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A STUDY OF THE EFFECT OF BODY ROTATION ON THE ARM PUSH IN SHOT PUT

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Abstract. The aim of the research is to study the mechanics of the combined motion of the body rotation and the arm push, and to find the means to maximize the velocity of the shot generated during the arm push. The appropriate equation of shot motion was derived, and its solution was fitted into a measured velocity curve of the shot. The influence of the speed of body rotation on the length of the put was calculated and the optimal speed of body rotation was searched successfully. It was concluded that an effective means to increase the efficiency of the arm push could be to twist the direction of the shot's path to the left at the beginning of the arm push. The speed of body rotation of the traditional slide technique was compared with the rotational technique. It was noticed that the speed of rotation of the traditional slide technique was 13.6 rad/s before the arm push, and it decreased to 10.8 rad/s during the arm push. Therefore, the essential thing seems to be that the exertion of the power of body muscles is so that the speed of body rotation does not decrease during the arm push.

Key words: motion analysis, sports research, biomechanics, muscle mechanics, shot put.

Introduction

This study is a research of the combined motion of the shot putter's body rotation and the arm push. The theme has conventionally been treated in sport research as giving guidance for coaching, [1-5]. KIHU - Research Institute for Olympic Sports provided the subject matter for the measured data, References [6, 7]. The method that was employed to measure the three-dimensional coordinate-data for the movements of shot put is presented in [8].

Reference [1] compares the glide and rotational technique and states as follows: «But a significant advantage turns out by the angular path for the shoulder and hip movement during the delivery: gliders reached no more than about 180 degrees, rotationists by contrast about 270 degrees». The conventional conception of sport coaching is that an important factor to reach higher velocity for the shot is the length of the path of acceleration. Its length is given in the above passage as the degrees of rotation of the shoulder and hip. The actual cause here is that gliders do not have sufficient length for the path of acceleration in order to reach the same level of angular velocity as the rotationists. The passage in Reference [1] continues «Under the precondition that the turner has clearly not more time for the delivery a greater increase of the shoulder velocity produces a greater pre-tension in the upper body also. The pre-tension needs the reaction forces in the legs and the lower parts of the body. After planting the left leg the shoulder twist continuingly increases as the result of the driving right leg. At the maximum twist starts the final extension of the throwing arm». This passage points out another important factor, «a greater pre-tension in the upper body». But the pre-tension cannot be due to «a greater increase of the shoulder velocity», as stated in the passage, because it refers to the rotational technique, and the increase of shoulder velocity takes place before the jumping phase, and has no effect on the delivery. But the pre-tension in the upper body is caused by the function of the legs during the delivery. Further on [1] continues: «The function of the legs during the delivery is to manage the straightening of the body with a heave-up push to give the base for the powerful trunk turn». This is not only function of the legs, but most of all to create the pre-tension of the whole body, and with maximum acceleration of the body and the shot, to create about half of the release velocity. This can be seen in Figs. 1 and 2. The previous passage continues: «At the maximum twist starts the final extension of the throwing arm». According to this passage, the body twist reaches the maximum value at the start of the final extension of the throwing arm, and therefore, the speed of body rotation decreases significantly thereafter. Consequently, it results in a loss of speed of the shot. Fig. 3 shows that a glider had a speed of rotation 13.6 rad/s before the arm push, which is the average value for rotationists in [1], and only after the arm push started it reduced to the value of 10.8 rad/s. Therefore, the low speed of rotation of gliders seems to be mostly a technical fault.

Methods

Initial values

By using the data fitting program of study [9], the following initial values were obtained for the 19.47 m put by Arsi Harju in Kyroskoski on July 22, 2000: velocity of release N_0 = 13.023 m/s, angle of release α_0 = 39.79°, point of release x_0 = 0.21 m (forward), and z_0 = 2.24 m (height). KIHU provided the data for the coordinates according to which the path of the shot was drawn in Figs. 4 and 5. The time of the arm push was calculated from the video camera images taken from above, and the value T_k = 0.112 s was obtained. The release of the shot occurs immediately at the end of the speed curve (Fig. 1), and therefore, by separating the time of the arm push, we get the beginning of the arm push. By using the time of arm push T_k = 0.112, we obtain the velocity before the arm push n_0 = 6.5 m/s in Fig. 1 (adapted from [12]). The inclination of the speed curve is the acceleration of the shot. The acceleration of the shot during the beginning of the arm push is approximately 80 m/s^2, and the corresponding force is approximately F_β = 80 m/s^2 · 7.27 kg = 580 N. As the velocity of the shot increases, the pushing force accelerating the shot decreases. At the end of the arm push, the acceleration of the shot is about 30 m/s^2, and the corresponding force is 220 N. Since the speed of the shot is in the vertical axis and the time in the horizontal axis in Fig. 1, the displacement of the shot during the arm push is the area between the curve "Speed of shot" and the line "Speed of shot at the beginning of the arm push n_0 = 6.5 m/s" (area marked by hatching). The length is calculated to be about 42 cm. In Fig. 5, the curve of the shot's path (displacement forward – height) at point 160 (point A in Fig. 1) yields the direction angle of velocity before the arm push φ = 41.7°. The value 9.82 m/s^2 is used for the acceleration of the gravity and 7.27 kg for the mass of the shot.

