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Biomechanical Analysis Hammer Throw: The Influence of Kinematic Parameters on the Results of Finalists World Championships

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Abstract **Background:** Hammer throw is the most complex athletic throwing discipline with a rotational trajectory and the strong action of several different forces that try to disable the projected throwing trajectory. Kinematic parameters are an important segment in the analysis of athletic disciplines, including hammer throw. **Aim study:** The aim of the study was to determine the influence of spatial and temporal biomechanical parameters on hammer throw results. **Methods:** The study was conducted on a sample of 56 male and female World Championship finalists (Berlin, 2009, Daegu, 2011, London, 2017). Multiple regression analysis was applied to determine the influence of defined kinematic parameters on the result performance of the throw. **Result:** The results of the male finalists confirmed the direct correlation between the starting speed (r=0.64 $^{p=0.001}$), the first turn speed (r=0.47 $^{p=0.017}$), the release velocity (r=0.86 $^{p=0.000}$), the release of angle (r=0.37 $^{p=0.049}$), and the inverse effect of the duration of the first (r=-0.40 $^{p=0.046}$) and third turn (-0.46 $^{p=0.020}$). The regression function of the male sample also confirmed the influence of starting speed, release of velocity (p=0.01 $^{p<0.05}$) and angle of release (p=0.04 $^{p<0.05}$). In the female finalists, the direct correlation is between the release of velocity (r=0.90 $^{p=0.000}$), the angle of release (r=-0.62 $^{p=0.000}$) and the fourth turn speed (r=0.50 $^{p=0.002}$). The regression function for the female sample confirmed a high negative influence of the starting speed, while the direct influence was recorded at the release of velocity (p=0.02 $^{p<0.05}$) at the given level of statistical significance of the regression function. **Conclusion:** The defined set of kinematic parameters had a significant impact on the result performance of male and female hammer throw finalists.

Keywords: *elite hammer throwers, world championships, influence, temporal and spatial kinematic parameters*

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1. Introduction

Hammer throw is a complex discipline of the acyclic type, which seeks to throw the device as far as possible in accordance with the propositions and rules of discipline and competition. The technique is characterized by very fast rotations of the launcher and the device around the vertical axis in the sagittal plane of the circle, generating a large kinetic energy. Hammer throw affects the entire musculature of the thrower, especially the musculature of the arms, shoulder girdle, improves the agility and speed of the competitors, as well as the rhythmic movement. This athletic discipline originally developed in Celtic culture as the throwing of a wooden hammer, only to be modified to today's modern athletic discipline over many years of development. Initially, hammer throw was dominated by American and later Russian throwers. All of them have contributed in their own way to today's modern variant. However, both the American and Russian variants were characterized by thrower rotations, depending on the technical and physical readiness of the competitors [1,2]. Hammer throwers possess a high level of development and manifestation of motor abilities during motor movement, where the body composition of the thrower occupies an important place. In terms of constitution, they belong to the meso-endomorphic somatotype, with a significant dominance of muscle mass (53-56%), bone mass (18-22%) and fat (15-19%) [3,4], while in comparison to other throwing athletes, they have higher muscle mass, lower body height, which are positively correlated with the achieved results [5,6]. From the motor aspect, hammer throw is primarily initiated by explosive activation of agonist muscles. After that, automatically, there is a period of their relaxation, due to the action of the antagonist muscles and passive stretching of the connective tissue with the integrated participation of motor and functional abilities. Maximum speed of movement is achieved through turns around the vertical axis until the moment of ejection, which requires sharpened kinesthetic feeling, high degree of synchronization of motor abilities, above all, speed, coordination of movement, excellent spatial orientation during the turn [2]. Regarding the structure of the movement, it was believed that four turns were performed by shorter and technically trained (faster) throwers, and three turns by stronger throwers. Today, there are pitchers who perform three, four or even five turns (Lingua). During the turn, the hammer thrower not only rotates around the vertical axis, but also moves in the direction of the throw with increasing rotation speed, producing a strong centrifugal force that tries to knock down the thrower [7,8]. Consequently, depending on the weight of the thrower, his physical fitness and technical mastery, the thrower leans to the opposite side of the hammer. The greater the weight of the thrower, as well as their power, the lower the inclination. It is almost impossible to maintain a vertical position during rotations, but every thrower should strive for that, because if the axis of rotation is left in the same position, the hammer rotation lever increases and in the end the flight distance of the device increases [9]. Identical to the parameters in other throwing disciplines, the flight distance of the hammer is conditioned by the initial flight speed, angle of release and emission height [10,11] where ejection velocity proved to be the primary component [12,13]. According to some authors [14] increasing the release of velocity increases the distance of any projectile throw in athletics, while [15] believe that increasing the speed by 5% increases the result by 7 meters, and the change angle by 5% changes the length by only 60cm. From the biomechanical aspect, the goal of hammer throw is to gain the highest starting speed (through turns) in the shortest possible time within the support surface, despite the action of gravitational, centrifugal and Coriolis forces and other phenomena that affect the functional flow of the final speed of the device [16]. It has been determined that positive factors cause an increase in the speed of the hammer head, and among the factors is the size and direction of the force of the hammer wire, which affects the development of speed, i.e. to its losses due to the negative force of the hammer wire. For a thrower that reduces the strength of the negative tangential force, it is more effective to reduce the angle of release. Also, pitchers should reduce the size of the angle of separation of the chest and pelvis during the double period, more precisely during the second and third turns, which results in a smaller loss of speed during the next phase of the throw [17]. Studies conducted with throwers of different levels [18,19,20] proved that the angular displacement of the hammers of better throwers, in the phase of the two-support period tends to decrease, so that the tangential velocity of the center of gravity at the end of the throw is more associated with an increase in the angular velocity of the thrower. Relevant studies [21] have shown that lengthening the time of the double-support phase and shortening the time of the single-support support is a trend in the development of hammer throw in the future. Dapena & Mc Donald [22] using three-dimensional cinematography proved the interrelation of the trajectory of the vector of angular momentum, the inclination of the body and the height of the plane of the hammer in relation to the mass system of the thrower. They concluded that some pitchers hold the hammer grip high, leaning back in all turns, while other pitchers hold the hammer grip low, leaning forward, and therefore in later turns the hammer grip is raised while the hull is tilted back. Dapena, Gutiérrez-Dávila, Soto, & Rojas-Ruiz [23] analyse the resultant success of hammer throw, neutralizing the airflow resistance, assuming that the centre of mass of the hammer coincides with the centre of the ball. To calculate the kinematic parameters during the hammer throw, they use three-dimensional throwing data of male and female competitors using a simulation of a mathematical model in vacuum conditions. The results showed that half of the distance loss produced by the air resistance was due to the action of forces on the ball, and the rest due to the forces exerted on the wire and the hammer grip.

