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Successful Pole Vault Influenced by Certain Kinematical Parameters

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A B S T R A C T

The objective of the research was to determine the pole vault kinematics parameters at Croatian vaulter in junior category, and to determine the relationship between kinematics parameters and maximum accomplished vault's altitude. Further on, the goal was to gain an insight in stability and technique quality in vaulting. To that purpose, kinematics parameters of the vaults were registered (totally 13 out of 24 vaults performed on three separate trainings). The style and conditions of vaults were the same (the same pole, grip height and approach length was used). Received results of the analysis of kinematics parameters emphasised certain constancy of vault performing, therefore higher discrepancy in values of kinematics parameters between vaults was not detected. The exceptions were two vaults where difference was more than obvious. The accomplished values of kinematics parameters in this research were different and lower than those done by the world's best junior vaulters. Further on, the best competitive results lagged behind the best young vaulters. According to these facts, it was clear that examinee vaulter lagged behind in the development of basic and specific motoric as well as in level of adopted technique. Results of regression analysis showed that only one parameter (MPB-maximum pole bending) positively influenced on variable (MABA-maximum accomplished body altitude). The speed of second to last and last step (SSLS and SLS) had relatively high regression coefficients, but those coefficients weren't statistically important. The research gives entire new approach toward entire kinematics description of vault techniques which determines: stability of technique realisation i.e. its adaptation by multiplying the vaults of one vaulter, comparison with the technique of the most qualitative world's vaulters, and quality assurance of the technique of the same vaulter in time function connected to development of basic and specific motoric abilities.

Key words: *pole vault, kinematic analysis*

Introduction

Pole vault is one of the most attractive athletic disciplines, where part of the equipment is used to move a vaulter from one place to another, instead of moving or throwing certain equipment (disc, hammer, spear and bowl). The increase of popularity is entitled to better media cover of athletics competition, especially pole vault on Olympic Games or European or World championships. It can be given to a fact that world record has been broken several times in last decade. Pole vault has always paid attention but especially since 1961 when World Athletic Federation introduced the use of flexible pole. Ever since then, the men's world record has increased up to 6,15m. Pole vault is technically demanding motoric activity, and there has been much practical and theoretical information about it gathered by both trainers and bio mechanists. Search of the factors that determine and influence the successful pole vault has been an object of many researches in biomechanics. These kinds of researches belong to following categories: 1) mathematic model and computer simulation and 2) kinematics and/or kinetic analysis of observed vaulters.

The application of the kinematics' metrical systems is common method of establishing the training condition as well as vaulter's technique. It is possible to get detailed insight into the moving structure by taking results of different kinematics parameters.

The most spread and acceptable theoretical model for pole vault technique is Hay model, presented in his book The Biomechanics of Sports Techniques (1993)[1] where four key pole vault phases have been identified:

1. The approach or run-up;

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2. The takeoff – where the athlete plants the pole and leaves contact with the ground;
3. The swing phase (pole support phase);
4. The free flight phase (realising the pole and clearing the bar).

The grip on the pole, during the approach, is one of the most important details in vaulter's modern technique (Petrov 2004)[2]. The ideal grip (width) varies from vaulter to vaulter and depends on multifactor (vaulter's height, arms' length, strength and flexibility of the shoulder and hand wrist). It is considered that the width should be 60–70cm. The vaulter is demand to develop the maximum approach speed and to prepare to put the pole into the box with minimum speed loss.

It should be mentioned that sprinting speed is higher without the pole. Gros and Kunkel[3–5] claimed that the maximum horizontal speed with pole is approximately lower up to 0.8–1.2m/s. The acceleration as an element of the pole vault has its own parts, which determine vaulter's activity during the approach. Any source of disruption or change violates the speed and acceleration efficiency. Analyses show that average approach of today's top vaulters is from 42m–46m, and average number of steps is 18–20.