Length of put

Velocity before the arm push is here called carrying velocity. The components of the carrying velocity are presented in Fig. 6. The horizontal carrying velocity

$$n_{v0} = n_0 \cos\varphi$$

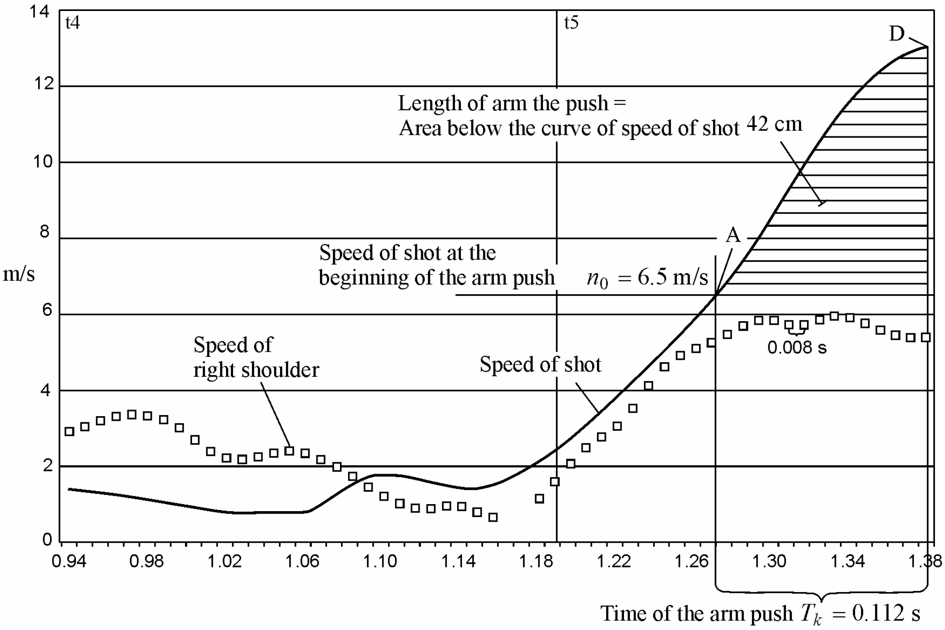

Fig. 1. The 19.47 m put. The measured speed of the shot and the length of the arm push.

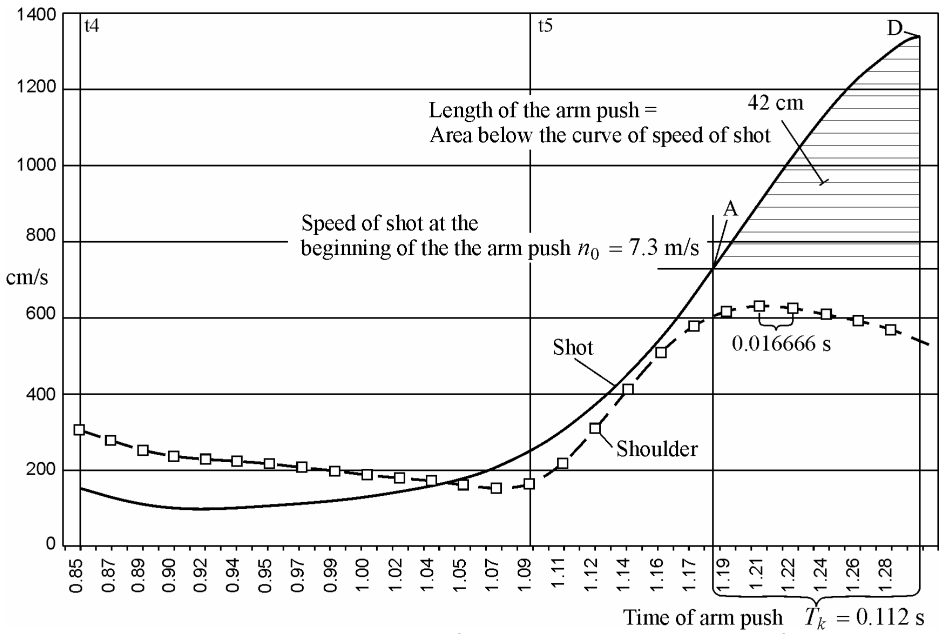

Fig. 2. The 20.90 m put. The corrected values of the shot's speed at the beginning of the arm push, the length of arm push and the time of the arm push.

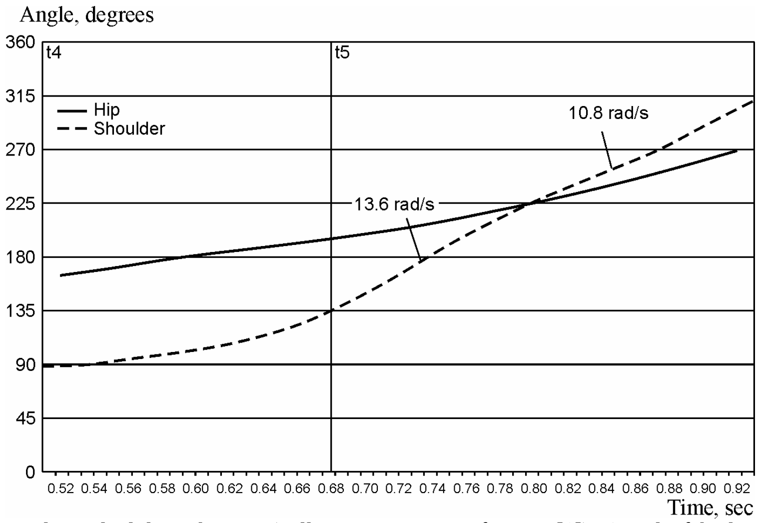

Fig. 3. Traditional glide technique (Ville Tiisanoja in Reference [6]): Speed of body rotation before and during the arm push.

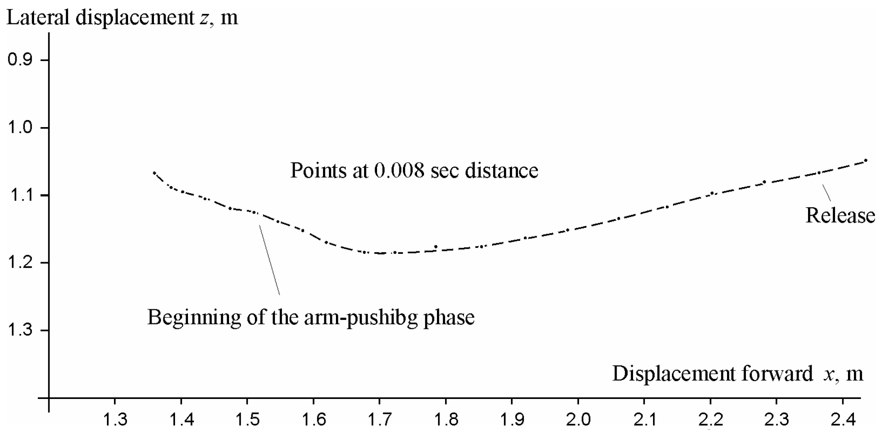

Fig. 4. The 19.47 m put. The shot's path during the arm push, looking from above.