Brice, Ness, Rosemond, Lyons, & Davis [24] analysed the five best hammer shots and compared the produced force acting on the hammer head with the force measured using a stress apparatus. The obtained results confirmed basically the same qualitative time dependence of the two forces, while quantitatively the average difference between the measured and calculated forces during the throwing was 76N, which corresponds to a difference of 3.8% for the hammer wire force of 2000N. Also [25] analyse the relationship between force and linear velocity of a hammer wire during ejection by identifying the influence of the magnitude and direction of the force on the fluctuation of the hammer speed. The obtained results showed a strong correlation between the decrease in linear velocity and the hammer wire force, with a strong correlation between the angle at which the hammer force lags in the radius of rotation towards its maximum and the magnitude of the hammer velocity decrease. Panoutsakopoulos, Vujkov, & Obradović [26] determined the connection between the duration and distance of throwing with three and four turns on a sample of elite hammer throwers. The results showed a high and strong correlation between the throwing time of the device and the throwing distance for throwers with 3 and 4 turns. Most throwers spent a percentage of time in a single-support than in a double-support phase, so it was concluded that the throwing distance and the duration of the turn are inverse. Okamoto, Sakurai, & Ikegami [27] analyse the influence of initial ejection conditions on hammer throw distance. The results confirmed the insignificant effect of airflow resistance, compared to javelin throw and discus throw, which is attributed to the aerodynamics of the device. It follows that the hammer throw distance is determined by the initial ejection conditions (initial velocity, angle of release, ejection height), not by the aerodynamic characteristics of the hammer. A similar study was conducted by [28] on a sample of Japanese top hammer throwers. They analyse the relationship of kinematic parameters with the throwing distance, where the results confirmed positive correlations between the distance and the starting speed of the hammer head, and negative correlations between the throwing distance, throwing angle and throwing height. A study [2] on a sample of male and female finalists at the World Championships in Daegu in 2011 confirmed statistically significant differences between male and female finalists in the release of velocity ($p < 0.004$) and the fourth turn speed ($p < 0.002$). The male finalists achieved an average throwing speed of 27.91 m/s, and the female 27.17 m/s, with an average turning speed of 4.67 m/s (male) and 4.03 m/s (female) throwers. The differences were attributed to the length of the training experience, the different training process, the experience of the competitors, the morphological profile, the motor and anatomical structures, the technique and the biomechanics of movement.

According to the results of the research [12,13,14], the initial speed of the hammer has the greatest influence on the hammer throw distance. The hammer head acceleration mechanism differs from other throwing movements in athletics because the hammer head is far from the thrower's hand while the javelin, disc, or shot put it is the grip of the hand, and therefore there are different mechanisms for throwing success [10]. It is known that the speed of the hammer gradually increases during rotations within the circle, with a pronounced fluctuation of speed in each turn. In some throws gravity produces greater fluctuations while in some there is a pronounced fluctuation after the effects of gravity are taken away. Fluctuation is produced by pulling the hammer in the direction alternately in front of and behind the centre of the hammer trajectory and by alternately shortening and lengthening the distance between the hammer head and the centre of its trajectory [29]. According to Brice [30] the thrower accelerates the hammer until the moment of release, performing rotations across the circle, whereby the linear speed of the hammer fluctuates. According to a study by [31], hammer throw efficiency is correlated with the athlete's lean body mass and higher bone mineral density, where the percentage of type IIa fibers is over 66%. However, maximum strength, explosive strength, muscle thickness, and strength characteristics decline with age and in throwing masters who actively train strength and throw for decades [32]. Also in top athletes maximum strength, muscle mass as well as the explosive force of the upper and lower extremities are at significantly higher levels than those recorded in of men of the same age. Studies of [11,33] have shown significant differences between the kinematic parameters of hammer throwers, which is related to many years of experience, the scope of training in anthropometric parameters, release of velocity, external forces that are different between the genders [34]. The main goal of the research is to determine the connection and the influence of kinematic parameters on the result success of hammer throw of male and female World Championship finalists.

2. Method

2.1. Participants

The population defined in the research has included top athletes in the World Championship in Berlin 2009, Daegu 2011 and London, 2017. The sample included a total of 56 finalists (28 male, average result 77,60±1,84m and 28 female, average result 73,16±2,87m), who participated in the Hammer throw Final.

2.2. Research Design

All data of kinematic parameters are taken from the Scientific Research Project Biomechanical Analyses at the IAAF World Championships (Berlin, 2009; Daegu, 2011; London, 2017). Independent variables were identified for estimating of biomechanical parameters in Hammer throwers (Table 1).

1. Starting velocity (m/s)
2. Release of velocity (m/s)
3. Angle of release (°)
4. Increase of velocity (m/s):
    a) Turn 1 (m/s); b) Turn 2 (m/s); c) Turn 3 (m/s); d) Turn 4 (m/s)
5. Path of the hammer during turns (m):
    a) Turn 1 (m); b) Turn 2 (m); c) Turn 3 (m); d) Turn 4 (m)
6. Duration of turns (s):
    a) Turn 1 (s); b) Turn 2 (s); c) Turn 3 (s); d) Turn 4 (s)

Table 1. Kinematics parameters of male and female World Championship finalists - Berlin, Daegu, London [35,36,37]

