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Shot Moment in Optoelectronic Training in the Air-Pistol Shooting

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Abstract. The aim of the research is to study the interdependence between the shot moment parameter and the result in shooting simulator training. The article considers the problem of the relationships between a shot moment parameter and a virtual result in training with the SCATT optoelectronic shooting simulator. Special technique is proposed and the experimental investigation with the parallel fixation of sighting point coordinates location and the hole centres on a real target and a SCATT virtual target has been conducted. The model of pellet internal ballistics in a barrel is developed. The calculated method that defines the parameters of virtual holes location imitation on the optoelectronic target at the specific shot moment is substantiated.

Keywords: shooting, optoelectronic simulator, shot moment, internal pellet ballistics.

1. Introduction

The current stage of shooting sport development is characterized by increasing of sports results, improving of sports weapons and bullets (pellets). In its turn, it requires further improvement of the shooting methodology. Experts believe that the crucial part of shooting training process is technical training. One of the promising directions of its improvement is to study the shooting technique based on quantitative characteristics of its microstructure [11, 13, 15, 20]. A variety of technical means is used in shooters technique study, which ensures an objective registration of the spatial characteristics.

Contemporary model of shot performance technique consists of three elements: aiming, triggering and weapon retention [17]. Quantitative parameters of shot performance technique can be obtained by the use of optoelectronic training systems [8÷10]. Weapon control process should interconnect all shooting technique elements: posture, aiming, triggering, and breathing control. A shooter has to develop them while training. At the retention moment all the shooter’s physiological and mechanical body movements are being transferred to a weapon. These are the physiological tremor of a hand that holds the weapon, the vibration motion of the athlete and his body parts, which arise as a result of various muscle groups of the body while balancing the action of external forces to maintain body equilibrium in the process of aiming, additional vibrations coming from the withdrawal of hand muscles that keep the weapon from a static equilibrium while pressing the index finger on the trigger, resulting from the reaction of anticipation (0,1 ÷ 0,2 s before the shot), etc. Thus, the weapon receiver vibrations are the result of all the above-mentioned movements. The hole location on the target and, consequently, athletic performance itself depends on the amplitude of these vibrations, and the position and direction of the weapon barrel at the shot moment as well [12].

In SCATT optoelectronic training system the shot moment is registered with a microphone which recognizes triggering mechanism vibration. The sensitiveness of the receiver is regulated with the software choosing an optimal scale, so as to recognize only the specified trigger lowering signal and not to respond to any other vibrations. With SCATT software one can simulate shot moment change that implies a corresponding change of a virtual hole’s location on a virtual target [8].

A shot moment imitation and other optoelectronic simulator capacities are widely used by athletes and coaches to develop technique in shooting sports events. Nevertheless, the understanding of the shot moment notion is problematic. Firstly, a bullet flying trajectory is affected by a barrel location at the moment when the bullet leaves the muzzle. However, time is needed for the bullet to reach muzzle leaving moment from the beginning movement. Secondly, in optoelectronic simulator manuals no difference is made between 'the moment when the receiver recognizes triggering mechanism operation' and 'the moment of the beginning movement of the bullet in the barrel'. Probably these moments should not be considered the same, because receiver sensitivity is set for a certain weapon type and interaction between powder gas (or compressed air) and a bullet (or pellet) is a complex dynamic process [2].

That is why the research of the shot moment influence on a virtual result in optoelectronic simulator training is important in theory and practice of technical training in shooting sports events.

Sports simulators are very popular among shooters because of their advantages, such as timely gathering of adequate information of a result of the performed motor actions. This is a prerequisite for the effective formation of motor skills. It was found that after a shot an athlete maintains a "feeling of the shot" for 15 ÷ 20 s. During this period the most effective evaluation of their actions can be done by comparing subjective and objective information. The best one is visual information which provides a better perception of the signals [12, 18, 19]. Another advantage of technical devices is that they give the athlete an opportunity for immediate information acquisition about the kinematical, dynamic and tempo characteristics of his movement technique. With this information shooter’s technique can be easily corrected. Owing to information, coming from a large number of different movements, only the one that help to achieve the desired result are selected and fixed [16]. The discussed issues of improving the shot performance technique, weapon retention, aiming and triggering processes are viewed with the simulators manuals help [8 ÷ 10]. Despite the presence of scientific publications based on research of shot performance technique using optoelectronic systems [1, 4, 6], hardly any research has been conducted to quantify the compliance of its models and computational algorithms for real shot parameters. Our studies have shown a statistically significant deviation of the virtual holes location from pellets holes location, starting from zero ballistic coefficient. Moreover, when this coefficient is increased the deviation increases as well. This indicates a significant deviation between SCATT simulation model and the real lateral component of pellet motion [5]. The method of point coordinates digitization on the trajectory graphs and distance from the axis of SCATT interface has been developed using MS Office computer programs. This method demonstrates its accuracy and ease of use to quantify the specificity of the optoelectronic method of training in air-pistol shooting [14].

