DIFFERENCES IN SOME KINEMATIC PARAMETERS IN POLE VAULTERS OF DIFFERENT QUALITIES

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Abstract
The aim of this study was to determine the differences in certain kinematic parameters of pole vaulters with different qualities and sports performance. For this purpose, the jumping performances of the pole vaulters with different qualities were analyzed to determine jumping performance and success. From the observed kinematic parameters analyzed in this study, it can be concluded that the subjects differ mostly in the variable velocity that is achieved at the end part of the run up prior to take off, the angle of ascent of the body, the duration of the take off and the difference of the height of the pole vaulters grip on the pole and the height that is cleared. Achieving a greater horizontal speed and maintaining that speed into the take off, a powerful take off and an optimal take off position of the body with a fast bending of the pole will accumulate a large amount of kinetic energy into the pole that will ultimately provide a better performance and result. Result efficiency in the pole vault is primarily determined by variables defined by motor abilities as well as by indicators for which jumping technique has been determined. The results of the research can be used by sports coaches in the programming of the training process.

Key words: *kinematic, pole, differences, jumping technique.*

Introduction

The pole vault is a discipline in the sport of athletics. Its beginnings are still mentioned from the mid-1800s. Official competitions were part of the German gymnastics system. The pole vault was included in the Olympic Games program in 1896 as one of the 17 athletic disciplines for men, and for women it was included in the official program of the 2000 Olympic Games in Sydney. This discipline is one of the most attractive and complex of athletic disciplines, which includes propelling the body over a bar with the help of the pole. According to the rules of the International Association of Athletics Federationa (IAAF) it is defined that "the pole may be made of any kind of material or combination of material and any length and diameter". Understanding the technique and mechanics of the pole vault is the basis of good performance due to its complexity in which several factors are carried out consecutively and / or simultaneously. These factors are mainly related to the speed of the jumper, kinetic or potential energy and stress energy, force and torque applied by an athlete and the design of the poles. With the development new pole-forming technology, an increasing number of scientists focused on researching the impact of new poles on the success of the jump itself. In the long-term preparation of the jumper, starting with the development of motor skills, and learning and adopting the jump technique, it is essential to determine the status of the levels reached. Determining the kinematic parameters during the jump allows us to clearly define the current condition by which an assessment of the accuracy of the technical level of complex motor activity is performed. It is not possible for a trainer-expert to make a quick and accurate analysis of the technique in the jump visually. It is therefore necessary to apply biomechanical systems in order to obtain reliable and accurate information, which will serve as a model for further procedures in the training process. Of course, good educators, coaches and athletes from biomechanics and training theories will contribute to more efficient and faster progress in achieving maximum achievements. According to literature (Shade, Arampatzis & Bruggemann, 2004), the most used models of jumping techniques are:

- The pet model is standard (Bubka has the main influence),
- Russian model (Volkov),
- The Australian model (Alan Launder states that there is no Australian model but only their interpretation of the Petrov model),
- French model (Houvion),
- Polish model (Krzesinsky, Szymczack)
- American model that implies many different jumping styles.

Frere, Chollet & Tourny- Chollet (2009) divided the pole vault in a phase that is most well-received by experts and trainers. There are 7 stages, which are: the run up, the lifting transition in the last three steps, a takeoff that includes the planting of the pole, the phase of the swing, the tuck, the inversion position and the transition over the bar. Hay (1993) shapes the pole vault into 4 levels of the total jump level: H1 is the height of the jumpers center of the body mass at the take off, H2 is the height of the body mass center at the moment when the pole is fully straight, H3 is the height of the body mass center when the jumper leaves the pole, and H4 is the vertical difference between the highest height of the center of body