is resulted from the body rotation, and the vertical carrying velocity

$$n_{p0} = n_0 \cos\varphi$$

results from the leg push. A leg push forward is not possible because at the end of the arm push the legs are up in the air, and therefore, the forward movement cannot be stopped. The angle of the arm push, Fig. 6,

$$\beta_0 = \mathrm{arctg}\left(\frac{N_0 \sin\alpha_0 - n_{p0}}{N_0 \cos\alpha_0 - n_{v0}}\right).$$

The angle of release, Fig. 6,

$$\alpha = \mathrm{arctg}\left(\frac{K \sin\beta_0 + n_{p0}}{K \cos\beta_0 + n_{v0}}\right).$$

The velocity of release, Fig. 6,

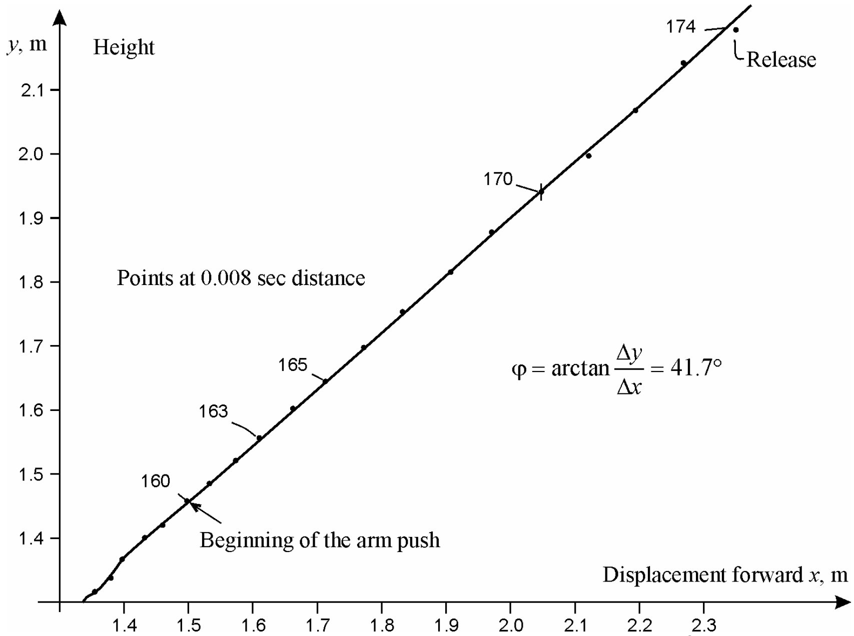

Fig. 5. The 19.47 m put. The shot's path during the arm push, looking from the side.

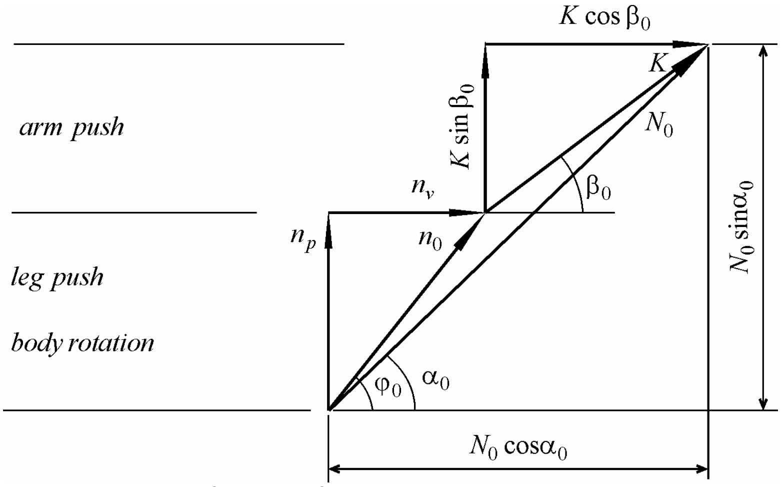

Fig. 6. The increase of velocity of the shot during the leg push and the arm push. The velocity increases: the leg push n_p, the body rotation n_v, the arm push *K*.

$$N_0 = \sqrt{\left(K\cos\beta_0 + n_{v0}\right)^2 + \left(K\sin\beta_0 + n_{p0}\right)^2}\ .$$

The velocity of the shot generated by the arm push, Fig. 6,

$$K = -\cos\beta_0 \cdot n_{v0} - \sin\beta_0 \cdot n_{p0} + \sqrt{\left(\cos\beta_0 \cdot n_{v0} + \sin\beta_0 \cdot n_{p0}\right)^2 + N_0^2 - n_{v0}^2 - n_{p0}^2}\ .$$

The length of the put (vacuum), [5] Eq. (6),

$$X_0 = \frac{N_0}{g}\cos\alpha_0\left[\sin\alpha_0 + \sqrt{\sin^2\alpha_0 + \frac{2gz_0}{N_0^2}}\right] + x_0 .$$

The length of the put (air), the shortening effect of air drag 0.5427 %, [10],

$$X_0(air) = \left(1 - \frac{0.54}{100}\right) \cdot X_0(vacuum) = 0.9946 \cdot X_0(vacuum).$$

The effect of the body twist at the end of the arm push is a decrease in the velocity generated during the arm push ΔK. If body rotation decreases, the effect is as follows: ΔK decreases, velocity increase during the arm push $K = K_0 - \Delta K$ increases, release velocity N_0 increases. As for the carrying velocity: horizontal carrying velocity decreases $n_v = n_{v0} - \Delta n_v$, if release velocity N_0 decreases. If the body rotation increases, the above procedure is inverse.

Effect of body rotation

1. Speed of the body rotation decreases. → Horizontal carrying velocity n_v decreases (Fig. 6).
2. Speed of the body rotation decreases. → Body turn at the end of the arm push decreases. → Velocity decrease caused by the body turn ΔK decreases. → Velocity increase during the arm push K increases.
3. Speed of the body rotation decreases. → Angle of release α_0 increases (Fig. 6).
4. Speed of the body rotation decreases. → Angle of the arm push β_0 remains the same.