As far as the establishment of the shot moment is concerned, besides the explanations of non-effectiveness to decrease this parameter in the SCATT settings so as to avoid unstable equilibrium during triggering process [8], no other works on this subject in open publications have been found.

2. Methodology of the Research

The purpose of the work is to study the interdependence between the shot moment parameter and the result in shooting simulator virtual training.

The research objectives are

1) to create a method and conduct an experiment with parallel fixation of aiming point location coordinates and centre holes on the real target and SCATT virtual target;

2) to develop a model of internal pellet ballistics and to measure the time of pellet motion in the barrel;

3) to prove the method of simulation parameters measuring of virtual holes location on the optoelectronic target at the specific shot moment.

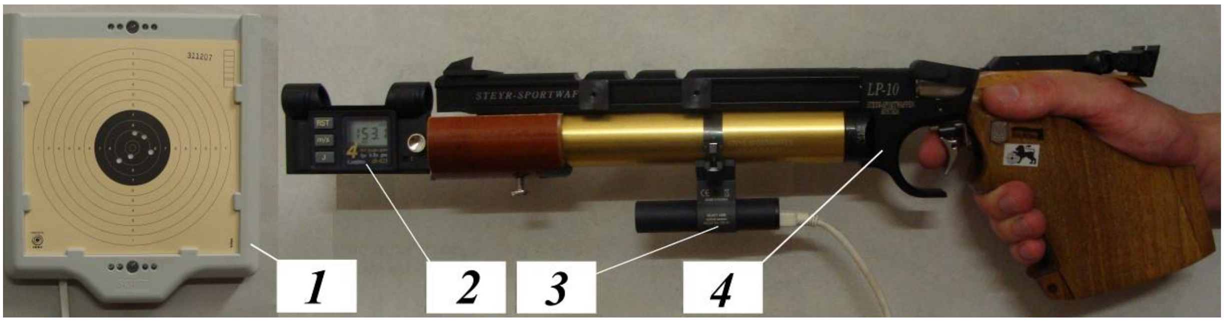

Fig. 1: Target and air-pistol during the experimental shot: 1 is SCATT ST4-12 optoelectronic target with a standard paper target; 2 is chronoscope Combro cb-625mk4; 3 is SCATT 01 OS simulator optical sensor; 4 is 4.5 mm Steyr LP-10 air-pistol.

Research methods and a subject. A highly-qualified athlete made 10 shots with pellets in a standard paper target according to the official air-pistol rules [7]. This target was set in the SCATT ST4-12 optoelectronic target frame. Others SCATT USB shooting simulator components such us a UTC 02 module with an OS 01 optical sensor, Steyr LP-10 air-pistol, and 4.49 mm Finale Match pellets (Fig. 1) were used in the experiment [8]. To avoid the subconscious motive for correcting the next shot, depending on the result of the previous one, the athlete did not look at the computer screen and on the target with a hole. That is the athlete tried to perform all 10 shots identically.

Correction of the pellet motion lateral component equalled zero value of the ballistic coefficient, as this SCATT system function only worsens the virtual holes location in comparison with the real holes location [5].

Muzzle velocity of a pellet was measured by the chronoscope Combro cb-625mk4 (see Fig. 1). It was fixed to the front part (muzzle) of the pistol barrel. The device is designed specifically for measuring a muzzle speed of an air-gun pellet. Its weight (0.055 kg) did not substantially affect the balance of a pistol. The relative error of measurements was within 1%, the velocity graduation interval was 0.1 mps, and pellet kinetic energy graduation interval was 0.01 J [3].

Besides, another series of 10 shots were made using the pellets from the same box and the same air-pistol which was held in a special stationary vice. Coordinates of hole's centres were measured using a millimetre grid with an accuracy of 0.5 mm.

The coordinates of the aiming points were extracted from a scatt file using the "samples.vbs" program (Copyright 2002 ZAO Scatt [8]). Those were eight sets with 10 pairs of coordinates each for shot moments from -0.01 to 0.06 s with increments of 0.01 s. The method of interpolation of polynomial functions was used to find the intermediate coordinates.

The parameters of the virtual holes' location on the optoelectronic target relative to the real holes of pellet shots were found with the computer experiment with the approximation of the law of pellet accelerating change in the barrel by step function. The method of interpolation of polynomial functions was used to find the coordinates of virtual holes at the specific shot moment.

Shapiro-Wilk test, statistical tests based on Student's *t*-test and *F*-Snedecor test, Excel, Paint, and Statistica computer programs were used to analyze the measurements.

3. Results of the Study

3.1. Holes' Coordinates

The coordinates of hole centres of training shots with pellets into a standard target (x_P, y_P), the coordinates of hole centres of viced pistol shots (x_E, y_E) and muzzle pellets velocity (v_B) are presented in Table 1. The coordinates of aiming points which were also taken as the coordinates of the centres of virtual holes (x_S, y_S) for eight values of 'shot moments' are presented in the appendix (see Table A1 and A2). Coordinates of centroid of virtual and real holes are defined with the following formulas:

$$M_{Sx} = \frac{\sum_i x_{Si}}{n}; \; M_{Sy} = \frac{\sum_i y_{Si}}{n}; \; M_{Px} = \frac{\sum_i x_{Pi}}{n}; \; M_{Py} = \frac{\sum_i y_{Pi}}{n}; \qquad (1)$$

where $n = 10$ is number of shots.