Sliding the pole into the box (the plant)

The key moment of every jumping technique for vaulters is position of sliding the pole into the box (the plant position). This part is characterized by increasing stride frequency while maintaining the same stride length. The second to last step is longer than last one for 10–20cm. The vaulter begins to leave the pole 5–6 steps before sliding the pole into the box, without the alteration of speed or body position. During the next two steps the vaulter is focused on pushing his hips forward without loosing the upper torso control and keeping its main role in the approach. The act of leaving the pole must not be abruptly and intermittent. During the last three steps, the vaulter must keep his abdomen tight, which will help him move his torso to the back even before leaving the pole. The most important moment is when the vaulter raise the pole up above his head, before he reach the vertical position with his left leg. The most dangerous moment during the plant is untimely reaching the box during transition from left to right leg. Continued acceleration during the last four steps is indicator of demanding skill in this part of pole vault. The example: Sergey Bubka (according to Petrov 2004)[2] developed takeoff speed: four steps before takeoff (9.5m/s), two steps before takeoff (9.7 m/s), takeoff moment (9.9 m/s). There are insufficient data that support the free takeoff concept presented by Petrov in 1985, where he emphasise that takeoff starts before the pole peak reaches the end of the box. Generally, it has been accepted that the sliding the pole in the box happens at the same time as takeoff. The time between the pole slides into the box and takeoff, or the pole support phase, is between 0.08 and 0.12 seconds (Gros and Kunkel, 1990)[5]. Takeoff speed and depth influence on following elements, moreover, it determines their rhythm: the hang, swing and rock-back. The foot distance of the takeoff leg from the end of the box is 4.20m–4.40m. Higher vaulters are usually at the distance of 4.10–4.20m while lower at 4.20–4.40m. There is a mutual agreement of trainers and research that the upper fist should be vertically placed above the front part of the foot of the takeoff leg at the takeoff position (Yagodin and Papanov 1987). If the vaulter is too much in or out, there will be great loss of horizontal speed and upper fist is going to block or prevent the vaulter from generating the vertical speed. The parameters, such as, the distance from takeoff place to the back of the box, torso elevation, support time and horizontal distance between top hand and front part of takeoff leg can help in identification of vaulter's body position during the plant and takeoff. Finally, vaulter must keep as long as possible rigid musculature in order to ensure efficient energy transfer, from body to pole. McGinnis[6,7] considers that top vaulters have straighter torso during the plant and takeoff than those in lower range.

The swing phase is the time from the takeoff moment to the moment when vaulter leaves the pole and begins the free-fall and turns over the cross bar. Many authors consider this phase as »pole support phase« or combination of three components: swing, rock-back and pole extension. The goal of this phase is to efficiently translate the kinetic energy accumulated from the approach into potential energy. It is possible to execute this by keeping the pole speed to the point where it cause the pole rotation or to vertical or »stand up« position. In order to minimalize the energy loss at the pole bending, the top vaulters create the pole rotation axis (TORQUE) by keeping the lower arm rigid and ensuring the pole resistance with their lower hand (McGinnis 1997[8] according to Osima 2001[9]). Further on, the pole bend on its maximum starts to rotate up to vertical position, the pole recoils, and returns stored energy to the vaulter.

Free flight and clearance height

After the recoil and cross bar turn, the body movement is in the function of speed and height of the mass centre body combined with the vaulter's body position. In this phase, the angle momentum and horizontal speed are constant and the only way vaulter can influence the result of cross bar turn is by bringing the body in the most optimal position. The vaulter needs to keep the prose of the body moving and by bending the knee increase the rotation axis speed. If previous moves were correct, the vaulter will be pressed up and cross bar turn will be effective. Every top vaulter has a good bar position feeling that keeps him overcome it in the most optimal body moving.

Methods

Only one examinee (Croatian's best 17 years old vaulter in junior pole vaulting discipline) was tested in this research. In period of ten days, the examinee made 24 pole vaults in total (3×8 pole vaults per training). The distance between first and second and second and the last training was five days which was enough time for body to recovers and rests. The pole vault was delivered in a way that bar was set 10cm lower than his best score which at the end of training was 4.70cm. Only in two attempts the vaulter failed. The characteristics of pole used by every attempt: Length 15 feet, and weight 155 pounds (flex 18.5). The same length of the approach and the same height of the grip were used constantly (top hand- right at 410cm). The vaulter weighted 72 kilos and his height was 181cm. all three trainings occurred in the ideal, almost identical weather conditions. The pole vaults occurred at the same time (afternoon) with light breeze. Ten days before the taping session, the coach and vaulter were contacted with the aim of explaining them the purpose of the project and receiving their consent on participating in the project. Prior to the video taping the vaulter were given the instructions, and the aims of the research as well as what was expected of him.