mass and the height of the bar. Angulo-Kinzler et al. (1994) specify four phases in the pole vault: run up, take off (planting the pole in the box and taking off from ground) split position (swinging into a tucked position) flight (from the release of the pole and the clearing of the crossbar and falling onto the mats). With this division, it was possible to analyze many biomechanical variables that were not possible with the Hay model of 4 phases.
Schade et al. (2004) divided into two phases: 1st phase - starts with a takeoff phase including the final contact with the ground and ends with the maximum bending of the pole. At this stage, the kinetic energy of the jumper is transferred to the pole and stored as kinetic energy. 2nd phase - begins with the maximum bending of the pole and ends with the highest height of the center of mass. At this stage the kinetic energy of the pole is transferred to the jumper as potential energy. The theoretical model of Hay (1993) is the most widespread and most preferred model in the pole vault. In his book, "The Biomechanics of Sports Techniques", Hay described the key phases of the pole vault:

1. Run up phase
2. Planting of the pole and take off
3. Swing phase
4. Crossbar clearance

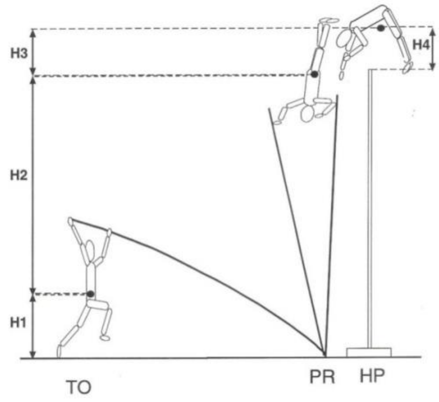

Figure 1. Four key phases of the pole vault (Hay, 1993).

Legend: TO – take off; PR - releasing the pole; HP – maximum point of CM; CM – center of mass; H1 – take off height; H2 – swing height; H3 – flight phase; H4 - clearance over the bar

Zagorac, Retelj & Katić (2008) conducted a research to determine the kinematic parameters of pole vault of a Croatian junior pole vaulter to determine the relationship between the kinematic parameters and the maximum jump heights achieved. Using the Hay model of the partial heights, 13 parameters and a total of 24 analyzed jumps were measured. The obtained results by the analysis of kinematic parameters indicate a certain constant when performing jumps. The results of the regression analysis showed that only one parameter (MPB - maximum bending of the pole) has a positive influence on the criterion variable (MHCM - the maximum height of the body mass in the jump). With these research facts it is proven that the pole vaulter lags behind the rest of the top pole junior pole vaulters. Gudelj, Zagorac and Babić (2009) repeated the experimental procedure after 7 months. With the use of the same kinematic parameters and the number of jumps, the realized values differed from those in the first experiment. In both cases, the results of the regression analysis indicated that there is a link in significant multiplicity between the predicted variables (kinematic parameters) and the resultant performance of the jump in the pole vault. In the first and second measurements, only one parameter showed up as a significant indicator of the success of the maximum lifting of the center mass of the body in the pole vault, which is the percentage (%) of the maximum bending of the pole. Frere et al., 2009, were studying the influence of carrying the pole during the run up and the effects it had on the run up coordination. This is surprising because the knowledge of the run up has a direct impact on training programs and consequently on the ability to improve performance by improving the run up.

The authors concluded that the loss of horizontal velocity was caused by a considerably smaller swing that is associated with significantly reduced maximum hip and knee flexion during the swing phase. Most authors (Dillman & Nelson, 1968; Braff & Dapena 1985; Ekevad & Lundbreg 1995; 1997) have been trying to determine the impact of the pole length as well as pole stifness on the pole vault performance. The results showed that the optimum length and stifness of the pole exist as important parameters that ensure the jumper achieves maximum performance. During the jumping phase the muscular energy of the pole vaulter was used to store energy into the pole (Hubbard 1980; Gross & Teradus, 1983). Also, some authors (Woznik, 1986; 1992; Angulo Kinzller et al., 1994) focused on research that studied the Hays partial heights model (1978).