Male and Female throwers in WCh Berlin, 2009		Starting velocity (m/s)	Increase of velocity (m/s)				Release of velocity (m/s)	Angle of release (°)	Path of the hammer during turns (m)				Duration of turns (s)			
			Turn 1	Turn 2	Turn 3	Turn 4			Turn 1	Turn 2	Turn 3	Turn 4	Turn 1	Turn 2	Turn 3	Turn 4
1	Kozmus	16,8	2,9	2,6	1,4	4,6	28,2	41,6	10,8	11,1	10,4	12,2	0,62	0,52	0,44	0,48
2	Ziolkowski	16,7	3,2	2,1	1,7	4,1	27,7	40,8	10,7	10,5	10,7	13,3	0,62	0,50	0,46	0,52
3	Zagornyi*	17,9	3,1	2,0	4,6	-	27,6	42,3	10,8	10,7	13,9	-	0,60	0,48	0,56	-
4	Pars	15,2	5,3	1,5	1,0	4,5	27,5	44,5	10,5	9,9	9,9	13,1	0,58	0,46	0,42	0,52
5	Litvinov	15,7	4,2	2,0	1,0	4,5	27,4	39,9	10,4	11,4	10,0	12,3	0,62	0,54	0,44	0,50
6	Esser	16,8	3,0	1,6	1,0	5,1	27,5	39,9	9,3	9,9	10,3	12,9	0,56	0,46	0,44	0,52
7	Haklitis	15,1	3,6	2,7	1,9	4,1	27,4	41,4	11,3	11,0	11,2	12,5	0,72	0,54	0,48	0,50
8	Kryvitski	15,3	3,3	2,5	1,6	4,6	27,3	40,2	10,2	10,4	10,9	12,4	0,64	0,52	0,48	0,50
1	Wlodarczyk	15,3	4,7	2,3	1,1	4,4	27,8	41,8	10,5	11,5	9,9	12,2	0,60	0,54	0,42	0,48
2	Heidler	18,6	2,5	1,6	0,9	4,4	27,9	39,1	10,4	9,5	10,2	11,8	0,54	0,42	0,42	0,46
3	Hrasnova*	15,2	4,7	2,8	4,8	-	27,5	37,6	9,7	11,3	12,6	-	0,60	0,52	0,52	-
4	Klass	16,9	3,0	2,2	0,9	4,1	27,1	42,3	9,8	10,3	9,3	12,1	0,56	0,48	0,40	0,48
5	Zhang	15,7	4,8	1,8	0,9	3,7	26,8	39,8	10,9	10,9	10,9	11,5	0,60	0,50	0,46	0,46
6	Lysenko	14,5	4,7	2,6	1,4	3,4	26,6	41,6	10,2	10,6	10,9	12,6	0,64	0,52	0,48	0,52
7	Cosby*	17,5	3,2	1,7	4,4	-	26,7	38,6	9,8	9,7	13,8	-	0,56	0,44	0,56	-
8	Clarett	16,4	3,3	2,7	0,8	3,6	26,7	39,5	10,0	10,3	9,5	13,3	0,58	0,48	0,40	0,52