The following initial values are obtained for the 19.47 m put: carrying velocity n_{v0} = 4.85 m/s, n_{p0} = 4.32 m/s, angle of the arm push β_0 = 37.9°, increase of velocity during the arm push K = 6.53 m/s, length of put (vacuum) X_0 = 19.57 m.

Equation of motion

The weight of the shot 7.27 kg and the weight of the hand approximately 2.73 kg, or a total of 10 kg, [11] page 117: mass of shot and hand – m, velocity of shot during the arm push – V, power generated by hand – P, time of the arm push – T.

The effect of velocity on pushing force and internal friction of hand: pushing force – P/V, internal friction in hand – $C\,V$.

Equation of motion in differential form

$$m\frac{dV}{dT} = \frac{P}{V} - CV . \tag{1}$$

The solution for the equation of motion is obtained by integrating

$$-\frac{m}{2C}\int -\frac{2CV}{P}\frac{1}{1-\frac{C}{P}V^2}dV = \int dT . \tag{2}$$

The initial conditions are stated in paragraph ”Numerical determination of the optimal speed of body rotation”. A solution of Eq. (2) is

$$T = -\frac{m}{2C}\ln\left(1 - \frac{C}{P}V^2\right), \tag{3}$$

$$V = \sqrt{\frac{P}{C}\left(1 - e^{-(2C/m)T}\right)}. \tag{4}$$

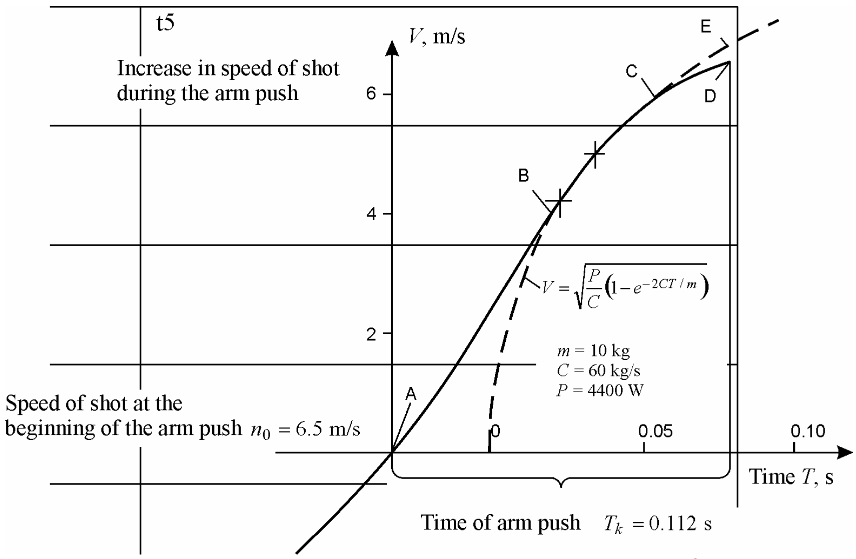

Fig. 7.The 19.47 m put. The shot's measured speed curve (section A-D from Fig. 1) is the continuous line, and the shot's theoretical speed curve is the broken line. The zero point $V = 0$ and $T = 0$ is 0.032 seconds from point A.

When Eq. (4) is fitted into the measured speed curve in Fig. 7, the following values are obtained for the constants

$$C = 60 \text{ kg / s}, P = 4400 \text{ W}.$$

Analysis of the 19.47 m put

When the time of the arm push is known, it is possible to determine the generation of the speed of the shot during the arm push with the speed curves of the KIHU Report, Figs. 1 and 7, [6, 12]. Thereby, the part corresponding to the time of the arm push is separated from the end of the speed curve. The time of the arm push is determined with the sequence of film frames taken from above. The time of the arm push in Fig. 1 is calculated to be 0.112 s. The shot's path in Fig. 1 is presented in Figs. 4 and 5. With the speed of video camera of 125 frames per second, it is possible to determine time and location with sufficient accuracy. The shot's path during the arm push is such that in section A-B in Fig. 7 the arm push continues to generate speed with the maximal pushing force, in which case the inclination of the speed curve is near a constant value. This is because the maximal generation of speed is limited by the shot putter's maximal arm-pushing force. As the arm push continues, in section B-C-D, the pushing force accelerating the shot decreases. This can be seen in the decreased inclination of the speed curve. There are three different factors that cause the decrease in velocity. First: as the speed of the shot increases, the rate of increase is not limited by a maximal pushing force, but by a maximal propulsive power, in which case force is power divided by velocity. Second: The internal friction of the pushing hand, which can be considered to be directly proportional to the velocity, decreases the velocity of the shot. Third: as the shot putter in the rotational motion turns sideways in respect to the direction of the arm push, the pushing force of the arm decreases, and disappears, and the arm just follows the shot without accelerating it. In Fig. 7, the curve marked with a broken line describes the effect of the first and second factor within the speed curve. In section B-C, the measured speed curve and the broken line become one. In this phase of the arm push, the two above-mentioned factors are the principal factors influencing the speed of the shot, decreasing acceleration. In section C-D, the measured speed curve travels under the broken line. In this phase of the arm push, the shot putter turns so much sideways in respect to the direction of the arm push, so that the acceleration of the shot decreases further. If the shot putter would not turn (or rotate) during the arm push, the measured speed curve would agree with the broken line in section C-E.

Shoulder angle relative to the direction of push

The film frames taken from above show the shoulder angle relative to the direction of push in which the arm push begins (A) and ends (B) (diagram of a half circle of a shot put in Fig. 8). The shoulder angle in the present shot put is the broken line in Fig. 8. The time interval between points A and B is 0.112 sec. By this means, the points at the beginning and end of the arm push can be marked on the time axis of the KIHU diagram. The speed of the body rotation can be calculated by the inclination of the broken line (shoulder angle relative to the direction of push). The result is calculated to be $\omega_0 = 14.8$ rad/s.