This model could be a clear and selective subtype of the height of the maximum center of body mass, but it is dependent on the technique and the anthropometric characteristics of the pole vaulters. The optimal pole height and stiffness (pole grip lenth and pole stifness) makes it easier to perform an efficient technique. Five Factors that affect the appropriate pole stifness and height: speed of the take off, body weight, pole grip height and force and aggressiveness. Chang (2002) and Katsgas (1992) (according to Jagodin, 1995) states that there are two main parameters that provide the energy needed to push the pole to the vertical position: 1) the run up speed and 2) optimal take off duration (0.11 -0.14s). Baković and Antekolović (2012) made a research: "3D kinematic analysis of the pole vault as a prerequisite for the modeling of the training process - the case of the Croatian recorder holder" in order to help improve the technique of

Croatian Olympian pole vaulter Ivana Horvat.The obtained results have determined that Ivan Horvat does not achieve a sufficient transfer from the maximum speed before inversion (4.86 m/s) to the vertical speed at letting go and leaving the pole (1.49 m/s). At the phase of going over the crossbar, it was found that the maximum height of the body's center of mass was 524cm at the height of the crossbar at 510 cm. The difference between the height of the crossbar and the grip height is 80 cm. This can be explained by the fact that the take off position was at a distance of 340 cm from the box while on the runway a checkmark that is ideal for the grip height of the pole is marked at 370cm from the. This indicates that the jumper was too far "under" at the take off point by some 30cm which initially started an early loading of the pole and prevented a full take off that would otherwise lead to the optimum production of the vertical velocity at take off and take off angle. The take off angle of the center of mass of Horvat is 14° while the top elite jumpers have an angle of 17- 22°. The results obtained were compared to other top jumpers, one of which was Sergey Bubka, to gain an insight into how far he was behind them. The aim of this research is to determine the differences in certain kinematic parameters for pole vaulters of different qualities and sports performance.

Methods

Subjects

In this research, the sample of the entities was made up of three pole vaulters with only successful jumps. The jumps that were taken for this research were filmed during the training process and at competition. The entities who were part of this research were: Sergey Bubka, Ivan Horvat, Siniša Zagorac. The age of the subjects ranged from 23 to 27 years, and the range of their best personal results ranged from 5.15m to 6.15m. Ivan Horvat 5,76m, Siniša Zagorac 5,15m, Sergey Bubka 6,15m.

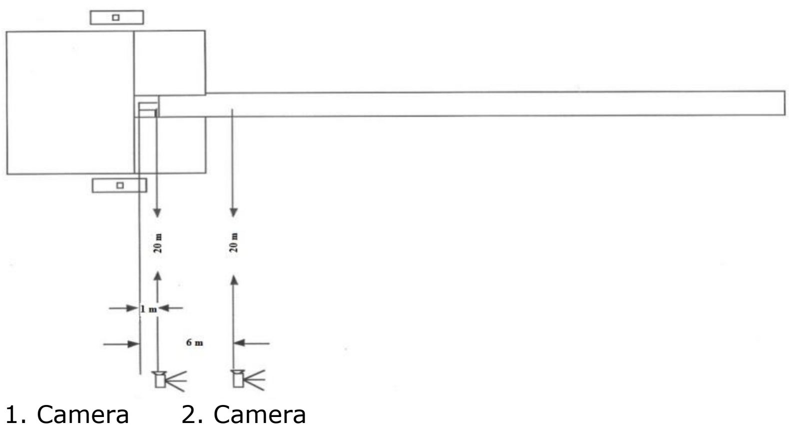

Figure 2. Camera positions in relation to the jumping pit

The first camera was positioned so that it is distanced 1m parallel to right of the box and 20m away from the middle of the runway. The camera was set at a height of 1.5m from the ground. Camera 1 was focused on recording the last step, and all the phases of the jump from planting of the pole in the box, take off and clearance of the crossbar. The other camera was set in a position that is 6m away from the end of the box and 20m from the middle of the path. The camera was set at a height of 1.2m from the ground. Camera 2 recorded the last 4 steps of the run up before planting the pole in the box.