The coordinate's values of the centroid were used as appropriate 'aim' corrections in SCATT system and in pistol sights to avoid systematic errors in aiming. Optoelectronic simulator 'aiming' is similar to weapons aiming. After a trial virtual 'shot' computer simulator program shifts the electronic target centre to the centre of this virtual hole. Typically, such a sight correction is performed on the basis of series shots results according to the midpoint. It is clear that the midpoint of a test series did not necessarily coincide with the centre of the adjusted target because of the influence of random factors. Therefore, we have corrected the results of a test series again, moving the centre of the target to the midpoint of this series (Fig. 2 a). Such revised coordinates are defined as follows:

$$x_S^* = x_S - M_{Sx}; \; y_S^* = y_S - M_{Sy}; \; x_P^* = x_P - M_{Px}; \; y_P^* = y_P - M_{Py}. \qquad (2)$$

Table 1. Holes' coordinates on the target and the muzzle pellet velocity with basic statistics

i	Subject		Viced air-pistol		Velocity
	x_P, *mm*	y_P, *mm*	x_E, *mm*	y_E, *mm*	v_B, *mps*
1	3.5	2.5	3.0	-5.0	161.9
2	-1.7	-8.3	2.0	-5.0	162.8
3	1.5	3.0	1.5	-6.0	161.8
4	-3.0	-2.0	2.5	-7.5	161.5
5	5.5	-2.5	3.0	-8.0	162.2
6	7.5	-3.5	2.5	-3.0	162.1
7	-9.0	2.5	2.5	-6.0	161.4
8	2.0	1.0	4.0	-5.0	163.1
9	10.0	2.0	3.5	-4.5	163.0
10	-3.0	-6.0	3.0	-5.0	162.4
*M**	1.3	-1.1	2.8	-5.5	162.2
*SD**	5.7	4.0	0.7	1.5	0.6

* *M* is arithmetic mean; *SD* is standard deviation.

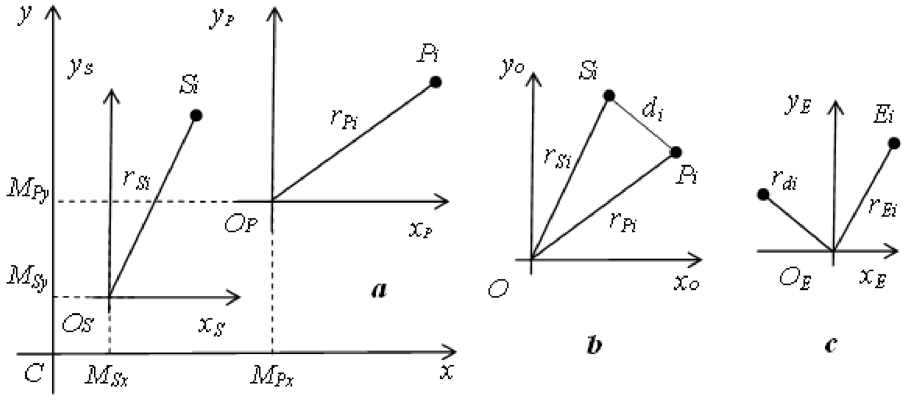

Fig. 2: The scheme the target centre shift to the midpoint of the shot series (***a***); the scheme of the distance projection between the centres of real and virtual holes (***b***); the scheme of the holes centroid in viced pistol shooting (***c***).

The projections of the distances between the centres of real and virtual holes are a quantitative measure of errors in the simulation of holes location in horizontal and vertical plane. They can be defined by the following expressions:

$$d_x = x_P^* - x_S^*,\ d_y = y_P^* - y_S^*. \tag{3}$$

The lengths of the segments that represent the absolute errors value of this simulation can be defined by the expression (Fig. 2b):

$$d = \sqrt{d_x^2 + d_y^2}\,. \tag{4}$$

The coordinates of the holes centroid in viced pistol shooting are found with the following formulas:

$$M_{Ex} = \frac{\sum\limits_j x_{Ej}}{N},\ M_{Ey} = \frac{\sum\limits_j y_{Ej}}{N}, \tag{5}$$

where $N = 10$ is number of holes. These coordinates are used as a systematic correction of an error of pistol aiming at the centre of the target as well:

$$x_E^* = x_E - M_{Ex},\ y_E^* = y_E - M_{Ey}. \tag{6}$$

The distance from the centre of the hole to adjusted target centre (see Fig. 2):

$$r_E = \sqrt{\left(x_E^*\right)^2 + \left(y_E^*\right)^2} \tag{7}$$

is a quantitative measure of errors random arising from different pellets and portions of compressed air in a series of shots.