Decrease in length of the arm push as a function of body turn

In shot put, the body rotation and the arm push are performed simultaneously, and therefore, it is difficult to observe that the arm push becomes shorter when the shot putter turns because of the following reasons. If the one pushes so that the shoulder joint remains in place, the length of the arm push is determined by the length of the arm. In this model of a static body, slight backward movement of the shoulder joint corresponds to the turning of the body. This is because the length of the arm push equals the length of the arm added to the length of movement of the shoulder joint, which decreases if the shot putter turns.

The progress of the component of horizontal carrying velocity in the direction of the arm push $n_v \cos\gamma$ is presented in Fig. 9.

The length of the arm push becomes shorter by a distance *dL* in the time *dt*

$$dL = (n_v - n_v \cos\gamma)dt\,. \qquad (5)$$

As $dt = d\gamma / \omega$, authors obtain

$$\Delta L = \int dL = \int_{\gamma_0}^{\gamma_1} (n_v - n_v \cos\gamma)\frac{d\gamma}{\omega}, \qquad (6)$$

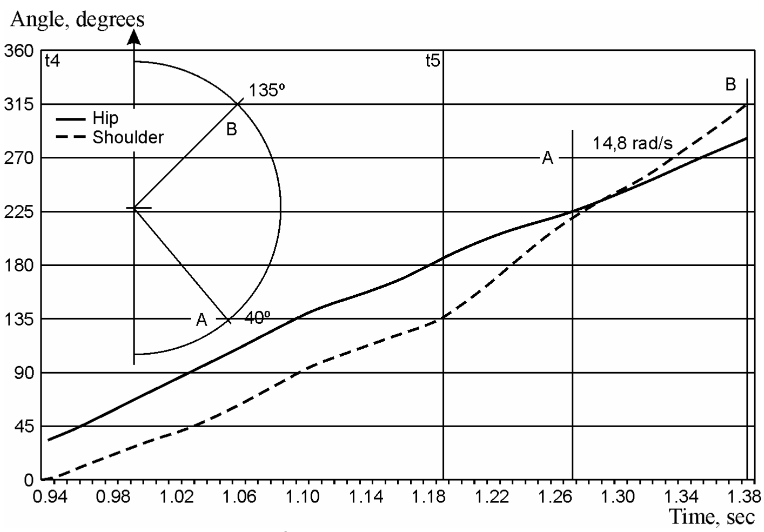

Fig. 8. The 19.47 m put. Orientation of the body rotation at the beginning (A) and at the end (B) of the arm push.

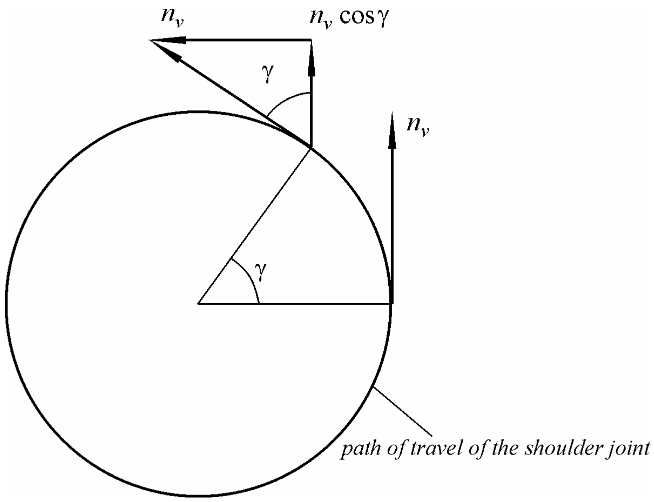

Fig. 9. The velocity $n_v \cos\gamma$ is a component of the horizontal carrying velocity n_v in the direction of the arm push.

and the solution is

$$\Delta L = \frac{n_v}{\omega}\left[(\gamma_1 - \sin\gamma_1) - (\gamma_0 - \sin\gamma_0)\right]. \tag{7}$$

From paragraph "Length of put", the horizontal carrying velocity is n_{v0} = 4.85 m/s, and from paragraph "Shoulder angle relative to the direction of push", the speed of the body rotation is $\omega_0 = 14.8$ rad/s. The angle γ_1 is the shoulder angle, at which the shot is released from the shot putter's hand. At that time, the angle γ_1 = 52° = 0.908 rad corresponds to the maximal shortening of the arm push 3.92 cm.

Length of the arm push

In the speed curve in Fig. 1, speed is in the vertical axis and time is in the horizontal axis. The distance that the shot travels during the arm push is the area between the speed curve and the carrying velocity. By dividing the time of the arm push T_k into parts ΔT_{ki}, the length of the arm push L can be calculated approximately by the formula

$$L = \sum_{i=1}^{n} \Delta L_i = \sum_{i=1}^{n} V_i \cdot \Delta T_{ki}\,, \tag{8}$$

where ΔL_i – increase of distance in the arm push, ΔT_{ki} – increase of time in the arm push, V_i – shot's speed corresponding to the increase of time.

By this means, the length of the arm push in the present shot put is about 42 cm. The time of the arm push 0.112 s can now be verified. Considering that in the rotational motion the length of arm push becomes shorter by about 4 cm, we get about 46 cm for the total length of the arm push. This fits with a sufficient accuracy to the measures of the arm push (from shot's point of start to point of release).

The effect of body turn on the speed increase in the arm push

The theoretical (Eq. 4) and measured (Fig. 1) speeds part each from other by 0.03 seconds before the end of the arm push (Fig. 10). At that time the turn of the shot putter's body begins to effect on the speed increase. It follows that the measured speed (thick line) has smaller values than the theoretical speed (thin line). The difference between them Δ*V* is the effect of the body turn presented in Fig. 9. The value Δ*V* was measured and was used to calculate the length of the put as a function of speed of body rotation.

The angle of body rotation θ, corresponding to the time $T_k - \Delta t$, is $\theta = \omega_0(T_k - \Delta t)$. The new speed of rotation is $\omega = \theta / T_k = \omega_0(T_k - \Delta t)/T_k$. With a higher speed of rotation ω, the shot putter reaches the position of body turn marked with Δ*T* in Fig. 10. In this point, the decrease of speed due to the body turn is Δ*V*. The effect of the body rotation ω is calculated so that the shot putter always uses the same time of the arm push T_k, and the speed of the shot *V* increases according to the theoretical speed curve (thin line) until the end of the arm push, the time T_k, and the decrease of speed Δ*V*, corresponding to ω, is then subtracted. The result is presented in Table.