Parameters taken for analysis: L2PSRU – Length of the penultimate stride in the run-up (cm), SL2PSRU – Speed of the penultimate stride in the run-up, L1LSRU – Length of the last stride during the run-up (cm), SL1SRU – Speed of the last stride during the run-up, HDLFTB – Horizontal distance between left toes to back of box at plant (m), PAP – Pole angle at Plant (degrees), DBTHLT – Distance between top hand and left toe at takeoff (m), TMDCMB – Time to minimal distance between CM and vault box (m), MPB% – Maximum pole bend (%), TMPB – Time to maximum pole bend, TPS – Time to pole straightening (sec), TMHCM – Time to maximum height CM, PR – Pole release, MHCM – Maximum height of CM.

Three cameras were used to capture footage of the pole vault trials. Camera 1 was set on the position where the optical axis intersected with the plane of motion at right angles at a point of 1 m back from the end of the box. The distance between camera 1 and the middle of the runway was 25 m. The height above the runway was 1.6 m. Camera 1 focused to record the last stride, and all phases from plant through to clearance. Camera 2 was set on the position where the optical axis intersected the plane of motion perpendicular to a point 5.5 m from the back of the box. The distance between camera 2 and the middle of the runway was also 25 m and distance above the runway was the same as camera 1, 1.6 m. Camera 2 was set to capture the last four strides prior to the takeoff as well as the takeoff and plant phase. To make a three dimensional evaluation possible, camera 3 recorded the vaults diagonally from behind at an angle of about 90 degrees to cameras 1 and 2. The frame rate was 50 Hz with a shutter time of 1/1000 sec. and the iris was open.

Collected data were processed by using statistics for windows 7.0 software package for basic descriptive parameters, correlations as well as Kolmogorov-Smirnov test for testing the distribution normality. Horizontal and Vertical Velocity data were obtained from the APAS System (Ariel Performance Analysis system), procedure standards that include: frame capturing, digitalization, 3 D transformation, data filtering and cinematic parameters calculation.

Potential Energy (PE) for the subject vaults was given by:

$$PE = mgh$$

m – mass, g – gravity, h – height

$$KE = \frac{1}{2}mv^2$$

Kinetic Energy (KE) was given by:

m – mass, v – velocity

Results

All kinematics parameters are presented in Table 1. In 22 out of 24 pole vaults, the vaulter raised CM above 4.79m. The highest altitude of CM was 4.95m in one vault, while in two other vaults CM was at 4.55m, but both of these vaults were unsuccessful, due to a fact that cross bar, set on 4.60m, fell down. The CM altitude of the takeoff was 125cm. In J.Osima's research back in 2001[9], the CM altitudes of New Zeeland's top four vaulters at the takeoff moment were from 103cm–127cm. The pole support phase or the altitude of swing phase reaches from 3.22m to 3.40m.

Table 1 presents the points of the pole vaulting movement. The TO point was defined as 0.0 seconds. The maximum pole bend (MPB) which is also referred to as the minimum chord length was defined as the frame when the pole reach its shortest chord length and this occurred between.41 –.50 seconds Duration of the vaults is ranged from 1.25 – 1.34 seconds. It is expected that the lowest altitude of the vault will have the lowest time to finish the vault. Only in two vaults (even when the cross bar fell down) the vaulter had negative value (between the plant moment and highest CM position the vaulter had negative free-fall phase), because he let go the pole before Cm reached the highest point. It was not possible to accomplish higher altitude unless CM has no pole support phase. Grabner's[10] study of women vaulters also produced evidence of this negative flight with five out of her seven subjects releasing the pole after their HP had been reached, (Osima, 2001[9]).

The objective of pole vault is for vaulter to transfer the kinetic and potential takeoff energy into maximum potential energy at maximum CM altitude and to increase total energy with additional work done during the swing phase. Potential vaulter's energy is determined by using the filtered data and equation as described in the data analysis section. Picture 1 presents diagram of kinetic and potential energy at highest vault. Diagram indicates the decrease of vaulter's kinetic energy at takeoff. Kinetic energy reaches its maximum at approach phase. The stronger efficiency of transfer of the kinetic energy, the vaulter is in better position to raise the CM as higher as possible. After the pole release (PR), the vaulter at his best vault has the best possible altitude.

