J. Biomechanics Vol. 23, Suppl. 1, pp. 35-41, 1990.
Printed in Great Britain

0021-9290/90 $3.00+.00
Pergamon Press plc

BIOMECHANICS OF HIGHLY PRECISE MOVEMENTS: THE AIMING PROCESS IN AIR RIFLE SHOOTING

V. M. ZATSIORSKY and A. V. AKTOV
All Union Research Institute of Physical Culture, Moscow, U.S.S.R.

Abstract—The position of the aiming line of the rifle in relation to the target center and fluctuations of the rifle were recorded with the specially designed optoelectronic device and 'Selspot' system respectively. It was found that while aiming, qualified shooters apply a 'fixation' strategy. With an increase in skill level, a decrease in general fluctuations at the rifle as well as random aiming error have been found. The decrease of aiming point fluctuation is partially achieved by compensating rifle movements relative to various degrees of freedom.

INTRODUCTION

Elite athletes exhibit a surprisingly high degree of movement precision. To illustrate this phenomenon consider the case of air rifle shooting from a standing position. At a distance of 10 m, the center of the target, which scores a 'ten,' is 1 mm in diameter while the bullet's diameter is 4.5 mm. If it is assumed that at the moment of shot release, there can only be angular errors in the aiming accuracy, a hit of 'ten' must be no worse than 56" (0.016°) of arc. The national record (U.S.S.R.) is set at 600 points, meaning that in 60 cases out of 60, the error was less than the value indicated above.

This resolution approximately equals the differential threshold of visual perception which equals the angle at which two dots are visualized as one (Travnikova, 1985). In reality the angular error must be smaller since at the instant of aiming there is obviously not only an angular error but an error of translational movement of the rifle as well.

The stability of the shooter-gun system and a vibration (tremor) of the gun and the shooter's body parts were measured in previously published investigations (Vasjucov, 1973; Rudina and Bik, 1978; Chugunov, 1973; Iskra *et al.* 1988). The position of the aiming point relative to the target center is registered in this study.

In our preliminary experiments, which are not presented in this paper, we analyzed the results of rifle shooting and archery. The losses in scoring points were presented as a result of both random and systematic errors. It was proved that among athletes of high caliber, the systematic error is practically equal to zero (in the case where it occurs, athletes eliminate it by changing the sight). So the authors analyzed only the random error (not to be confused with systematic errors of aiming as discussed below).

METHODS

The following was recorded for air rifle shooters (Fig. 1):

(a) the position of the barrel (i.e. aiming line) in relation to the target center;
(b) fluctuations of the rifle (by 'Selspot');
(c) fluctuation of the whole body (stabilography);
(d) pressure on the trigger (tensosystem).

Vertical and horizontal deviations of the hit point from the target center have also been registered. The position of the barrel in relation to the target center was recorded by an opticoelectronic system (Verutin, 1977). The principle of the system is as follows. The dark background directly around the target board is projected through a lens onto a photosensitive transducer indicator made up of four independent closely located photodiodes. Uniform illumination intensity of all photodiodes is obtained and the voltage at the amplifiers is equal to zero only when the rifle is aimed at the target center.

When moving the rifle to the right, for example, the projection of the dark background shifts leftward, thus one of the photodiodes is illuminated more, and correspondingly the second is illuminated less. This effect increases the output voltage. When shifting takes place in the opposite direction, the output voltage changes polarity. The same may be observed in recording the vertical shift of the rifle.

The experiments have proved a good linearity of the transducers if the rifle is moved within the circle of '6' (20 mm) for the air target at a distance of 10 m, as well

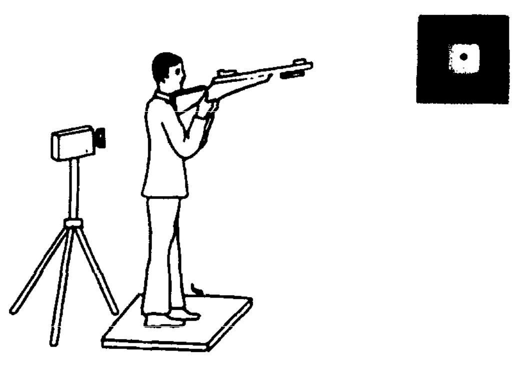

Fig. 1. Schematic drawing of the equipment.

as a good correspondence of the recorded signal to the target aiming point ($r=0.97$ for $n=30$).