Assuming the correctness of the model simulation of virtual hole's centres corresponding pairs of virtual and real holes should be statistically identical. Dispersion of the virtual holes on target centre should correspond to dispersion of the pellets holes. Relevant statistical hypotheses provide equality of variances of holes dispersion in these two sets in horizontal and vertical plane, as well as statistical equality of average distances between pairs of holes, and the average distance from the target centre to the centre of the hole in a shot from viced pistol. From these considerations four statistical hypotheses were formulated.

Zero hypothesis 1. Dispersal distances between the centres of virtual and real holes in horizontal plane, with the elimination of systematic errors of pistol sighting and optoelectronic target sighting equals horizontal dispersion of the centres of holes shot from a viced pistol ($\sigma_{dx}^2 = \sigma_{Ex}^2$).

Zero hypothesis 2. Dispersal distances between the centres of virtual and real holes in vertical plane, with the elimination of systematic errors of pistol sighting and optoelectronic target sighting equals vertical dispersion of the centres of holes shot from a viced pistol ($\sigma_{dy}^2 = \sigma_{Ey}^2$).

Zero hypothesis 3. The distance between the centres of virtual and real holes, with elimination of systematic errors of pistol sighting and optoelectronic target sighting, equals the distance between the centres of holes shot made from a viced pistol and the midpoint ($\rho_d = \rho_E$).

Zero hypothesis 4. Dispersal distances between the centres of virtual and real holes, with elimination of systematic errors of pistol sighting and optoelectronic target sighting, equals the dispersion of hole centres shot from a viced pistol ($\sigma_{rd}^2 = \sigma_{rE}^2$).

The first, second and fourth hypotheses were tested using *F*-Snedecor test, and the third – *t*-Student's test for related sets. The calculations were performed by 'two-sample *F*-test for dispersions' and 'Doubles two-sample *t*-test for the median' programs from statistical analysis packet of MS Excel.

3.2. Model of Interior Pellet Ballistics

The time during which a pellet is moving in the barrel (internal ballistics) can be measured using the barrel length, velocity of a pellet leaving the barrel (the so called muzzle velocity), and certain assumptions about the nature of the changes in pellet acceleration. It is clear that the initial velocity of pellets is equal to zero, and the final one is its muzzle velocity.

Let us assume that the pellet is moving in the barrel with a constant acceleration. In this case, its barrel moving equals twice the length of the barrel divided by the speed of its flight. We found the time of pellet moving according to the linear law of acceleration change. The average value of the moving duration is obtained assuming that a pellet speed decreases from the initial maximum value to zero when the pellet leaves the barrel. In this case, the time of its movement in the barrel will be equal to 1.5 barrel length to the speed of flight.

The upper boundary of the moving duration is received from the linear law assumption of pellets speed increase from zero at the beginning of the movement to the maximum when the pellet leaves the barrel. In this case, the movement time of pellets in the barrel is equal to the triple length of the barrel divided by the speed of flight. Theoretically, the lower boundary of the length of the pellets internal ballistics process is the ratio of the length of the barrel to the speed of flight. This abstract case would occur if the pellet moved in the barrel all the time at a constant speed, i.e. at the rate equal to the muzzle speed. However, for this one needs an instant increase of pellet speed to infinitely large number that is practically impossible at the beginning of movement.

The initial conditions of pellets movement in the barrel: $t = 0$, $s = 0$, $v = 0$; the ultimate conditions: $t = t_B$, $s = l$, $v = v_B$, where s is a longitudinal pellets movement in the barrel; l is the length of the barrel; v is current speed of the movement; t_B is pellets moving time in the barrel; v_B is muzzle velocity.

For the linear law of acceleration growth we have:

$$a(t)=a_0\left(t/t_B\right),\ v(t)=\frac{a_0t^2}{2t_B},\ \ s(t)=\frac{a_0t^3}{6t_B}. \tag{8}$$

From the last two equations when $t = t_B$, we get:

$$t_B=\frac{3l}{v_B}. \tag{9}$$

To analyze the rest of the above models of interior ballistics let us represent the dependence of the pellets acceleration in time with the step function:

$$a(t)=a_0\left[1-\left(\frac{t}{t_B}\right)^k\right], \tag{10}$$

where a_0 is the initial acceleration; k is index of the step function.

Taking into account the initial and final conditions of motion, a function of velocity and displacement of pellets in the barrel, and the twice acceleration expression time integrating, we get: $v(t)=a_0t\left[1-\frac{t^k}{(k+1)t_B^k}\right]$, $s(t)=a_0t^2\left[\frac{1}{2}-\frac{t^k}{(k+1)(k+2)t_B^k}\right]$, from which we derive an expression for the time of pellets movement:

$$t_B=\frac{l}{v_B}\frac{2(k+2)}{k+3}. \tag{11}$$

Whereas the speed of pellets can not be negative, we consider only the positive, that is, practically significant quantity indicator of the step function, namely $k > 0$. When $k = 1$ there is movement with uniform acceleration of the maximum value decreasing to zero:

$$t_B=1{,}5\frac{l}{v_B}. \tag{12}$$

When $k = \infty$ the acceleration is constant (a = const), pellet movement is uniformly accelerated, the velocity increases linearly from zero to a maximum value when the pellet leaves the muzzle:

$$t_B=2\frac{l}{v_B}, \tag{13}$$

Because $\lim\limits_{k\to\infty}\frac{k+2}{k+3}=1$.