TABLE 1
DESCRIPTIVE STATISTICS OF KINEMATICS PARAMETERS OF THE POLE VAULT

Variable	N	Mean	Min.	Max.	Variance	SD	Skewness	Kurtosis
L2PSRU	23	210.783	203.000	218.000	18.360	4.2848	–0.1211	–0.7321
SL2PSRU	23	7.6948	7.3600	7.9200	0.0260	0.1613	–0.3875	–1.0070
L1LSRU	23	178.783	164.000	186.000	32.269	5.6806	–0.6431	0.4257
SL1SRU	23	7.5039	7.1300	7.8600	0.0411	0.2026	–0.2255	–0.3255
HDLFTB	23	335.391	326.000	354.000	53.613	7.3221	0.7567	–0.0108
PAP	23	35.097	34.250	35.900	0.1570	0.3963	0.0333	0.3808
DBTHLT	23	0.0996	0.0200	0.1900	0.0023	0.0478	0.3191	–0.4648
TMDCMB	23	0.5617	0.5000	0.6200	0.0008	0.0289	0.2323	0.3848
MPB%	23	22.830	19.079	24.382	4.6077	2.1466	–0.6969	–0.6938
TMPB	23	0.4635	0.4000	0.5000	0.0008	0.0287	–0.5350	–0.5854
TPS	23	0.4974	0.3600	0.5600	0.0023	0.0476	–1.3598	2.2265
TMHCM	23	1.2565	1.2000	1.3400	0.0015	0.0382	0.3249	–0.4516
PR	23	0.0574	0.0200	0.2000	0.0017	0.0410	2.0941	5.9190
MHCM	23	479.174	458.000	495.000	141.332	11.888	–0.0952	–1.1769

L2PSRU – Length of the penultimate stride in the run-up (cm), SL2PSRU – Speed of the penultimate stride in the run-up, L1LSRU – Length of the last stride during the run-up (cm), SL1SRU – Speed of the last stride during the run-up, HDLFTB – Horizontal distance between left toes to back of box at plant (m), PAP – Pole angle at Plant (degrees), DBTHLT – Distance between top hand and left toe at takeoff (m), TMDCMB – Time to minimal distance between CM and vault box (m), MPB% – Maximum pole bend (%), TMPB – Time to maximum pole bend, TPS – Time to pole straightening (sec), TMHCM – Time to maximum height CM, PR – Pole release, MHCM – Maximum height of CM

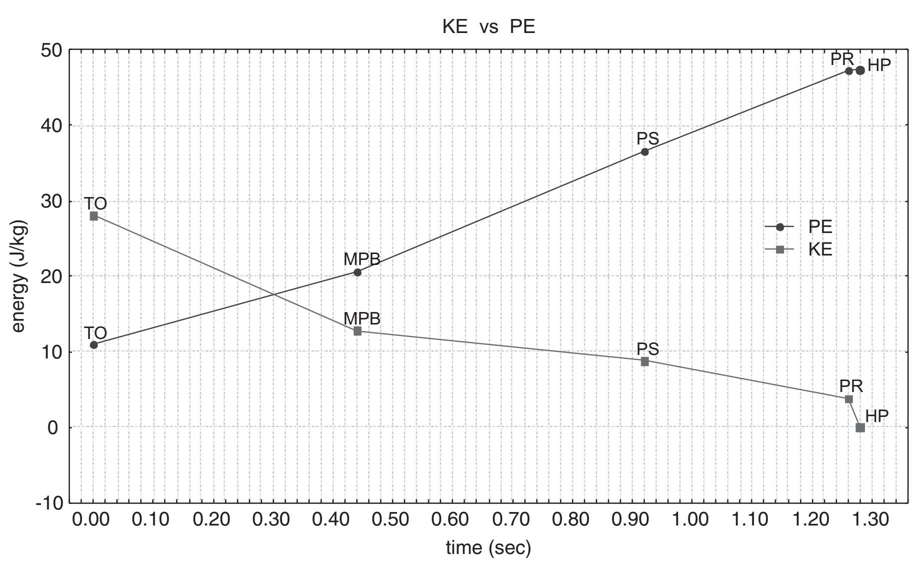

Fig. 1. Potential Energy (PE) and Kinetic Energy (KE) for pole vaulter, MHCM – Maximum height of CM = 4.95m, TO – Take off, MPB – Maximum pole bend, PS – Time to pole straightening, PR – Pole release, HP – Highest point.

The aim is to accomplish high horizontal speed at the approach and along with accomplish optimal body position for the takeoff. Four parameters (Table 1), used in McGinnis' research in 1987[6], were measured to describe approach phase. Vaulter tested in this research is right-handed so his takeoff leg is left. The second to last step length was defined as the horizontal difference between the toe of the left foot at touchdown for the second last step, and the toe of the right foot at touchdown of the last step. Therefore a step or stride length was defined as starting at the touchdown moment of the toe of the one foot, and ending with the touchdown of the toe of the opposite foot. Vaulter had longest second to last stride length of 218 cm and average value of 210 cm. The average stride length of the top three vaulters at 1986 IAAF Championship was 208 cm (Gros and Kunkel, 1986)[3] and McGinnis (1987)[6] reported that non-elite men vaulters had average stride length of 207 cm.