Male and Female throwers in WCh Daegu, 2011		Starting velocity (m/s)	Increase of velocity (m/s)				Release of velocity (m/s)	Angle of release (°)	Path of the hammer during turns (m)				Duration of turns (s)			
			Turn 1	Turn 2	Turn 3	Turn 4			Turn 1	Turn 2	Turn 3	Turn 4	Turn 1	Turn 2	Turn 3	Turn 4
1	Murofushi	16,7	3,4	2,4	1,3	4,6	28,3	41,4	10,5	10,5	10,2	12,3	0,60	0,48	0,42	0,48
2	Pars	18,1	2,9	1,6	1,0	4,6	28,2	44,1	11,2	10,3	10,1	12,8	0,60	0,46	0,42	0,50
3	Kozmus	16,4	3,5	2,2	1,2	4,7	28,1	39,0	10,9	11,2	10,3	12,5	0,62	0,52	0,44	0,50
4	Esser	16,3	3,8	1,9	0,9	5,0	27,9	41,1	9,8	9,9	10,3	12,6	0,58	0,46	0,44	0,50
5	Kryvitski	16,1	3,5	2,3	1,4	4,7	27,9	39,1	10,2	10,4	10,3	12,2	0,60	0,50	0,44	0,48
6	Ikonnikov	15,9	3,7	2,4	1,2	4,6	27,7	44,1	10,5	10,5	10,8	12,3	0,64	0,50	0,46	0,50
7	Ziolkowski	16,4	3,3	2,3	1,3	4,5	27,8	38,9	10,4	11,5	10,6	12,5	0,60	0,54	0,46	0,50
8	Vizzoni*	17,6	2,6	2,3	5,0	-	27,4	43,9	10,8	10,7	12,0	-	0,62	0,50	0,50	-
1	Lysenko	16,4	4,5	2,3	0,8	3,8	27,8	43,1	11,1	10,6	10,6	12,1	0,64	0,48	0,44	0,48
2	Heidler	18,4	2,6	1,7	1,0	3,9	27,6	40,1	10,9	9,9	10,7	11,2	0,56	0,44	0,44	0,44
3	Zhang	17,9	3,1	1,9	1,1	3,4	27,4	42,6	10,8	11,4	10,9	11,8	0,58	0,50	0,44	0,46
4	Moreno	14,4	4,0	2,9	1,6	4,4	27,3	41,1	10,2	9,9	10,6	13,3	0,66	0,50	0,46	0,52
5	Wlodarczyk	15,5	3,7	2,6	1,3	4,4	27,4	36,6	10,3	11,1	11,0	12,0	0,62	0,54	0,48	0,48
6	Perie	16,2	2,9	2,4	0,9	4,4	26,8	40,3	10,4	10,7	9,4	12,0	0,62	0,52	0,42	0,50
7	Klaas	17,5	2,8	1,8	0,8	3,9	26,7	41,9	9,8	10,3	9,3	11,5	0,54	0,48	0,40	0,46
8	Marghieva	13,6	5,2	2,5	1,1	4,0	26,4	43,1	10,3	10,8	10,5	11,0	0,68	0,52	0,46	0,46
Male and Female throwers in WCh London, 2017		Starting velocity (m/s)	Increase of velocity (m/s)				Release of velocity (m/s)	Angle of release (°)	Path of the hammer during turns (m)				Duration of turns (s)			
			Turn 1	Turn 2	Turn 3	Turn 4			Turn 1	Turn 2	Turn 3	Turn 4	Turn 1	Turn 2	Turn 3	Turn 4
1	Fajdek	14,6	5,2	3,8	3,1	0,9	27,7	46,2	10,6	10,1	10,9	12,3	0,66	0,50	0,45	0,48
2	Pronkin	17,4	4,5	2,3	3,4	-	27,6	41,9	12,5	9,8	13,3	-	0,57	0,45	0,54	-
3	Nowicki	15,9	4,4	3,2	2,2	2,4	28,1	39,1	10,9	10,6	11,3	13,1	0,65	0,52	0,48	0,52
4	Bigot	16,7	4,7	2,1	1,5	2,5	27,6	39,7	9,76	10,6	11,3	13,1	0,54	0,48	0,42	0,50
5	Sokyrskii	14,7	6,3	3,7	1,8	0,9	27,4	40,9	10,9	11,4	10,8	8,3	0,64	0,52	0,44	0,44
6	Miller	16,7	4,5	2,5	1,8	1,8	27,4	42,1	11,2	10,4	10,4	11,2	0,61	0,48	0,44	0,46
7	Nazarov	15,6	5,7	2,2	1,5	1,9	27,1	43,0	10,3	10,7	10,6	13,3	0,60	0,51	0,46	0,54
8	Marghiev	15,3	5,0	2,5	1,3	2,9	27,1	42,3	9,7	10,0	10,4	11,7	0,57	0,48	0,45	0,48
9	Bareisha	15,1	5,1	3,7	2,0	1,3	27,2	44,7	11,3	10,0	10,5	12,8	0,66	0,47	0,43	0,51
10	Lingua	13,6	5,9	3,0	2,2	1,6	27,3	39,5	10,7	11,0	10,8	10,61	0,72	0,58	0,49	0,44
11	Halasz	15,2	5,1	3,5	1,7	2,0	27,5	36,7	11,6	10,2	10,7	13,5	0,71	0,51	0,48	0,55
12	Baltaci	14,3	4,9	3,0	2,6	2,1	26,9	39,3	10,6	9,6	9,5	12,5	0,68	0,50	0,44	0,52
1	Wlodarczyk	16,19	4,3	2,6	1,6	3,5	28,3	41,8	11,28	10,0	10,9	12,1	0,64	0,49	0,48	0,48
2	Wang	17,55	4,3	2,4	1,5	2,2	28,0	38,5	10,4	9,5	9,7	11,5	0,55	0,44	0,40	0,45
3	Kopon	15,66	5,5	2,9	2,4	1,3	27,8	39,7	9,5	9,8	10,0	11,8	0,56	0,46	0,42	0,46
4	Zhang	15,65	4,9	3,1	2,3	1,7	27,6	41,6	11,3	11,1	10,9	11,8	0,64	0,52	0,46	0,46
5	Skydan	15,16	5,0	3,0	1,3	3,8	27,8	36,9	11,3	11,5	10,4	14,2	0,68	0,57	0,48	0,60
6	Fiodorow	16,71	4,5	2,0	1,6	2,9	27,8	39,2	10,9	9,5	10,3	10,9	0,60	0,44	0,44	0,44
7	Hitchon	15,60	5,5	3,0	1,9	0,9	26,9	40,3	10,4	9,6	9,4	13,5	0,58	0,45	0,40	0,53
8	Šafrankova	15,56	5,8	2,6	1,5	1,3	26,8	44,4	11,9	10,7	11,5	11,7	0,66	0,50	0,50	0,48
9	Price	15,19	3,6	2,9	2,2	2,9	26,9	38,5	11,1	9,4	9,4	11,1	0,67	0,48	0,42	0,46
10	Malyshik	15,29	5,5	3,0	1,6	1,3	26,7	42,9	9,7	11,0	10,1	12,9	0,57	0,53	0,44	0,52
11	Klaas	16,69	4,8	3,0	1,2	0,6	26,3	42,8	10,5	9,9	10,9	10,6	0,57	0,45	0,44	0,42
12	Tavernier	16,99	4,3	2,3	1,9	0,5	26,0	41,2	10,7	10,7	11,1	11,0	0,58	0,50	0,48	0,46

2.3 Statistical Analysis

The data obtained in the study were given as central and dispersions parameters. To assess the influence of kinematic parameters on the results success of hammer throwing, a multiple regression function was applied and the relevant regression parameters were calculated. Statistical analysis was done using the statistical program Statistica 10.0.

3. Result

Inspection of the results of central and descriptive statistics (Table 2) shows the normality of the distribution of results with a slight heterogeneity in both subsamples. This was especially manifested in the time parameters (speed of all turns), which was expected, considering the different morphological characteristics and motor abilities of the finalists. The average starting speed of the finalists is almost uniform, with a slightly higher speed of the female finalists (16.15m/s) compared to the male finalists (16.00m/s). Also, almost identical results of kinematic parameters are evident in the speed and duration of all turns, the spatial trajectory of the hammer, as well as the value of the angle of release, 41.34° (male) 40.60° (female), release of velocity 27.60 m/s (male) and 27.19m/s (female) finalists (Table 2). The average release of velocity of the device is slightly higher with male throwers (by 0.41s), and the angle of release (by 0.26°). The range between the minimum and maximum results of kinematic parameters records various oscillations that define the time and space parameters of the participants of the World Championships, from the smallest (duration of rotation speed 0.11-0.18s) to the highest (changes in starting speed, angle of release, travelled distance of the hammer).

Pearson's male sample correlation matrix recorded 6 significant correlations with the result (Table 3). High positive correlations with the throwing result were recorded by the parameters: starting speed (r=0.64 $^{p=0.001}$), first turn speed (r=0.47 $^{p=0.017}$), release of velocity (r=0.86 $^{p=0.000}$), angle of release (r=0.37 $^{p=0.049}$). The negative correlation was shown by the variables of the duration of the first turn (r=-0.40 $^{p=0.046}$) and the duration of the third turn (r=-0.46 $^{p=0.020}$).