To register the rifle fluctuations, a light emitting diode (LED) was fixed to the rifle butt plate. The instability of the rifle was recorded by the 'Selspot' system, whose cameras were positioned at a distance of about 40 cm from the shooter. The accuracy obtained was approximately 0.1 mm.

All the signals were recorded by a tape recorder (Shlumberge) and then the data were input into a computer. The rifle fluctuation data in the 5 s interval before shooting with the allowance ('step') being 0.25 s and at a sampling frequency of 64 Hz were analyzed. Two techniques were applied: a technique of 'stepping', and accumulated data (Fig. 2). Preliminary experiments proved that when analyzing the accumulated data, the regularities were more explicit, therefore it was decided to present the results of that analysis only.

The shooters performed 25 shots each using a 'Finewerkbay-600' air rifle and 'Match' bullets in near competitive conditions. Out of 25 shots, five shots were sighters (practice shots) and 20 were recorded shots.

RESULTS

(1) *Strategy of aiming*

There are two logically possible variants to ensure hitting the target center:

(a) by fixing the aiming line on the target just before shooting ('fixation' strategy);

(b) by correct timing of the movement, that is by pulling the trigger just at the moment when the aiming line intercepts the target center ('interception' strategy).

Two research approaches were applied in determining which strategy exactly had been used by the shooters:

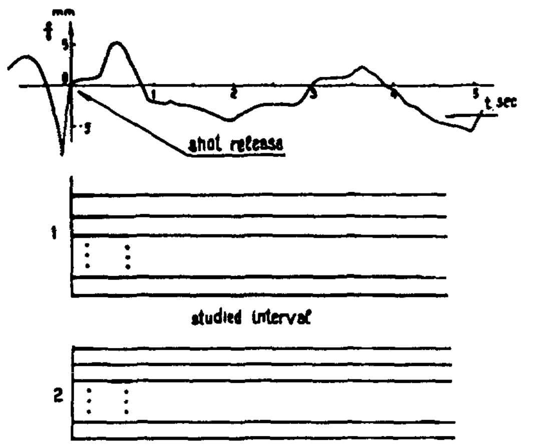

Fig. 2. The techniques of dividing the time prior to shooting to separate intervals for the study. 1—based on accumulated data; 2—based on 'stepping' the data.

(a) determination of the systematic and random aiming error;

(b) determination of the velocity of the aiming points movement at the moment of shot release and just before the shot.

The *systematic aiming error* was calculated by the formula:

$$A_t = \frac{\sum_{i=1}^{n} X_i}{n} \quad (1)$$

where:

- A_t mean value of aiming point per time interval prior to shooting ($t=0.25, 0.50, \ldots, 5.00$ s)
- X_i discrete values of the aiming point coordinates ($i=1, 2, \ldots, 320$)
- n number of values processed (for $t=0.25$ s before shooting, $n=16$; for $t=0.50$ s, $n=32$; etc.).

The data given reflect the accuracy of rifle aiming. *Random aiming error* was calculated by the formula:

$$D_t = \frac{1}{n-1} \cdot \sum_{i=1}^{n} \sqrt{(X_i - A_t)^2} \quad (2)$$

where

- D_t random aiming error per time interval prior to shooting ($t=0.25, 0.50, \ldots, 5.00$ s)
- A_t systematic error, and X_i and n have the same values as in formula (1).

The value given characterizes the degree of rifle instability.

Figure 3 illustrates changes of the systematic aiming error, while Fig. 4 illustrates changes of the random

