes in individual input parameters for the model output variables monitored. These parameters include e.g. the actual physical properties of the model of a man (properties musculoskeletal, how quickly muscles react to external stimuli, the stiffness of individual connections, mass and inertial properties of bone, etc.), the properties of weapons and ammunition (position of center of gravity to the axis of the barrel, scattering recoil force, changes location of the place of contact between man and weapon, possession of a weapon strength ...). All of these changes result in the displacement of the rotation of the gun barrel for each shot is slightly different. Fig.13 and Fig.14 represent the time dependence of the rotation arms in vertical and horizontal directions. There are showing time periods with a length of 0.1 s for 12 different shots.

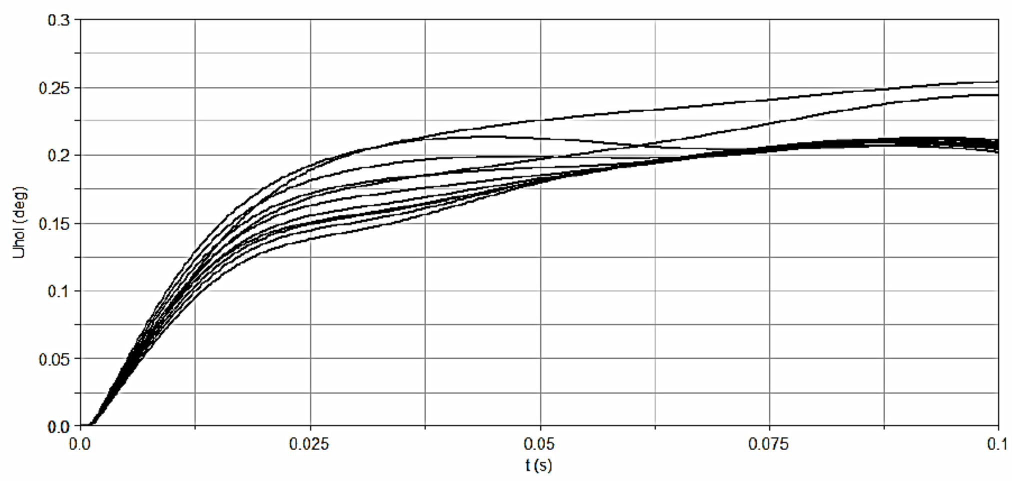

Fig. 13 *Effect of changes in model parameters on the angular rotation of arms in the vertical direction*

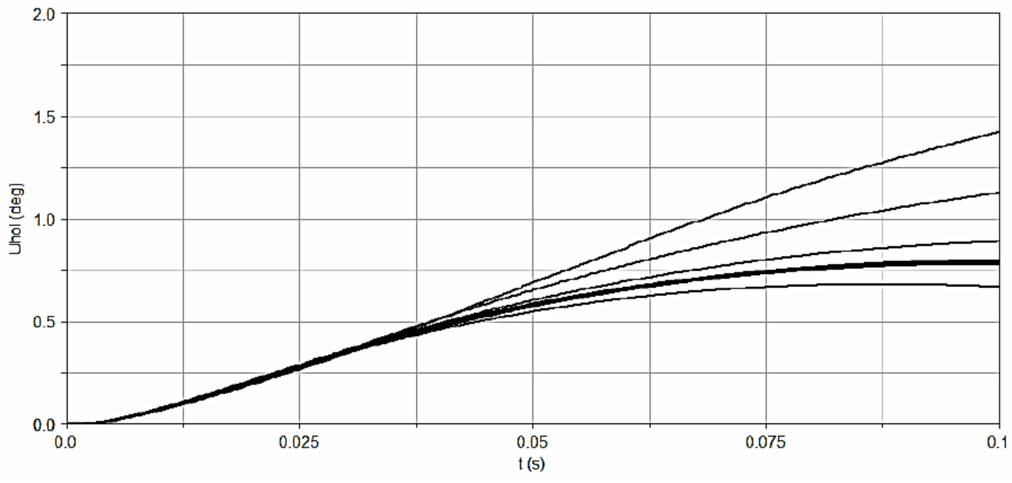

Fig. 14 *Effect of changes in model parameters on the angular rotation of arms in the horizontal direction*

3.4 Dispersion of shooting

In terms of the accuracy of the shot is interesting as it has changed position at the moment when the projectile leaves the barrel muzzle. The shooting of one and the same weapon even if it acts consistently maintains accuracy and a level playing field shooting, each shot describes the influence of many stochastic causes its own path and has its own point range (impact), which usually does not share with others. This distribution path of bullets while shooting is called dispersion of fire [1].

During considerable number of shots provides a path projectiles bundle of paths, which is reflected on the target as the number of hits that are spaced at different distances. At Fig.15 is a dispersion pattern for shooting at a distance of 100 m in standing and kneeling.

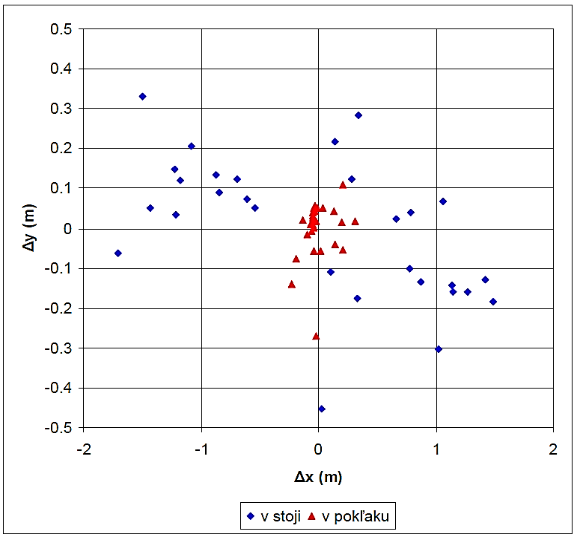

Fig. 15 *Dispersion hits the target at a distance of 100 m if the shooting in the standing and kneeling*

4 Conclusion

Presented is a complex mathematical model biomechanical human interaction man - weapon. With this model it is possible to carry out calculations for two typical shooting positions - standing shooting and kneeling shooting.

The calculations are made for shooting with ammunition of caliber 5.56 mm. For this type of ammunition is provided a recoil force which acts as the external loading of the virtual model of a man.

Mathematical model of biomechanical systems man - hand gun permit a deflection weapon during firing and misalignment caused when bursts shooting.

During the actual shot kickback occurs due to misalignment weapons in the horizontal and vertical directions. The results of simulations show that the deflection direction has a decisive effect on the actual shot that deflection caused but the following shots, as the influence of inertial forces and damping systems human-weapon for the time between shots weapon not manage to return to the position the desired direction of aim.

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