Numerical determination of the optimal speed of body rotation

The length of the put is calculated with the initial values of vertical carrying velocity n_p, angle of the arm push β_0 and point of release x_0 and z_0, as in paragraphs ”Initial values” and ”Length of put”.

The length of the arm push becomes shorter, see Eq. (7) and Table,

Table. Effect of the speed of body rotation on the result of the put.

coeff. Φ	ω, rad/s	Δ*T*, s	Δ*L*, cm	Δ*V*, m/s	*X*, m
1.05	15.54	0.0056	-1.135	-0.5	19.24
1.00	14.8	0	0	-0.28	19.47
0.95	14.06	-0.0056	0.96	-0.17	19.38
0.90	13.32	-0.0112	1.751	-0.11	19.17
0.82	12.14	-0.020	2.894	-0.056	18.71

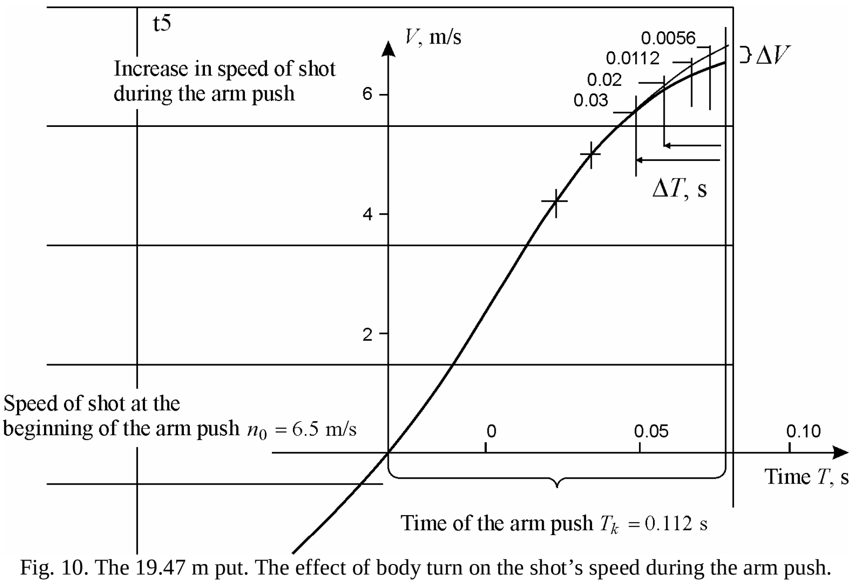

Fig. 10. The 19.47 m put. The effect of body turn on the shot’s speed during the arm push.

$$\Delta L = \frac{n_v}{\omega}\left[(\gamma_1 - \sin\gamma_1) - (\gamma_0 - \sin\gamma_0)\right].$$

Time of the arm push, Eq. (8)

$$T_K = T_k + \frac{\Delta L}{N_0 - n_0}.$$

The fitting of the shot's theoretical velocity, Eq. (4), to the shot's measured velocity is in Fig. 1. In section A-D, the value of speed can be considered to be the same as the value of velocity of the hand, because the shot travels almost in the same direction. The zero point V = 0 and T = 0 is 0.032 seconds from point A in Fig. 7. The velocity at the end of the arm push without the effect of body turn, Eq. (4),

$$T = T_k - 0{,}032\,\text{sec},$$
$$V = \sqrt{\frac{P}{C}\left(1 - e^{-2CT/m}\right)}.$$

Horizontal carrying velocity, coefficient Φ from Table

$$n_v = n_{v0} \cdot \Phi.$$

Carrying velocity

$$n_0 = \sqrt{n_p^2 + n_v^2}.$$

The release velocity N_0 is the sum of the carrying velocity n_0 and the increase of velocity generated during the arm push without the body turn $\boldsymbol{V}$, from which the effect of the body turn ΔV in Table is subtracted

$$N_0 = n_0 + V - \Delta V. \quad (9)$$

The angle of carrying velocity n_0 is φ = 41.7° and the angle of release velocity N_0 is α_0 = 39.79°, and they are so close to each other that the velocity vectors of carrying velocity and velocity generated during the arm push can be added as scalar quantities. In this case, the change in horizontal carrying velocity must be minimal, Φ being within the limits of [0.8; 1.05]. Otherwise, the vector calculus method in paragraph "Length of put" should be used. The effect of the change in release angle (α_0 = 39.79°) is minimal within the angles 39°-44°, and can be discarded.

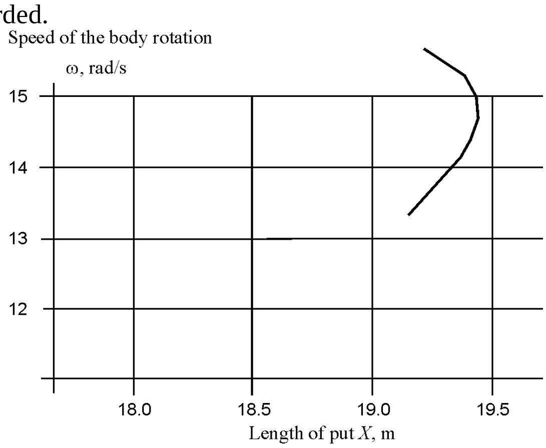

Fig. 11. The 19.47 m put. The effect of the speed of the body rotation ω on the length of the put X according to Table.