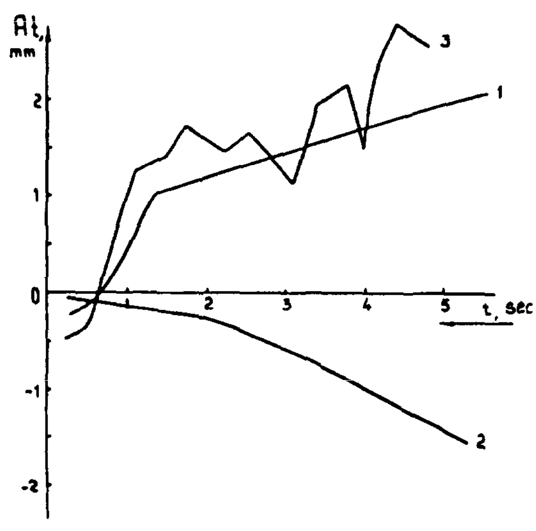

Fig. 3. Variation of the systematic aiming error with the approach of shot release. Shooter average score was 9.4 points. 1—deviation from right to left; 2—deviation up and down; 3—deviation from left to right; processing by mean 'stepping' technique (Fig. 2); considerable fluctuations are observed when utilizing this technique for data processing. The positive direction of the ordinate corresponds to the deviation of the aiming point upward (curve 2) and rightward (curves 1 and 3) from the target center.

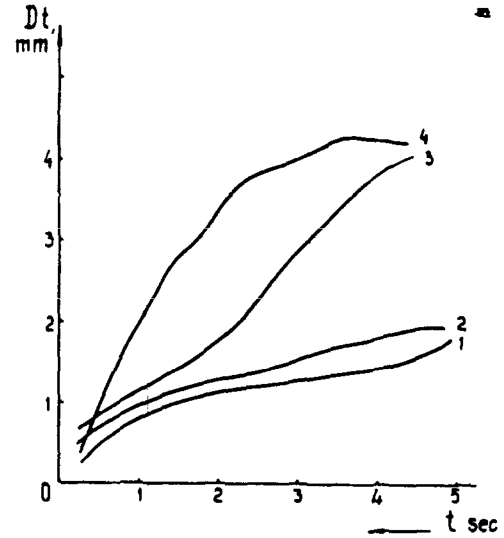

Fig. 4. Variation of the random aiming error among athletes showing different results. Four groups of shooters ($n = 3$ for each group). 1—mean result 9.4 points; 2—mean result 9.0 points; 3—mean result 8.7 points; 4—mean result 7.6 points.

error. It is obvious that both random and systematic errors decrease as the moment of shot release approaches. The first indicates that, on average, the approach of the aiming point towards the center occurs in the process of aiming and the second indicates that a decrease of fluctuations of the aiming point occurs with the approach of the shooting moment. These facts obviously prove that when aiming at the target the shooters use the 'fixation' strategy, but not that of 'interception'. The data also confirm that as the shooting moment approaches, the aiming point velocity slightly decreases.

Analysis of the aiming point fluctuation amplitude was made together with the calculation of the systematic and random aiming error according to the formula:

$$R_t = |\max X_i - \min X_i| \qquad (3)$$

where

R_t amplitude of aiming point fluctuation per time interval prior to shooting ($t = 0.25$, 0.50, ..., 5.00 s)

X_i discrete values of aiming point coordinates ($i = 1, 2, \ldots, 320$).

The data obtained together with the aiming random error characterize the degree of rifle stability. This indicator is more acceptable for coaches and athletes since it provides the opportunity to assess the area of the target where fluctuations of the aiming point were observed.

When analyzing the results of the 'left–right' and 'up–down' aiming point amplitude, the area of fluctuation was taken into account. This value was calculated as an area of rectangle circumscribed around the figure formed on the target plane by moving the aiming point.

Table 1. Change of the amplitude and area of fluctuation of the rifle in 1 and 3 s prior to shooting with gain of skill

Group of athletes	Results, average points per shot	Amplitude, mm				Area, mm²	
		Left–right		Up–down			
		1 s	3 s	1 s	3 s	1 s	3 s
IV	7.6	9.4	21.6	9.8	17.0	90.9	425.5
III	8.7	7.1	13.1	5.4	12.7	42.2	175.6
II	9.0	6.5	12.2	4.7	8.3	31.4	101.2
I	9.4	5.4	10.2	4.5	6.7	24.3	67.8