A lower (theoretical) limit of duration time of pellets movement in the barrel will be the following (k=0):

$$t_B=\frac{4}{3}\frac{l}{v_B}. \tag{14}$$

Thus, a shot moment can be defined as the duration time of the internal ballistics process, namely within the value limits of the dimensionless parameter:

$$t_B\frac{v_B}{l}=1.(3)\div 2.0. \tag{15}$$

It was experimentally [2] found that the pellet has a maximum acceleration at the beginning of the movement. When the pellet moves in the barrel its acceleration evenly decreases with slight variations, reaching zero at the muzzle. That is, in the first approximation we can take $t_B\frac{v_B}{l}$=1.5 (k = 1). Along with this, the sensitivity of the model was evaluated to determine the internal ballistics duration to exponent inaccuracy of a step-function of pellet acceleration. The relative error of computation of pellets movement time (= (tBvB/l – 1.5)/1.5)×100% ranges from -11.1 to 33.3% (Table 2) of the theoretical limits ($0 \le k \le \infty$) but it does not exceed the absolute value of 5% of possible limits ($k = 1.0 \pm 0.5$) (Fig. 3).

Table 2. Quantitative characteristics of the sensitivity of pellet internal ballistics model to the model's parameter*

k	0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	∞
$t_B v_B / l$	1.33	1.38	1.43	1.47	1.50	1.53	1.56	1.58	2.00
t_B, ms	2.06	2.13	2.20	2.26	2.31	2.36	2.40	2.43	3.08
δ, %	–11.1	–7.7	–4.8	–2.2	0.0	2.0	3.7	5.3	33.3

*$l = 0.25$ m

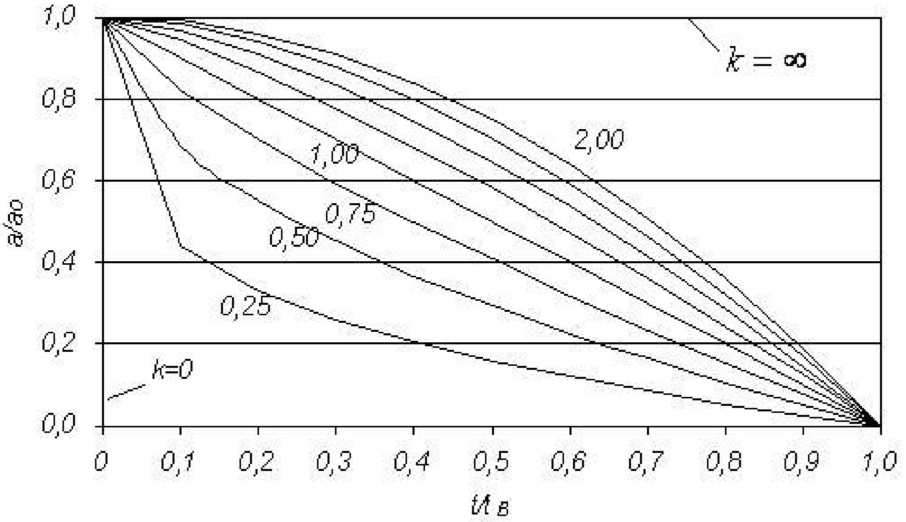

Fig. 3: The acceleration dependence to the current time of pellet motion in the barrel for the different variants of the interior ballistics model.

3.3. Simulation of virtual holes location on optoelectronic target at a given shot moment

The shot moment is set in SCATT software with the increments of 0.01 s, and the shot moment calculated by us is 0.0023 s (see Table 2). So we define the aiming point shift, depending on the time by interpolation method. A polynomial function was used to obtain such an approximation. The coordinates of the trajectory were taken to zero value of the pellets movement lateral component coefficient, that is precisely for the trajectory of the aiming point (point *S*, see Fig. 3), but not for the predicted points which positions are calculated with a computer program that simulates the lateral motion component pellets. Since the gravitational component of pellets movement while aiming within the target is a constant value (within the accuracy of fixed holes 0.1 mm), we consider it when moving the aiming point to the target centre [11].