The second last step velocity was measured by taking an average of the CM horizontal velocities over the frames taken for the second to last step to be completed. As for the stride length, the step was defined as starting at the touchdown moment of the toe of one foot, and ending with the touchdown of the toe of the opposite foot. The horizontal velocity of the CM at second to last step was between 7.36 m/s and 7.92 m/s. These values are much lower than those taken at 1986 IAAF World Junior Championship – from 9.3 m/s to 9.8 m/s for this part of the vault.

The last step length was defined in the same manner as the second last step length. The results, as shown in Table 1 indicate that for successful vaults a shortening of the stride length occurred when compared to the results of the second last stride length. This aligns with previous research which stated that vaulters shorten their last stride in order to position their body for takeoff. Comparison of stride length with the IAAF Junior Championship data (Gros and Kunkel, 1986)[3] shows that the standard for the top three athletes was 206 cm. The results from the 24 vaults had a standard of 178 cm.

The last step velocity was a measure of the horizontal velocity during the last stride. It was determined using the same method that was used for the velocity for the second to last stride.

The difference in velocity value represents the difference between the two velocity figures. A negative result indicates that vaulter decelerated into the TO. In this research speed deceleration did not occur at the takeoff.

The horizontal distance between left toe and the back of the box at plant was measured to give representation of the position of the subject on the runway relative to the box. The distance was from 345 cm to 355 cm, and average value was 335 cm. The distance between back of the box and position of top of the foot at the maximum top hand reach, as well as vertical body position, was 345 cm. Therefore, the oscillations were at minimum regarding the position of takeoff leg. Horizontal value between centre of top hand and front part of the foot of the takeoff leg was measured for each vault. Higher value points out the vaulter's proximity to the box. The negative value points out that the foot was behind the line which goes from top hand and reaches the front part of the foot. McGinnis[8] estimated the average distance of 16 cm for top vaulters.

The pole angle at plant and takeoff phase was measured as angle between pole and approach. The pole angle depends also on grip altitude as well as on vaulter's morphological characteristics. In this case that angle was 35 decrees.

Swing phase parameters

The swing phase is the component that is H2 in Hay,s model. The minimum distance of the CM to the box coupled with the time that this minimum is reached gives an indication of the path of the CM during the swing phase. The distance value is also influenced by the grip height of the vaulter.

The maximum pole band is a measure of pole band described as a percentage. It was calculated as:

$$\frac{LP-SL}{LP}\times 100$$

LP – length of pole, SL – shortest length

This is a measure that shows pole bending at the vault. This parameter is affected by pole stiffness. McGinnis (1987)[6] and Gros and Kunkel (1986)[3] estimated the maximum pole bending of 26–33%. Osima (2001)[9] pointed out the angle of 17–23%.

In this research the vaulter accomplished the maximum pole bending of 19–24%, with the time of 0.49–0.56 seconds. Junior vaulters accomplish similar values – 54 seconds (McGinnis 1987[6], Gros and Kunkel 1988[4], Angulo-Kinzler and associates 1994[11]).

The time to pole straightening was measured as the time from TO = 0.0 to the frame when the pole was straight and no longer extending. The results ranged from 0.85 do 1.06 in this study.

Table 2 presents the results of regression analysis (13 kinematics parameters with criteria – maximum CM altitude). Only one variable (MPB% – maximum pole bending) has predictor value in relation to criteria variable.

TABLE 2
REGRESSION ANALYSIS OF KINEMATICS PARAMETERS WITH CRITERIA

Variable	β	
L2PSRU–Length of the penultimate stride in the run-up (cm)	0.31	
SL2PSRU–Speed of the penultimate stride in the run-up	0.55	
L1LSRU–Length of the last stride during the run-up (cm)	0.35	
SL1SRU–Speed of the last stride during the run-up	0.52	
HDLFTB–Horizontal distance between left toes to back of box at plant (m)	0.42	
PAP–Pole angle at Plant (degrees)	0.18	
DBTHLT–Distance between top hand and left toe at takeoff (m)	0.17	
TMDCMB–Time to minimal distance between CM and vault box (m)	0.03	
MPB%–Maximum pole bend (%)	0.87	*
TMPB–Time to maximum pole bend	0.28	
TPS–Time to pole straightening (sec)	0.14	
TMHCM–Time to maximum height CM	0.40	
PR–Pole release	0.31	
ρ	0.65	

β – regression coefficient, ρ – coefficient of multiple correlation, *$p<0.01$

It is important to mention that SSLS (speed of second to last step) and SLS (speed of the last step) parameters have medium high beta regression coefficients, but however, those values are not statistically important.