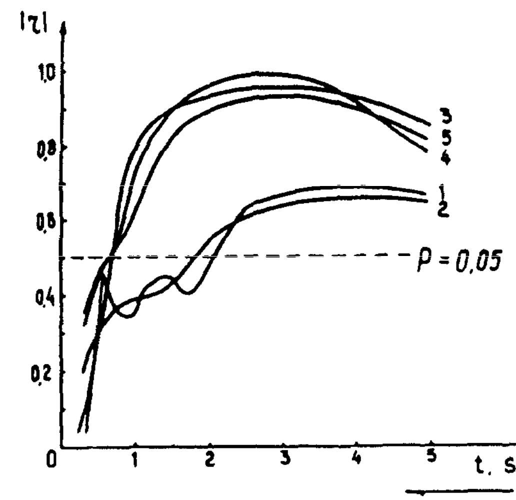

Fig. 5. Variation of the interrelation between a mean of the results and the values under study. 1—random aiming error, left–right; 2—fluctuation amplitude of the weapon, left–right; 3—random aiming error, up–down; 4—fluctuation amplitude of the weapon, up–down; 5—area of the weapon fluctuation.

The dependence of the fluctuation amplitude with respect to two axes from the study interval has the same form as the relationship of random fluctuation error; fluctuation amplitude decreases with the approach of the moment of shot release. At the same time this values decreases with experience and skill gained by the athletes (Table 1).

The following can be noted: among highly skilled athletes the aiming point one second prior to shooting is within circle '9', which taking into account the diameter of the bullet, ensures a hit in the '10' region. The area of the figure circumscribed by the aiming point (24.3 mm) is approximately equal to the area of the target within circle '9' (23.7 mm).

A distinct correlation was observed between the average results of some athletes (based on 20 shots) and averaged dispersion values (Fig. 5). It is also clear that the results of shooting more closely correlate with random vertical deviations of the aiming point rather than horizontal deviations. Unfortunately, the small number of cases ($n = 12$; correlation coefficient statistically significant at a value of $p = 0.05$, if $r \geqslant 0.497$) does not permit a more detailed statistical study.

When analyzing the correlation of score-values of one shooter (interindividual variance) we always found statistically significant relations between deviation of the holes in one of the axes and random error (rifle instability) in relation to the axis given. However, various shooters are observed to have maximum correlation values at different time intervals prior to shot release (Fig. 6). Thus:

(a) when aiming, shooters apply the 'fixation' strategy;

(b) with an increase of skill level we observe a decrease in general fluctuations of the rifle (amplitude, sighting area), as well as random aiming error (deviation of the rifle from the average position at a given time interval);

(c) the correlation between fluctuation of aiming points at different time intervals prior to shooting and the success of a shot are clearly observed.

In addition, the data indicate that vertical fluctuation decreases with skill improvement to a greater extent in comparison with horizontal fluctuation.

We next consider a frequency analysis of the aiming process. When recording the aiming point, low frequency and high frequency components can be observed (Fig. 7). We often associate low frequency components with volitional aiming of the rifle at the target (in a servosystem which includes visual feedback and a purposeful rifle movement) and high frequency with involuntary tremor. The frequency characteristics of the aiming process seem to verify this observation. Using harmonic analysis, however, usually it is not possible to identify two dominating frequencies in the spectral density profile (Fig. 8). This evidently is due to the fact that the process is of short duration and not stationary, resulting in a spectral density tending toward the low frequency range.

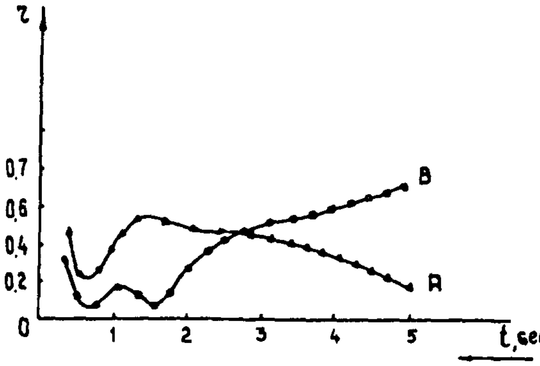

Fig. 6. Variation of the interrelation between the value of random aiming error and the hole deviation from the target center for some shots ($n = 20$, r statistically significant at $p = 0.05$, if $r > 0.378$). Different shooters: mean results of shooter $A = 9.4$ points; mean results of shooter $B = 9.0$ points.

Among athletes of high skill level a tendency toward uniform rifle levelling at the target center was observed. Out of ten observed athletes, six levelled their rifles predominantly down–up and four right–left. At the same time damping of fluctuations (decrease of random aiming error) was observed by the time of shooting.