Table 2. Descriptive statistics male and female finalists

Kinematic Parameters		Gender	N	Mean±SD	Min	Max	Range	CV%	Skew	Kurt
Starting velocity (m/s)		Male	28	16,00±1,10	13,60	18,10	4,50	6,87	-0,05	-0,34
		Female	28	16,15±1,22	13,60	18,60	5,00	7,54	0,20	-0,30
Increase velocity (m/s)	Turn 1	Male	28	4,16±1,03	2,60	6,30	3,70	24,69	0,36	-0,97
		Female	28	4,20±0,97	2,50	5,80	3,30	23,19	-0,26	-1,09
	Turn 2	Male	28	2,50±0,63	1,50	3,80	2,30	25,30	0,67	-0,15
		Female	28	2,45±0,47	1,60	3,10	1,50	19,00	-0,40	-1,06
	Turn 3	Male	28	1,88±1,03	0,90	5,00	4,10	54,76	1,87	3,33
		Female	28	1,60±0,96	0,80	4,80	4,00	60,31	2,32	5,69
	Turn 4	Male	25	3,38±1,46	0,90	5,10	4,20	43,26	-0,45	-1,52
		Female	26	3,03±1,32	0,50	4,40	3,90	43,70	-0,76	-0,93
Release of velocity (m/s)		Male	28	27,60±0,36	26,90	28,30	1,40	1,31	0,28	-0,49
		Female	28	27,19±0,59	26,00	28,30	2,30	2,19	-0,05	-0,99
Angle of release (°)		Male	28	41,34±2,21	36,70	46,20	9,50	5,34	0,27	-0,28
		Female	28	40,60±2,02	36,60	44,40	7,80	4,97	-0,23	-0,68
Path of hammer (m)	Turn 1	Male	28	10,66±0,64	9,30	12,50	3,20	5,99	0,47	1,77
		Female	28	10,50±0,59	9,50	11,90	2,40	5,64	0,30	-0,37
	Turn 2	Male	28	10,51±0,52	9,60	11,50	1,90	4,95	0,28	-0,70
		Female	28	10,41±0,67	9,40	11,50	2,10	6,45	0,06	-1,27
	Turn 3	Male	28	10,80±0,94	9,50	13,90	4,40	8,66	2,08	4,98
		Female	28	10,53±1,00	9,30	13,80	4,50	9,50	1,42	3,40
	Turn 4	Male	25	12,33±1,06	8,30	13,50	5,20	8,58	-2,56	8,51
		Female	26	11,98±0,88	10,60	14,20	3,60	7,34	0,81	0,39
Duration of turns (m/s)	Turn 1	Male	28	0,62±0,05	0,54	0,72	0,18	7,41	0,62	0,10
		Female	28	0,60±0,04	0,54	0,68	0,14	7,24	0,35	-1,11
	Turn 2	Male	28	0,50±0,03	0,45	0,58	0,13	6,12	0,49	0,28
		Female	28	0,49±0,04	0,42	0,57	0,15	7,61	0,00	-0,60
	Turn 3	Male	28	0,46±0,03	0,42	0,56	0,14	7,46	1,48	2,40
		Female	28	0,45±0,04	0,40	0,56	0,16	8,79	0,88	0,92
	Turn 4	Male	25	0,50±0,03	0,44	0,55	0,11	5,33	-0,45	0,55
		Female	26	0,48±0,04	0,42	0,60	0,18	7,80	1,38	2,94

Table 3. Regression Summary for Dependent Variable: Result Hammer throw (male)

		b*	Std.Err. of b*	Partial Cor.	b	Std.Err. of b	t (9)	p-value	Pearson correlation p<0,05
Intercept					-58,8	20,21	-2,91	0,02	
Starting velocity (m/s)		0,82	1,01	0,26	1,6	1,97	0,82	0,44	0,64, $^{p=0,001}$
Increase velocity (m/s)	Turn 1 (m/s)	0,68	1,07	0,21	1,3	2,05	0,64	0,54	0,47, $^{p=0,017}$
	Turn 2 (m/s)	0,22	0,50	0,15	0,6	1,47	0,44	0,67	-0,27
	Turn 3 (m/s)	0,48	0,48	0,32	1,7	1,72	1,01	0,34	-0,25
	Turn 4 (m/s)	0,73	1,20	0,20	1,0	1,59	0,61	0,56	0.38
Release velocity (m/s)		0,65	0,34	0,53	3,3	1,74	3,60	0,01*	0,86, $^{p=0,000}$
Angle of release (°)		0,42	0,12	0,77	0,4	0,10	1,89	0,04 *	0,37, $^{p=0,049}$
Path of hammer (m)	Turn 1 (m)	-0,18	0,26	-0,23	-0,6	0,89	-0,71	0,50	0,01
	Turn 2 (m)	0,02	0,54	0,01	0,1	1,97	0,03	0,98	0,16
	Turn 3 (m)	-0,08	0,19	-0,14	-0,4	0,86	-0,42	0,68	-0,03
	Turn 4 (m)	-0,14	0,34	-0,14	-0,3	0,63	-0,42	0,69	0,04
Duration of turns (m/s)	Turn 1 (m/s)	0,03	0,40	0,03	1,4	16,54	0,08	0,94	-0,40, $^{p=0,046}$
	Turn 2 (m/s)	0,18	0,70	0,08	11,4	44,64	0,25	0,80	-0,28
	Turn 3 (m/s)	-0,05	0,30	-0,05	-4,3	27,59	-0,15	0,88	-0,46, $^{p=0,020}$
	Turn 4 (m/s)	0,02	0,34	0,02	1,6	24,51	0,06	0,95	-0,22

Analysis of Variance	Sums of - Squares	df	Mean - Squares	F	p-value
Regress.	86,06	15	5,737	12,65	0,000
Residual	4,08	9	0,453		
Total	90,14				

R= 0,977. R^2= 0,954, Adjusted R^2= 0,881, F(15,9)=12,653, p< 0,00029.