The pole bend happens under the influence of the forces along the entire pole axis (centrifugal and inertia force) which occur at acceleration of approach centre and forwarded a side – opposite to acceleration. The top of pole bending happens when body is in horizontal position, parallel to the ground. By increasing the pole bend the elastic force occur within the pole. At the top of pole bending moment, the bending force and elastic force equalises, but given the fact that centre of vaulter's mass heads toward pole axis, and his acceleration becomes negative, the pressure on pole decelerate and it reclines. The action period lasts from the moment of body extension along the pole to the moment of leaving the pole, after the repulse. The period consists of body extension phase, outstretching with turn off and pole press. His efficiency depends mostly on successful accomplishment of the previous swing period and use of strength to raise the recoil pole. At the moment of pole grouping and propelling the vaulter, the CM speed shouldn't be less than pole recoil speed. The speed of lifting the body and legs is up to 6m/s (Mansvetov, 1983 in Zagorac 1995[12]). During the extension phase, the pole has the highest upward recoil speed, so merging the pole raising force and vaulter's extension force makes the acceleration of the movements, and at the end of extension the vaulter reaches the highest vertical speed. The increase of the grip is essential condition for even higher pole bending and in accordance with that for higher results achievement. This part should be considered subsequently, taking care of parallel development of all relevant motoric abilities which will ensure successful and effective realisation of this complex motoric activity. The parallel optimalisation of development of the »conditional« elements as well as pole vault technique elements and control of the applied methods effectiveness in overall development of young vaulters presents the way in which the efficiency of the process is ensured[12–15].

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UTJECAJ KINEMATIČKIH PARAMETARA NA IZVEDBU SKOKA S MOTKOM

SAŽETAK

Istraživanje je provedeno s ciljem da se utvrde kinematički parametri u disciplini skok s motkom kod jednog hrvatskog skakača s motkom juniorske kategorije, te da se utvrdi u kakvim su odnosima kinematički parametri i ostvarena maksimalna visina skoka. Nadalje nastojao se dobiti uvid u stabilnost i kvalitetu izvođenja tehnike prilikom skokova. U tu svrhu registrirani su kinematički parametri skoka (ukupno 13) od svih dvadeset i četiri skoka koje je skakač izveo na tri izdvojena trening natjecanja. Pri tom su način i uvjeti izvođenja prilikom skokova bili uvijek isti (koristila se ista motka, visina »gripa« te dužina zaleta). Dobiveni rezultati analize kinematičkih parametara ukazuju na određenu konstantnost prilikom izvođenja skokova, dakle nisu uočena veća odstupanja u vrijednostima kinematičkih parametara

između pojedinačnih skokova. Izuzetak su samo dva neuspješna skoka gdje je razlika uočljiva. Ostvarene vrijednosti kinematičkih parametara kod ispitanika u ovom istraživanju razlikuju se i niže su od najboljih svjetskih skakača s motkom – juniora. Nadalje i najbolji ostvareni natjecateljski rezultat je zaostajao u odnosu na najbolje mlade skakače motkom. Shodno tim činjenicama jasno je da ispitanik iz ovog istraživanja zaostaje i sa razvojem bazične i specifične motorike a isto tako i sa nivoom usvojenosti ukupne tehnike. Rezultati regresijske analize ukazuju da samo jedan parametar (MPB – maksimalno savijanje motke) utječe pozitivno na varijablu (MHCM – maksimalna ostvarena visina tijela). Relativno visoke regresijske koeficijente imaju parametri SL2PSRU i SL1SRU (brzina predzadnjeg i zadnjeg koraka) ali ti koeficijenti nisu statistički značajni. Istraživanje daje jedan novi pristup za cjelovitu kinematičku deskripciju tehnike skoka s motkom kojim se određuje: stabilnost realizacije tehnike, tj. njena usvojenost temeljem većeg broja ponavljanja jednog skakača, komparacija te tehnike sa tehnikom najkvalitetnijih svjetskih skakača iste kategorije i praćenje kvalitete izvođenja tehnike istog skakača u funkciji vremena a povezano sa razvojem bazičnih i specifičnih motoričkih sposobnosti.