A visual analysis proved that two aiming variants typical of different shooters can be distinguished (Fig. 9). In the first case we observe a spasmodic rifle shifting from one sighting zone to another with the rifle remaining for some time in each of the zones (up to 0.5–1.0 s). The rifle is then usually shifted toward the target center. These movements are repeated 2–5 times. In the trajectory of aiming this appears in the form of 'tiny balls'. The aiming variant described can be called multi-stage. In the second variant, only one 'tiny ball' is preceded by even fluctuation damping in an almost unchangeable aiming zone (single-stage aiming). Single-stage aiming is predominant among high class athletes.

(2) *Movement of the weapon*

High stability of the aiming point on the target can be achieved by two techniques (or by a combination of the two techniques):

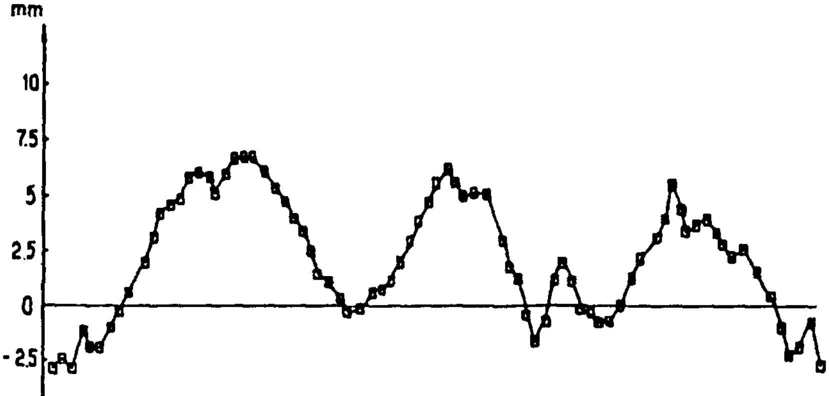

Fig. 7. Weapon fluctuations. Axis left–right, result of the shot 9.0.

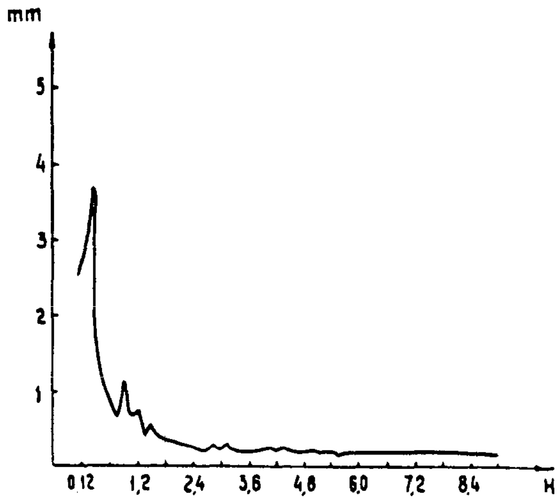

Fig. 8. Spectral density of weapon fluctuation. The shot drawn in Fig. 7 was adopted for analysis.

(a) insignificant fluctuation value of the weapon;

(b) shifting of the rifle in such a way that its shifting in one of the degrees of freedom is compensated by another.

A rifle as a solid body has, naturally, six degrees of freedom. Three of them (turning and shifting back–forth along the aiming line as well as vertical translation movement of the rifle) either do not affect the results of shooting or are extremely insignificant.

The rifle movements which are most influential in shooting results are:

(a) in the vertical plane—angular movement relative to the butt rest point against the shoulder;

(b) in the horizontal plane there are two movements—translation movement and angular movement.

The last two can compensate for each other. As we recorded simultaneously the shifting of the aiming points on the target in the horizontal plane and that of