Table 3 presents the basic parameters of the multiple regression function for male hammer throwers. The resultant success of hammer throw in the finals of the world championships indicates a statistically strong correlation between the entire system of kinematic parameters and the achieved results of the thrower, with a significantly high multiple correlation coefficient (R=0.977) and a high coefficient of determination (R^2=0.954). High projections of regression coefficients indicate that the common variability between the predictor system and the criterion variable is explained by kinematic parameters with 95%, while the remaining 5% is due to other factors not covered by this study, primarily motor, specifically motor and technical qualities of throwers etc. The analysis of the values of regression coefficients (b*) in the system of predictor variables defines a high contribution to the result performance of time parameters (starting speed and release of velocity) as well as space (angle of release). However, although in the first place, with high projections, the starting speed (integrated through 4 turns) did not have a statistically significant impact on the results of hammer throw (b*=0.82; p=0.44). In contrast to the starting velocity, the ejection velocity with a coefficient (b*=0.65) proved to be a good predictor of a system with statistically significant influence (p=0.01) and individual contribution to the function, t=3,60 (Figure 1). Also, the throwing angle (b*=0.42; p=0.04) significantly influenced the throwing results, where a significant individual contribution was recorded in the explanation of the throwing results (t=1,89). Given that all parameters had a direct impact on the results of hammer throw, it can be concluded that the regression model is a direct impact. Based on the analysis of variance F (15,9)=12,653, it is evident that the regression model proved to be good, so that the regression variability is statistically significantly higher than the residual variability at both levels, which guarantees statistical significance of the regression relationship (p<0.00029). This confirmed the information provided by a slightly lower corrected coefficient of determination (Adjusted=0.88). In general, the defined kinematic parameters (starting speed, release of velocity, angle of release) were identified as good predictors of the success of male finalists, where release of velocity and angle of release also achieved a statistically significant correlation (p<0.05).

In the correlation matrix of the female sample, 3 significant correlations were recorded with the result performance of hammer throw (Table 4). High positive correlations were recorded by the parameters: fourth turn speed (r=0.50 p=0.001), release of velocity (r=0.90 p=0.000) and angle of release (r=-0.62 p=0.002). The presented parameters of the multiple regression function of female throwers clearly indicate a statistically strong correlation of the entire defined system of kinematic parameters with the hammer throw distance (Table 4). The regression function was defined by a strong multiple correlation (R=0.983) and a high coefficient of determination (R^2=0.968). High projections of regression coefficients indicate that the common variability was explained by 98% of the predictions, while the remaining

2% was conditioned by other factors not covered by this study. The analysis of the values of regression coefficients (b*) in the system of predictor variables defined high predictions of the results by the parameters of time (starting speed, release of velocity) and space (angle of release). It can be concluded that the situation is identical to that of the male finalists, but with different numerical projections of the regression coefficients (b*). In female throwers, in the first place, with high negative projections on the throwing distance, the starting speed was extracted (b*=- 0.90; p=0.51). It turns out that the initial speed of the blow followed through the turns did not affect the length of the hammer throw. In contrast to the starting velocity, the ejection velocity with a coefficient (b*=1.04) proved to be an extremely strong leading predictor of the system (p=0.02) and an individual contribution to the function, t=1.61. (Figure 2). The throwing angle (b*=0.24; p=0.10) did not significantly affect the throwing distance with a significant individual contribution in explaining the throwing results (t=2.19). Based on the analysis of variance F (15,10)=20,176, it can be concluded that the regression model is good, where the regression variability is statistically significantly higher than the residual variability at both levels, which guarantees statistical significance of the regression function (p<0.00002). This confirmed the information provided by the corrected coefficient of determination (Adjusted=0.92) on the significant influence of kinematic parameters on the results of hammer throw. Compared to the male finalists, the starting speed of the female finalists of the negative sign proved to be an unfavourable parameter in the hammer throw. In contrast to the starting speed, the release of velocity of the device had a direct statistically significant effect on the results of hammer throw (p<0.05).

Table 4. Regression Summary for Dependent Variable: Result Hammer throw (Female)

		b*	Std.Err. of b*	Partial Cor.	b	Std.Err. of b	t (10)	p-value	Pearson correlation p<0,05
Intercept					-33,6	16,16	-2,08	0,06	
Starting velocity (m/s)		-0,90	1,33	-0,21	-2,2	3,19	-0,68	0,51	0,28
Increase velocity (m/s)	**Turn 1 (m/s)**	-0,52	1,06	-0,15	-1,5	3,14	-0,49	0,63	-0,25
	Turn 2 (m/s)	0,03	0,48	0,02	0,2	3,12	0,07	0,95	-0,29
	Turn 3 (m/s)	-0,07	0,55	-0,04	-0,4	3,40	-0,13	0,90	-0,18
	Turn 4 (m/s)	0,07	1,40	0,01	0,1	3,11	0,05	0,96	0,50, $^{p=0,009}$
Release velocity (m/s)		1,04	0,64	0,45	5,0	3,11	1,61	0,02 *	0,90, $^{P=0,000}$
Angle of release (°)		0,24	0,11	0,57	0,4	0,17	1,19	0,10	-0,62 $^{P=0,002}$
Path of hammer (m)	**Turn 1 (m)**	0,31	0,21	0,41	1,6	1,09	1,44	0,18	0,12
	Turn 2 (m)	0,26	0,45	0,18	1,2	2,01	0,58	0,57	-0,06
	Turn 3 (m)	0,27	0,50	0,17	1,2	2,23	0,55	0,60	-0,05
	Turn 4 (m)	-0,09	0,57	-0,05	-0,3	1,92	-0,16	0,88	0,18
Duration of turns (m/s)	**Turn 1 (m/s)**	-0,58	0,42	-0,40	-38,5	28,02	-1,37	0,20	-0,09
	Turn 2 (m/s)	-0,39	0,58	-0,21	-31,3	46,50	-0,67	0,52	-0,17
	Turn 3 (m/s)	-0,26	0,55	-0,15	-25,5	53,13	-0,48	0,64	-0,18
	Turn 4 (m/s)	0,23	0,66	0,11	18,0	52,16	0,35	0,74	-0,03

Analysis of Variance	**Sums of - Squares**	**df**	**Mean - Squares**	**F**	**p-value**
Regress.	208,97	15	13,931	20,176	0,0000
Residual	6,90	10	0,690		
Total	215,87				

R= 0,983, R^2= 0,968, Adjusted R^2=0,920, F(15,10)=20,176, p<0,00002.