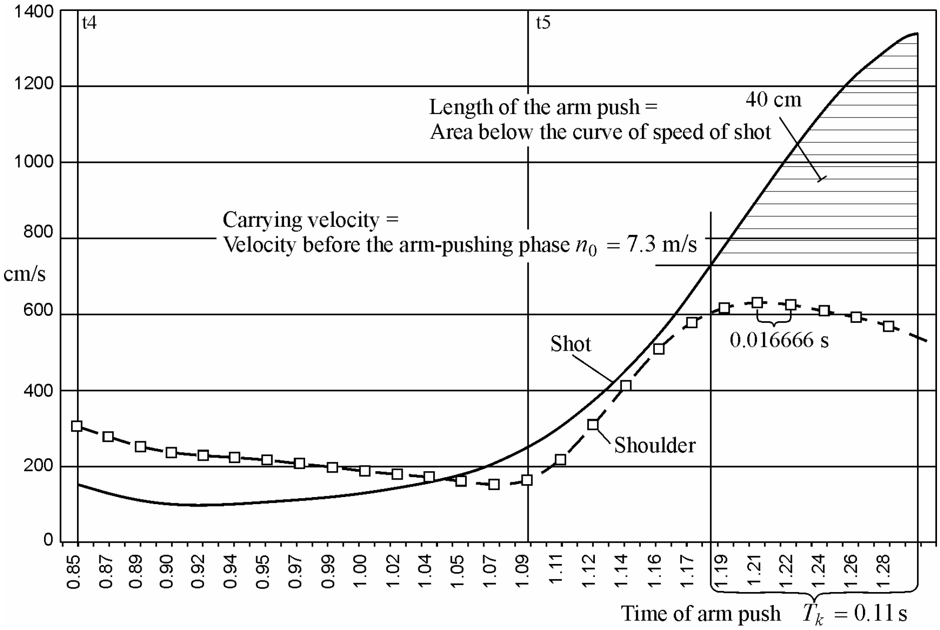

Fig. 12. The 20.90 m put. The shot's speed before the arm push and the length of the arm push as they are in References [13, 14].

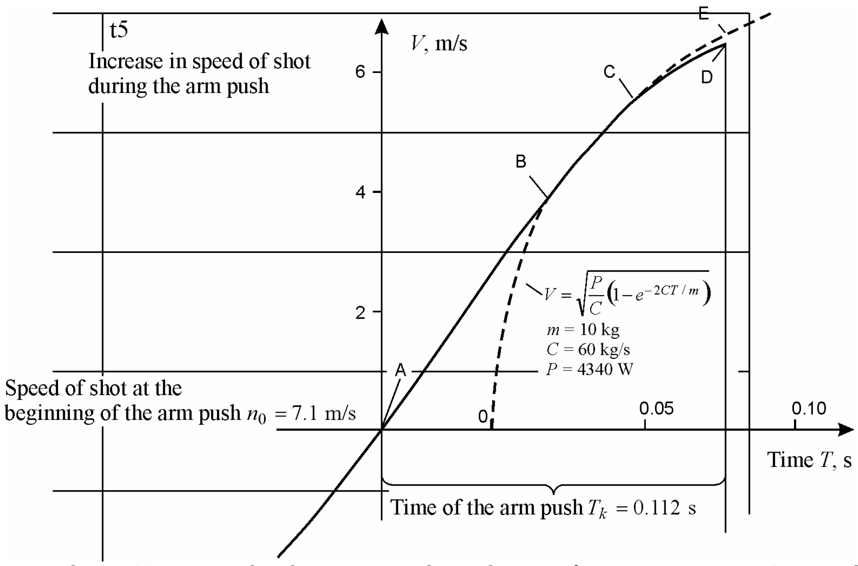

Fig. 13. The 20.90 m put. The shot's measured speed curve, from Fig. 2 section A-D, is the continuous line, and the shot's theoretical curve, Eq. 4, is the broken line. The zero point $V = 0$ and $T = 0$ is 0.036 seconds from point A.

In Table, the speed of body rotation used in the present shot put, $\omega_0 = 14.8$ rad/s, is multiplied by the coefficient Φ, and a new speed of body rotation ω is obtained. The time of release is changed by the time ΔT (Fig. 10), the length of the arm push becomes longer (or shorter) by the distance ΔL (Eq. 7), the difference between the theoretical and real speed is ΔV (Fig. 10), and the result of the put is X. The speed of the body rotation as a function of the length of the put is presented in Fig. 11.

Analysis of the 20.90 m put

Another shot put by Arsi Harju was analyzed in order to be able to compare the two puts and to learn more about the characteristics of the arm push. That analysis is also necessary to confirm the validity of the equation of motion because the fitness of one analysis may just be a lucky coincidence. The other put was the 20.90 m put in [7], which has previously been used as the source for data in [13, 14]. The measured speed curve of this put is presented in Fig. 12 (adapted from [14]). When the speed of the shot calculated by Eq. (4) was attempted to fit into the measured speed curve of this other put in Fig. 12, it did not fit. This mean that there was something wrong. The measurement of the shot's speed in Fig. 12 was made with a camera of low film speed, 60 frames per second, and there is reason to believe that this was the cause of failure. The determination of the time of the arm push was made with the images taken from above, and from there it can be distinguished in which frame the arm push begins and ends. But because the consecutive frames were too far from each other (interval between frames 0.01666 s), it was impossible to determine the exact times for the beginning and end points of the arm push. The shot's speed of the 19.47 m put in Fig. 7 was measured with a camera of much higher film speed, 125 frames per second (interval between frames 0.008 s), and this camera speed is sufficient for the proper determination of the time of the arm push. It was calculated to be 0.112 seconds, with the corresponding length 42 cm, as calculated in paragraph "Length of the arm push". The length of the arm push in Fig. 12 is 40 cm. This means that it is too short because the arm pushes of the same shot putter must be nearly equally long. Therefore, the length in Fig. 12 must be 42 cm. The increase in length of the arm push is equal to the velocity increase in the arm push multiplied by the time of the arm push $\Delta V \cdot T_k$ = 2 cm. The value ΔV is equal to the decrease in velocity before the arm push ΔV = 0.02 m / 0.112 s = 0.2 m/s. This means that the velocity before the arm push in Fig. 12 must be n_0 = 7.3 m/s – 0.2 m/s = 7.1 m/s. The corrected speed of the shot is presented in Fig. 2. After this corrective operation, the speed calculated by Eq. (4) coincides with the speed in Fig. 2 (section B-C in Fig. 13). The propulsive power of the arm push is approximately P = 4340 W. The arm push in Fig. 7 has a greater pushing force than one in Fig. 2, but at the end of the push the decrease in velocity in Fig. 7 is so great that the total velocities generated during both arm pushes are almost equally high. The reason for the large decrease is probably due to muscle mechanics, maybe a pressure decrease in muscles at the turning the body is getting larger. In the optimal arm push, this large velocity decrease must be eliminated. The difference between the velocities in Fig. 2 and in Fig. 4 at the end of the arm push, sections C-E and C-D in Fig. 13, may be due to the effect of the turn on the velocity of the shoulder joint n_V, presented in Fig. 9. This is because the velocity V in Eq. (1) should be $V + (n_v - n_v \cos\gamma)$. If the optimal speed of the body rotation is calculated with the speed curve in Fig. 13, this will be slightly higher, but not much, because in any case the effect of the turn increases rapidly.