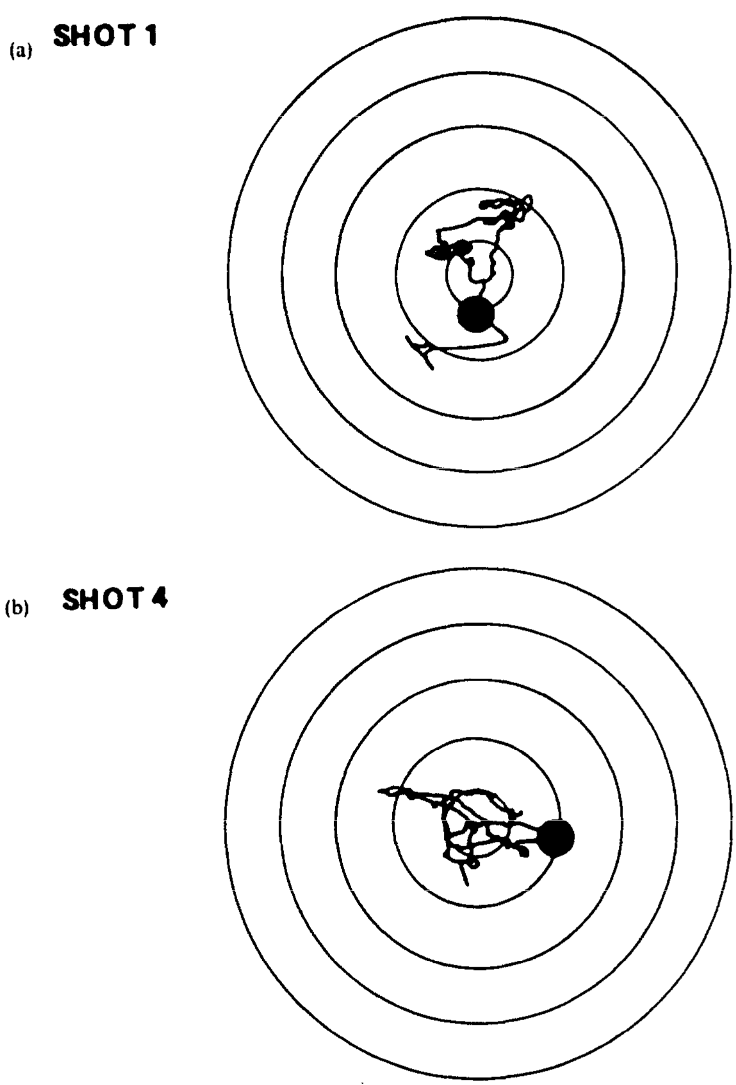

Fig. 9. Two variants of aiming. (a) Multistage aiming (availability of 'tiny balls' is observed). (b) Single stage aiming.