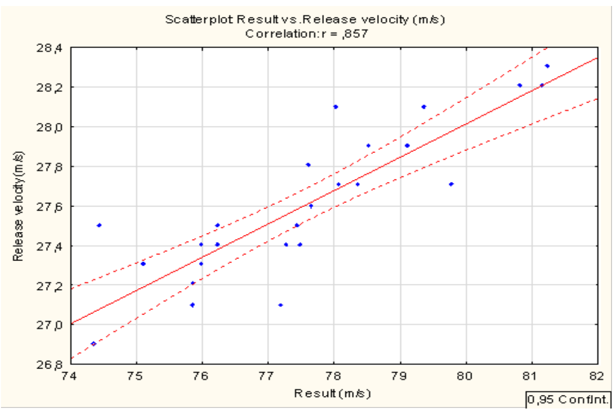

Figure 1. Release velocity and result of male finalist

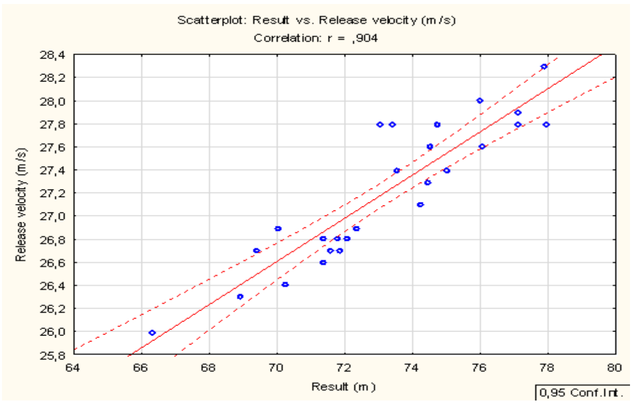

Figure 2. Release velocity and result of female finalist

4. Discussion

Hammer throw is one of the most common competitions in outdoor athletics and, compared to other disciplines, it has the longest world record (86.74m), achieved by Juriy Sedykh (USSR, 1986). There is no doubt that hammer throw is defined by complex human motor skills that include rapidly rotating the body around a vertical axis in the sagittal plane, dynamic balancing and creating explosive energy in order to project the hammer head as far as possible, and the main factor contributing to success is hammer speed at the moment of ejection [30]. Throwers show the initial force on the device, by performing initial swings and collecting speed to enter the first turn. The rotary technique is most often used by throwers in four turns, although there are throwers with three turns (Sedykh, Litvinov, Vizzoni, Zagornyi, Pronkin, Hrasnova, Cosby) or with five turns (Lingua). Each rotation, regardless of their number, is characterized by a single-support and double-support phase of attitude. In general, the competitors try to enable the generation of kinetic energy from the very beginning of the swing, with the help of their own physical abilities, technical and biomechanical characteristics. In coordination, hammer throw is the most complex competition in throwing disciplines that integrates the influence of several different forces on the throwing distance, technical performance which depends on many years of experience of competitors and training process of the athlete [3,33].

The main goal of this research was to determine the influence and connection of kinematic parameters with the hammer throw distance, male and female finalists of world championships. The obtained results confirmed the significant influence of the defined kinematic parameters on the results of throwing with a high coefficient of determination over 95% participation. The connectivity of the system is extremely strong, which was confirmed by the coefficients of multiple correlations (Table 3 and Table 4). In both subsamples of the finalists, the starting speed, the speed of the first turn, the speed of the ejection, the angle of release achieved significant correlations with the length of the hammer throw. The results obtained in this study partially confirm the results of previous studies on the influence of starting speed and accompanying turns on the throwing distance [10,12,13,14,27]. The throwing angle proved to be an extremely strong and statistically significant predictor in male throwers, while it was not significant in female throwers, which was confirmed in the study by [28]. Similar to other throwing disciplines, the technique of movement depends on the progression of the maximum speed of the hammer through turns to the moment of ejection of the device [38,39], the angle of release [15], which is partially confirmed by the results of this research. It is evident that the number of turns primarily depends on the training of the thrower, his anatomical and physiological structures, motor abilities [31]. Each movement of the thrower is characterized by the initial swinging of the device, creating conditions for entering the first turn, whereby the thrower achieves the necessary rhythm and good concentration of attention, which is extremely important for further stages of the technique. During the swinging of the device, the initial speed of rotation (12-16 m/s) is announced, where the common centre of gravity of the system (thrower-hammer) is within the limits of the support surface [1,8]. The results of the current research are in line with the above, where the average starting speed of the finalists ranges from 16.00m/s (men) to 16.15m/s (women), with a maximum speed over 18m/s. The male hammer is more massive than the female hammer, resulting in a different overcoming of the force of inertia and centrifugal force. Women are more upright during the throw due to their lower body weight and lighter device, so they need less effort than men when confronting forces of inertia and centrifugal force [40,41]. Due to lower body weight, lower ball weight, centre of mass of rotation, differences in weight and mass distribution during turns and throws, female pitchers have a higher starting speed [12,25,42], which was also confirmed by the results of this study (Table 1). In the phase of overtaking the device, a high speed of rotation is achieved, when the thrower and the hammer form an integrated system in rotational motion [26,34]. Next, the competitor rotates around his vertical axis, from the back to the front of the circle at maximum speed, in order to achieve maximum speed and act on the device in the ejection phase [13].

During the rotation of the thrower, the speed of the hammer increases and at the moment of ejection it reaches a speed close to 28 m/s [34], which is slightly higher than the speed recorded in this research. The male finalists threw the hammer with an average throwing speed of 27.60 m/s, and the female finalists with a speed of 27.19 m/s, while the maximum throwing speed was 28.30 m/s. The results of the research confirm that the release of velocity, if communicated to the hammer at the appropriate angle, is almost always a decisive factor in the final result [1,7,34], which was also shown by the results of this research. According to some authors [15], the ideal throwing angle is 40°, and it depends on the height of the athlete and ranges from 42 to 44° [8,9,43], which is in contradictions with the results of this research. The average angle of release of male finalists is 41.34°, female 40.60° with individual higher or lower values of competitors, which is in line with the statements of [15]. It is important to point out that, if the coordination of the thrower's turn is of better quality, the speed of each subsequent turn increases in the presence of fluctuations in the speed and strength of the centrifugal force, which has a negative effect on the competitor's balance. The action of the centrifugal force is countered by the thrower tilting the body backwards with compensatory movements and flexion of the caudal extremities, lowering the centre of gravity of the body [1,7,8,9]. In order for the swing to be performed in as large a circle as possible, which allows the device to travel a longer distance (about 12m), generating a higher speed, the thrower makes twists with synchronous soft movements of the joints of the spine and hips. When the hammer moves away from the body, the thrower moves the pelvic part of the body to the opposite side of the, device accelerates it and performs another pre-swing, which creates the preconditions for starting the second or third swing [1,7,11].