Results

The optimal speed of the body rotation was calculated to be ω = 14.8 rad/s, which was actually used in the present put. As the speed of the body rotation was decreased 0.95–fold relative to the speed used in the present put (14.8 rad/s→14.1 rad/s), the result was 9 cm shorter, 19.47 m→19.38 m. As the speed of the body rotation was decreased 0.9-fold (14.8 rad/s→13.3 rad/s), the result was 30 cm weaker, 19.47 m→19.17 m. Also, if the speed of the body rotation was increased, a weaker result was obtained. When the speed of the body rotation was increased 1.05-fold (14.8 rad/s →15.54 rad/s) the result was 23 cm weaker, 19.47 m→19.24 m. Therefore, it can be concluded that the optimal speed of the body rotation is about 14.8 rad/s, which is approximately 2.35 rps. The speed of the body rotation can be decreased from 14.8 rad/s to 14 rad/s without a substantial reduction in the result.

Conclusions

In shot put, the speed of the body rotation is an important factor to increase the speed of the shot at the point of release. For this reason, it is sought to employ the speed of the body rotation as high as possible. When the benefit of the body rotation is maximized by increasing its speed, the disadvantageous effect of the body turn on the arm push becomes greater and decreases its benefit. In order to perform an effective arm push, the shot putter must turn sufficiently in the direction of the throwing path which represents the quarter of a circle. However, the optimal speed of body rotation turned out to be so high that it is hardly ever exceeded. Therefore, the actual goal is to minimize the disadvantageous effect of the body turn. Since it is known that the optimal speed of the body rotation in the present put was about the same as the speed of the rotation that was actually used in the put, it is not worth exerting great force in order to increase the speed of the body rotation, because it will not increase the length of the put. Instead, the exertion of force may be concentrated for some more profitable effort.

This study determined the optimal speed of the body rotation of the 19.47 m put by Arsi Harju. Another put of 20.90 m was analyzed in order to be able to compare the two puts, and in that way to learn more details about the characteristics of the arm push. Within different shot puts and shot putters, the situations may vary somewhat. However, shot puts generally are so much of the same technique, that the result gained here is also valid on a larger scale. Other factors that may influence the optimal speed of the rotation are a significant increase in the magnitude of the pushing force in the arm push and the timing of the arm push. An effective means to increase the efficiency of the arm push could be to twist the direction of the shot's path to the left at the beginning of the arm push, when the speed of the shot is still low. It was also found that the length of the arm push most effectively increases the length of the put. An increase of length of the arm push in Fig. 2 by 2 cm yields an increase of release velocity of about 0.2 m/s, which correspondingly increases the length of the put by about 0.5 m. Traditionally, this effect has been utilized by pushing the shot with finger tips.

A shot putter using the traditional glide technique in Fig. 3 had the speed of the body rotation before the arm push of 13.6 rad/s, and it decreased during the arm push to the value 10.8 rad/s. This kind of retardation of the speed of the rotation, weakening the result of the put, is a frequent technical fault. It can also be seen in Fig. 8. Supposing that the effect of the turn is similar to that in Fig. 11, a rough evaluation of the effect of the speed of the rotation on the result of the put can be made. If the speed of the body rotation in the rotational technique is 14.8 rad/s, then the traditional glide technique, due to the lower speed of the body rotation of 10.8 rad/s, loses about 1.3 m. However, if the speed of the body rotation before the arm push in the traditional glide technique (13.6 rad/s) would remain during the arm push, the shot putter using the glide technique would win 1.1 m, and he would get only 20 cm less than the shot putter using the rotational technique. Therefore, a powerful exertion of the body muscles during the arm push is the most effective means to increase the length of the put.

A long body structure is ideal for the traditional glide technique, whereas the shot putters using the rotational technique usually have a smaller body structure. A longer arm of a shot putter using the traditional technique yields a longer path of motion for acceleration during the arm push. However, the shot putters using the rotational technique have the advantage of a higher speed of the body rotation. For this reason, the traditional glide technique and the rotational technique can compete equally.

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ ВРАЩЕНИЯ ТЕЛА НА УСИЛИЕ РУКИ ПРИ ТОЛКАНИИ ЯДРА

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Цель данного исследования – изучение механики составного движения, включающего вращение тела и толкание ядра рукой, а также поиск возможности максимально увеличить скорость ядра во время выполнения толчка. Было получено соответствующее уравнение движения, решение которого совпало с экпериментальной кривой скорости. Авторами было численно установлено влияние скорости вращения тела на дальность полета ядра и получена оптимальная скорость вращения тела. В результате оказалось, что действенный метод увеличить эффективность толчка рукой заключается в закручивании трактории ядра влево в начале выполнения упражнения. Скорость вращения тела при «традиционной» скользящей технике сравнима со скоростью при вращательной технике. Было отмечено, что скорость вращения тела в первом случае составляет 13,8 рад/с до толчка рукой и снижается до 10,8 рад/с во время толчка рукой. Поэтому существенным моментом кажется то, что мышцы тела работают так, что скорость вращения туловища не снижается во время толчка рукой.

Примечание: 1. проверить после окончания перевода

Примечание: 2. проверить после окончания перевода

Ключевые слова: анализ движения, исследование спорта, биомеханика, механика мышц, толкание ядра.

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