Let us conduct an approximation of the coordinates of the virtual hole centres with hypothetical function in the form of polynomials:

$$x(t) = \sum_{j=0}^{m} b_{xj} t^j \,,\; y(t) = \sum_{j=0}^{m} b_{yj} t^j \,. \tag{16}$$

Table 3. Approximation of the coordinates of the predicted points on the optoelectronic target

t, 0,01 s	Coordinates, mm				Relative approx. error, %	
	Horizontal		Vertical			
	$x(t)$	$x(.23)$	$y(t)$	$y(.23)$	δx	δy
0; 1	$-1.538\,t + 7{,}077$	6.72	$-0.802\,t + 5.612$	5.43	0.24	-0.71
-1; 0; 1	$0.058\,t^2 - 1.596\,t + 7.077$	6.71	$-0.263\,t^2 - 0.539\,t + 5.612$	5.47	0.09	0.14
0; 1; 2	$0.141\,t^2 - 1.679\,t + 7.077$	6.70	$-0.156\,t^2 - 0.645\,t + 5.612$	5.45	-0.13	-0.20
-1; 0; 1 ;2	$0.0277\,t^3 + 0.058\,t^2 - 1.6237\,t + 7.077$	6.71	$0.0355\,t^3 - 0.263\,t^2 - 0.5745\,t + 5.612$	5.47	-	-

For example, for $m = 2$ we have a quadratic parabola, and for $m = 3$ − a cubic parabola. The corresponding approximation polynomials of the first, second and third order, as well as the numerical results for the predicted coordinates at the current shot moment that equals 0.0023 s, are shown in Table 3.

The quadratic parabola approximation with a midpoint located closer to the shot moment (-0.01, 0, and 0.01 s) gives better results in horizontal and vertical coordinates with absolute accuracy value. The relative errors are respectively 0.09 % and 0.14 % in comparison with the approximation of a quadratic parabola with a midpoint located twice as far from the shot moment (0, 0.01, and 0.02 s), where such errors are -0.13 % and -0.20 %. The linear function has quite acceptable accuracy results compared to the cubic parabola approximation. Relative errors on the horizontal and vertical coordinates are 0.24 % and -0.71 % respectively (see Table 3), therefore, the linear function is used to calculate the coordinates of the virtual hole centres in time limited moments when the pellet leaves the barrel at a given moment of triggering ($t = 0$).

Parameters of simulation of virtual hole centres location on optoelectronic target relative to the real holes according to the linear law of pellet speed reduction in the barrel, and adjusted parameters of a distance between the hole centres ensued from viced pistol shots are given in Table 4.

Table 4. Parameters of simulation of virtual hole's centres relative to the real holes according to the linear law of pellet speed reduction in the barrel

i	$x_S^* - x_P^*$	$y_S^* - y_P^*$	r_d^*	r_E^*
1	4.55	1.80	4.89	0.56
2	1.68	-0.93	1.92	0.90
3	-9.40	-6.90	11.66	1.35
4	0.00	4.78	4.78	2.02
5	-1.32	1.10	1.72	2.51
6	0.87	-2.51	2.66	2.51
7	1.96	3.19	3.75	0.56
8	6.96	2.79	7.50	1.35
9	-4.57	-0.96	4.67	1.25
10	-0.72	-2.38	2.49	0.56

Normal character of the distribution in parent population has to be verified for correct using of a parametric method of mathematical statistics in shooting results analyses because of the small sample size (10 shots). For this purpose Shapiro-Wilk test is used, as it is recommended in the cases when the sample size equals or is larger than ten. A zero statistical hypothesis assumes the existence of a normal distribution law. The criteria values in Shapiro-Wilk test appeared to be in the range from 0.870 to 0.968 at a significance level from 0.101 to 0.867 (Table 5). That is why we have taken the zero hypothesis about normal distribution law of parameters in all eleven samples. Calculations were performed using the Statistica 9.0 program packet.

Table 5. Statistical processing results of parameters of virtual hole's centers location simulation

Parameters	$x_S^* - x_P^*$	x_E^*	$y_S^* - y_P^*$	y_E^*	r_d	r_E
Shapiro-Wilky	0.957	0.968	0.958	0.925	0.876	0.870
α	0.756	0.876	0.760	0.402	0.116	0.101
M	0	0	0	0	4,60	1,36
SD	4.57	0.72	3.44	1.45	3.03	0.76
F- Snedecor	40.68		5.61		15.83	
t- Student					3.28	
$\alpha\ (F)$	<0.000001		$0.017^{\#}$		$0.000338^{¤}$	
$\alpha\ (t)$					0.00826^{+}	

$F_{(0,05;\ 9,9)} = 3.18$; $t_{(0.05;\ 18)} = 2.1$;

$^{\#}$ $\alpha\ (F) = 0.000332 \div 0.000357$ are values span of the significance level according to the distribution of the Fisher-Snedecor;

$^{+}$ $\alpha\ (t) = 0.00818 \div 0.00850$ are values span of the significance level according to the Student's distribution.

Zero statistical hypothesis about the similarity of the laws of dispersion of virtual and real holes is rejected with high confidence due to the results of statistical parameters processing of simulation of virtual hole centres location on the optoelectronic target in the linear law of pellet speed reducing in the barrel (α <0.02).

The computational experiments for the limiting moments of time (t_{min} = 2.06 ms; t_{max} = 3.08 ms), when it is possible for the pellet to leave the muzzle, were conducted to get the answer to these hypotheses at all theoretically possible range of parameters of pellet internal ballistics. Limits of the confidence levels obtained in this way (see notes to Table 5), which do not fit the zero hypothesis, confirm the preliminary finding of statistically significant difference between the dispersion laws of virtual and real holes.