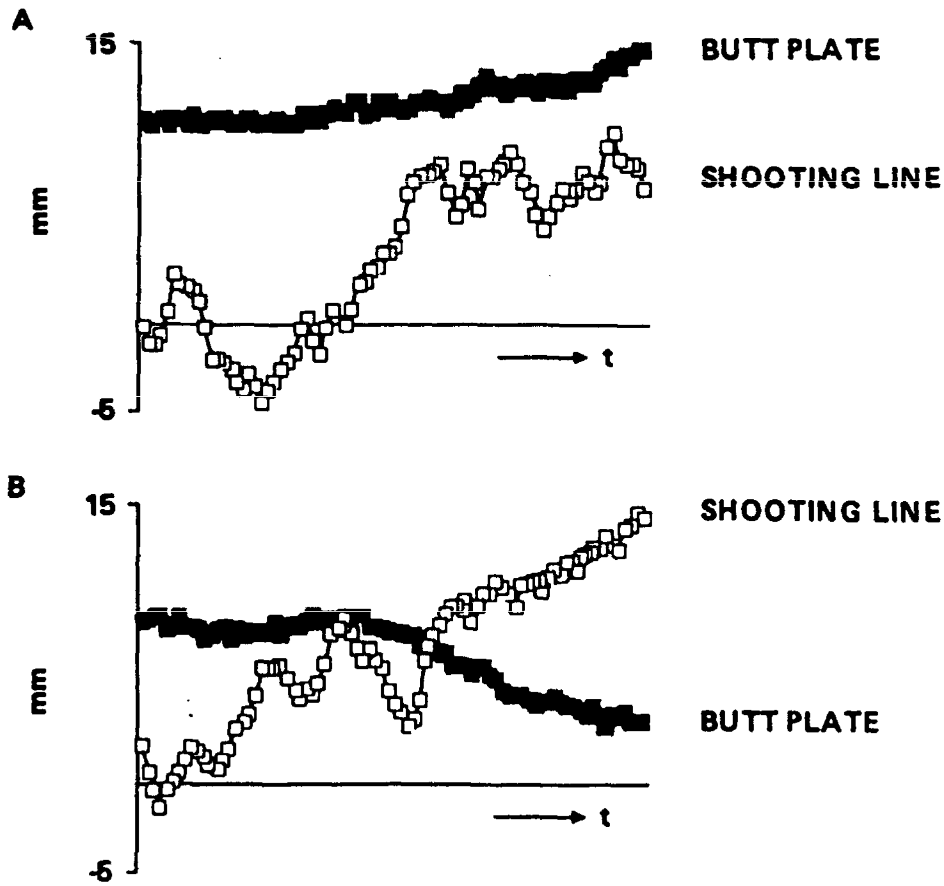

Fig. 10. Parallel (A) and compensated (B) fluctuations of the weapon. Fluctuation left-right. 1—butt shift; 2—aiming point shift.

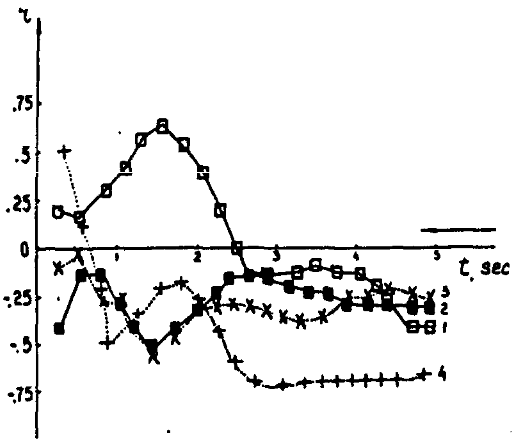

Fig. 11. Interrelation of the degree of fluctuation compensation (r) and the result of shooting. 1—shooter with mean result 9.0; 2—shooter with mean result 7.9; 3—shooter with mean result 9.4; 4—interindividual correlation ($n = 12$); 1, 2, 3—intraindividual correlation ($n = 20$).

the rifle butt on the shooter's shoulder, we could assess the relation between the translation and angular rifle movement in the horizontal plane. The movement of the aiming point and that of the butt in different directions prove that the translation due to butt shifting is compensated for by the angular movement of the rifle and their combined uni-directional movement indicates an absence of such a compensation. The correlation between the butt shift on the one hand and the target aiming point on the other can be, in some shots, within 0.90 to −0.90 (Fig. 10). On the average the correlations among the majority of athletes appear negative or closer to zero.

If we consider the effect of rifle shift compensation on the shooting results, we might observe a negative interrelationship among one group of athletes, a positive among another group, and no relation in the third group. By carrying out an interindividual study, a negative interrelationship between rifle movement compensation and mean shooting results of different athletes was discovered (Fig. 11). Obviously, this observation of such a compensation leads to lower fluctuation of the aiming point in the horizontal plane in comparison with the vertical plane (another possible reason being the necessity of counteracting the rifle weight).

SUMMARY

The specific mechanisms which provide a surprisingly high precision of human movement remain

unknown. When shooting at immobile targets, shooters apply the 'fixation' strategy during aiming. The decrease of aiming point fluctuation is partially achieved by compensating rifle movements relative to various degrees of freedom.

REFERENCES

Chugunov, J. L. (1973) The determination of the shooter-gun system stability for the selection of the gifted shooters. *Theory Prac. Phys. Cult.* **9**, 59–61 (in Russian).

Iskra, L., Gajewski, J. and Wit, A. (1988) Spectral analysis of shooter-gun system. In *Biomechanics XI-B* (Edited by Groot, G. de, Hollander, A. P., Huijing, P. A. and Ingen Schenau, G. J. van), pp. 913–919. Amsterdam Free University Press, The Netherlands.

Rudina, T. D. and Bik, A. E. (1978) Interrelation between movements in the shooter-gun system. *Theory Prac. Phys. Cult.* **9**, 17–20 (in Russian).

Travnikova, N. P. (1985) Efficiency of visual search, Moscow. *Mashinostroenie* (in Russian).

Vasjucov, G. V. (1973) Tremor as a selecting factor in shooting classes of sports schools. *Theory Prac. Phys. Cult.* **8**, 35–36 (in Russian).

Verutin, V. (1977) Photoelectric shooting gallery. *Radio* **11**, 19–22 (in Russian).