Hammer throw is characterized by a complex spatial and temporal structure, with the aim of achieving maximum speed of movement through periods of swinging and transition to rotational movement, moving linearly through the centre of the throwing circle. This further complicates changes in the spatial orientation of the plane by defining the path of movement of the hammer in each turn [20]. The prevailing opinion is that the acceleration of the hammer is achieved in the phase of double-support contact (traction force of the hammer directed down and forward, builds the stability of the thrower, achieves a higher speed), and not single-support (traction force of the hammer is very strong and the thrower opposes from the position of the hammer). Both phases are of very short duration that decrease as one goes from the first to the fourth turn, which is confirmed by the results of this study, where the average turn duration of male finalists (0.62 to 0.50s) and female (0.60-0.48s). The duration of the turn has a negative correlation with the distance in all finalists, which is in line with the research of [26], especially in the first and third turns in men. Also, during the turns, the distance between the feet decreases and the speed increases, from the initial 16 m/s to close to 28 m/s at the moment of ejection, which is confirmed by the results of this research (Table 2).

The results of studies by [22,24,41,43] believe that the hammer can be accelerated in the single support period by transmitting the angular momentum, which is contrary to the results [44,45,46], and that the speed of the hammer head is the most important factor contributing to the throwing distance. Structurally, during hammer throw, the thrower rotates with the hammer three, four or five times alternately between the double-support and single-support, with the left foot always in contact with the ground and the right foot spending a good portion of the time deviating from the ground. The actual turning time depends on the thrower's technique, as well as the order of a particular turn. The forces with which the feet press the ground allow the thrower to successfully transfer the optimal amount of kinetic force to the hammer. Therefore, some right-foot throwers perform a "kicking" action, as that foot comes in contact with the ground to complete the turn, while others bring the foot into contact with the ground in a "softer" or neutral manner during the foot action phase. Precisely because of such movements in the sample of finalists there is a fluctuation of speed through turns (Table 2), where female finalists have a slightly higher average speed in the first turn (Turn 1=4.20m/s) than men (Turn 1=4.16). The second, third and fourth turns are dominated by male finalists (Turn 2 =2.50m/s; Turn 3=1.88; Turn 4=3.38m/s). From a technical point of view, it is important that when entering the first turn, the shoulders and hips are parallel. With the exit from the turn and the transition to the single-support phase, the hips move faster, they overtake the device, in order to achieve another double-support period as quickly as possible. At the moment of the double-support phase, the first turn ends, generating a large torque [22], when the thrower achieves the best anatomical-biomechanical parameters for the most efficient and favourable entry into the turn with synchronized concentric-eccentric muscle contractions. Therefore, the hammer must enter the second turn at a higher speed than the entry into the first, and the entry and exit in the next three turns is performed according to the same principle. This theory was confirmed in our study where from a starting speed of about 16m/s, the release of velocity increased by 11m/s, successively at a slightly lower speed than in the first turn (Table 1), which is consistent with the study [2,13].

The movement of the hammer is performed with two to three blows, which are then followed by turns with which the thrower rotates synchronously, and the speed of the hammer constantly increases until the moment of ejection [38]. During the technical execution, the circular movement of the hammer around the thrower, the gradual change of the inclination of the plane of movement of the hammer and the horizontal trajectory of the thrower-hammer system within the circle are observed. In the initial part of the throw, the hammer is in a horizontal trajectory of 37° [9] but it becomes steeper as the speed increases and reaches an inclination of about 40° during the last turn. The thrower keeps the hammer in its circular path and the centrifugal force, during the last turn, is transmitted through the wire to the centre of the ball. In the turn of the wire, it acts equally and opposite to the force of the thrower's hand, which tends to pull it forward [1,22,24]. The turn duration of the hammer thrower ranges from 1.64sec. (with 3 turns) up to 2.16 sec. (with 4 turns). The average turn duration of the male finalists of this study was 2.06sec, and the female 2.02sec had a negative effect on the hammer throw distance. When throwing hammers, the action on a longer path is not a guarantee of a good result, but it is necessary to report the maximum force in the shortest time interval [26], which is in line with the results of this study where the average hammer path of the male finalists was 44,27m, women's 43.42m proved to be an irrelevant predictor of hammer throw distance. According to [34,47] each gender has morphological characteristics that contribute to success, due to the different genders of competitors, which probably affects the optimal technique, which is the case with the results of this research.

Simply put, hammer throw, should be understood as a system of spatial, temporal, dynamic, energy factors, which are closely correlated, resulting in greater motor efficiency, where each throw contains different technical elements within the basic mechanism [48].

5. Conclusion

The study included a sample of 56 male and female finalists of the World Athletics Championships Berlin (n=16), Daegu (n=16), London (n=24) with the aim of determining the relationship and impact of kinematic parameters on performance.

The results of the research of the male finalists confirmed the direct connection between the starting speed ($r=0.64^{\,p=0.001}$), the release of velocity ($r=0.86^{\,p=0.000}$), the first turn speed ($r=0.47^{\,p=0.017}$), and the angle of release ($r=0.37^{\,p=0.049}$), and the inverse effect of the duration of the first ($r=-0.40^{\,p=0.046}$) and third turn ($-0.46^{\,p=0.020}$). The kinematic parameters of the female finalists, the release of velocity ($r=0.90^{\,p=0.000}$), the angle of release ($r=-0.62^{\,p=0.000}$) and the fourth turn speed ($r=0.50^{\,p=0.002}$) acieved a direct relationship. The regression function of the male sample confirmed the influence of the starting speed, release of velocity and angle of release, where the release of velocity ($p=0.01^{\,p<0.05}$) and the angle of release ($p=0.04^{\,p<0.05}$) also achieved a statistical significance. The regression function for the female sample confirmed a high inverse effect of the starting speed but without statistical significance, while the direct influence was recorded at the ejection rate (p=0.02 $^{p<0.05}$) at the given level of statistical significance of the regression function.

Conflict of interest

The authors declare no conflict of interest.

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