Since the location simulation results of the virtual holes at zero shot moment are inaccurate, we doubt the time period of the vibration receiver response. Supposing that the sensor receives information before or, what is more likely, later than the time of the pellet leaving the barrel, the above tested zero statistical hypotheses about the laws of dispersion of virtual and real holes could be accepted with the appropriate significance level.

The results of the computational experiment for such a parameter as a ‘shot moment’ from -0.01 to 0.06 s with increments of 0.01 s is represented with the graphs (see Figure 4, 5). The smallest differences in the hole centers dispersion in horizontal plane are found at a shot moment value of 0.02 s, and in vertical plane – of 0.04 s, and the significance level value ($\alpha = 0.231$) allowed to accept the appropriate zero hypothesis (Fig. 4).

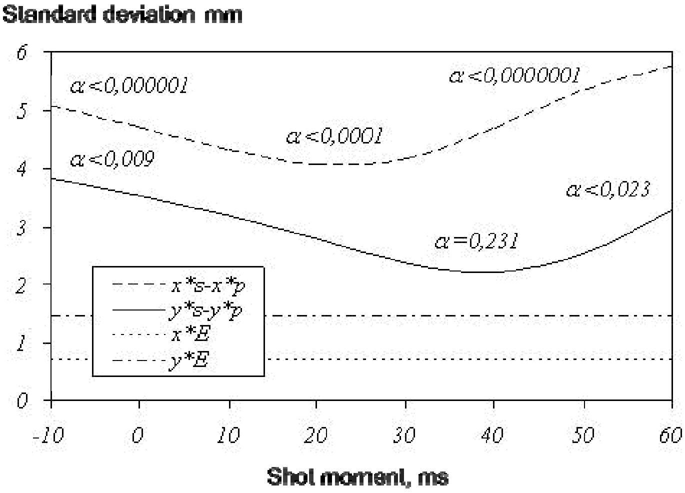

Fig. 4: Comparative quantitative characteristic of dispersion of the virtual and real hole’s centres coordinates in a test series of shots and the coordinates of the hole’s centres in series of shots with viced pistol.

The smallest difference in the distance dispersion between the hole centre and the adjusted target centre is found at a shot moment value of 0.03 s. However, the corresponding significance level value ($\alpha = 0.021$) is not high enough to accept an appropriate zero hypothesis (Fig. 5). Thus, there is no point in analyzing the differences in the variations of these distances.

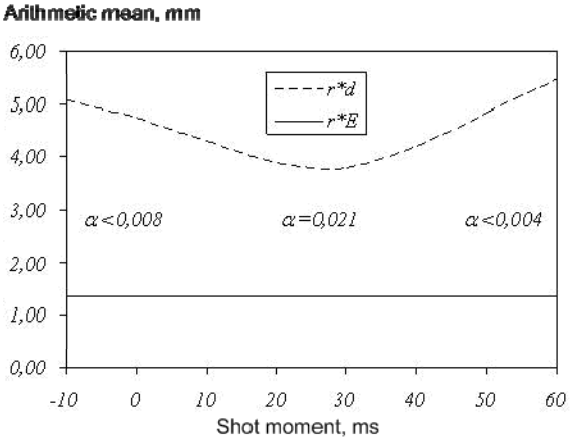

Fig. 5: Comparative quantitative characteristic of the distance between the virtual and real hole’s centres in a test series of shots and the distance between the hole’s centres in series of shots with viced pistol.

SCATT system settings provide the possibility to predict the change of virtual hole location at the shot moment shift. Setting a negative value of the shot moment parameter, one obtains the prediction for the case, as when the triggering occurred before the given time period. Setting a positive value, as when the triggering occurred later. The reliability of these predictions requires clarification, because its algorithm does not take into account the triggering influence on the weapons movement. This process is transient, but not instantaneous. A weapon changes the nature of its movement depending on the shooter's qualification from the beginning of pressing the trigger to pellet leaving the muzzle. Ideally, such a prediction should be credible when the triggering did not affect the weapon's movement. It is impossible, however, to avoid changes of the weapon movement during the triggering. It may well be so that there is proprioceptor motion as well (i.e. kinematical chain changes before triggering).

In general, the error of the holes location simulation of the distance between the centre of the hole and the target centre is equal to $| r_S - r_P |$, and the error of the interval length between the centres of virtual and real holes is in the range of $| r_S - r_P | \le d \le r_S + r_P$ (see Fig. 2). Therefore, the first criterion is a special case of the second one and can lead to the erroneous conclusions about the validity of the simulation method [11]. Hence statistical hypotheses were formulated to conduct a complete comparative analysis of real and virtual holes concerning the coordinates dispersion of the hole centres, as well as the distance between the centres of real and virtual holes. These hypotheses are more informative than the hypothesis about the distance between the holes centres of the midpoint of 10 shots series.

4. Conclusions

1. The method based on the statistical parameters comparison of the dispersion of virtual hole's centres and the hole's centres of the shots made from the viced pistol is proposed. This method of error measurement has shown itself as being useful and suitable for the scientific research practice in the field of shooting sport. Particularly, it can be used to determine a shot moment in the optoelectronic training.

2. It is found that a pellet movement time in the barrel is between 4/3 to 2 integer values of the ratio of barrel length to pellet muzzle velocity while using the developed model of the pellet internal ballistics. And in the practically significant range of this value (1.43 ÷ 1.56) relative error of determining of the pellet internal ballistics time does not exceed 5 %, which is quite acceptable for the training with the optoelectronic simulator.

3. The developed method of determining the imitation parameters of virtual holes location on the optoelectronic target at a given shot moment based on linear interpolation is useful and practically suitable as well. It allows calculating the coordinates of the virtual holes centres with a relative error within 1 %.

4. Statistical analysis of dispersion parameters of virtual and real holes in air-pistol shooting are advised to be carried out with the methods of parametric statistics because the hole centres distribution obeys the laws of normal distribution (with the significance level from 0.101 to 0.867).

5. The results of statistical analysis of simulation parameters of virtual hole centres on the electronic target, with the linear law of pellet speed reduction in the barrel, allows with a high significance level ($p < 0.03$) to reject the zero statistical hypothesis about the similarity of the laws of dispersion of virtual and real holes. This means that the model adopted in the SCATT shooting simulator is not correct enough.

5. Research Prospects

The research prospects are based on the main conclusion about SCATT imitation model incorrectness. We must have two scalar components of the muzzle vector to determine the transverse velocity of the muzzle, for example, the projection on the horizontal and vertical axes of the transverse plane. The size of each component is determined by a pair of independent scalar quantities which characterize the kinematics of the barrel in an appropriate plane. For instance, to determine the horizontal velocity component we must have either the horizontal speed component of the two points of the barrel in the projection on a transverse plane, or one of such components and the angular velocity of the barrel in a horizontal plane. These two cases can be considered as one which will predict a coordinate of the instantaneous centre of barrel rotation and the corresponding angular velocity of the barrel. The same applies to the vertical component of the transverse velocity of the muzzle. Thus, to find the transverse component of the muzzle velocity one must have four scalar values of the velocities of the barrel projected on a transverse plane. Firstly, a mathematical model of the lateral component of barrel velocity of pellets taking into account the spatial movement of the barrel weapon have to be developed to resolve this problem. Moreover, on the basis of this model one will be able to design a schematic diagram of the system simulation instrumental implementation of the pellets movement lateral component [11].

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8. Appendix

Table A1. Horizontal coordinates of virtual hole's centres in 10 shots series (x_S, mm) with different 'shot moment' parameters (t)

i \ t, ms	-10	0	10	20	30	40	50	60
1	3.85	1.79	-0.37	-2.80	-5.50	-7.50	-7.60	-6.14
2	-7.45	-6.81	-6.68	-7.50	-9.46	-11.51	-12.05	-11.09
3	-13.83	-14.58	-14.94	-15.48	-16.60	-17.42	-16.59	-14.34
4	-9.09	-9.56	-10.42	-11.88	-13.52	-13.99	-12.74	-11.20
5	-2.99	-2.65	-2.36	-2.61	-2.99	-2.52	-1.42	-1.16
6	2.17	1.79	1.01	-0.38	-2.36	-3.85	-3.76	-2.78
7	-14.83	-14.02	-13.08	-12.54	-12.35	-11.43	-9.17	-6.67
8	4.03	2.65	0.69	-1.93	-4.33	-4.79	-2.91	-0.33
9	-1.75	-1.35	-1.28	-2.08	-3.57	-4.57	-4.59	-4.83
10	-8.92	-10.13	-11.66	-13.63	-16.17	-18.40	-18.98	-18.05

Table A2. Vertical coordinates of virtual hole centres in 10 shots series (y_S , mm) with different 'shot moment' parameters (t)

i \ t, ms	-10	0	10	20	30	40	50	60
1	9.72	8.88	7.62	6.25	5.11	4.42	4.11	3.85
2	-4.98	-4.95	-4.88	-4.76	-4.64	-4.69	-5.10	-6.10
3	0.69	0.39	0.41	0.92	1.80	2.72	3.21	2.94
4	7.55	7.14	6.86	6.66	6.32	5.77	5.06	4.36
5	4.31	3.07	2.30	2.11	2.44	3.05	3.60	3.86
6	-1.52	-1.80	-1.44	-0.60	0.51	1.79	3.10	4.12
7	9.30	10.02	9.87	8.89	7.21	5.01	2.56	0.34
8	11.13	8.60	6.38	4.89	4.38	4.88	6.12	7.83
9	5.41	5.36	5.25	5.19	5.28	5.62	6.03	6.24
10	-3.29	-4.03	-4.27	-4.00	-3.49	-3.13	-3.19	-3.83