Variables- Kinematic parameters

The horizontal velocity of the penultimate step and the horizontal velocity of last step - is defined by measuring the average horizontal velocity of the center of mass in the time it takes for its execution. Measuring begins at the point when the foot is lowered on the ground at first contact and lasts to the lowering of the other foot on the track at the same position i.e. Toe to ground. The length of the penultimate step and length of the last step - is defined as the difference between the penulatimate and last step and is measured by calculating the distance between the two. The measurement begins when one foot makes first contact with the ground i.e. toe to ground, and ends when the other foot makes first contact with the ground. Grip height at take off - is the height of the grip on the pole at take off and is measured from the distance of the ground to the top hand gripping the pole. Grip height at the end of take off – is the measurement and difference of the height of the top hand gripping the pole and the ground when the take off leg leaves the ground i.e. last contact with the track. Height of body mass at begining of take off - according to Hay (1993) is H1 and the jumper's height of center of mass is measured relative to the ground. This parameter is influenced by body type, body position at the point of take off, jumper's height and body mass. The taller the athlete the higher his or her center of mass will be, therefore allowing for more potential energy to be transferred into the jump. Height of body mass at end of take off - the height of the jumper's center of mass is measured at the moment when the take off foot leaves the ground (last contact) Take off duration – is measured from the moment the heel of the take off leg strikes and makes contact with the ground and ends with the last contact of the foot with the ground. Take off angle after last contact with the ground - is the measurement of the angle of the jumpers center of mass relative to the ground after the take off and ends when the vaulter is in a tucking postion. Maximum pole bend° - is the angle measured when the pole reaches its maximum bending after the take off. This is the angle at which the maximum bending of the pole is reached. Maximum pole bend° - is the angle that is measured when the pole reaches its maximum bending after the take off/penetration into the pole. This is the angle at which the maximum bending of the pole is reached. Time needed for maximum pole bend - is the time it takes to fully bend the pole. It is measured from the moment when the athlete takes off to the maximum bending of the pole in °. Pole uncoil time - is the time it takes for the pole from its maximum bending point in ° to reach a fully extended position. Maximum height of the body's center of mass - measures how high a jumper has lifted his or her center of mass over the crossbar. This height, minus the height of the crossbar, is the H4 in the Haye model. The time it takes to reach the minimum distance between the bodies center of mass and the pole box - is the time measured from the moment the jumper takes off, all the way till his center of mass reaches the minimum distance from the pole box (continues the jump towards the next phase – into tuck position). The difference between the maximum height of the crossbar and the jumpers grip on the pole - is the distance that is measured from the height at which the crossbar is placed up to the upper hand on the pole at the point of leaving the pole and passing over the crossbar.

Table 1. Representation of the kinematic variables in the pole vault.

Full variable name	Variable abbreviation	Units of measurement
Length of last step	LLS	cm
Length of penultimate step	LPS	cm
Horizontal speed of last step	HLS	m/s
Horizontal speed of penultimate leg	HPL	m/s
Grip height at take off (flat)	GHT	m
Grip height at the end of take off	GHET	m
Height of body mass at beginning of take off	HBMBT	m
Height of body mass at end of take off	HBMET	m
Take off duration	TD	ms
Take off angle after last contact with the ground	TALCG	°
Maximum pole bend °	MPB	°
Time needed for maximum pole bend	TMPB	sec
Pole uncoil time	PUT	sec
Maximum height of the body's center of mass	MHBM	m
The time it takes to reach the minimum distance between the bodies center of mass and the pole box	TMDBM	sec
The difference between the maximum height of the crossbar and the jumpers grip on the pole	DMHCJ	cm

Results and discussion

In Table 1, the values of the kinematic parameters /total 16/ which were later used for analysis and comparison of the accomplished jumps made by three pole vaulters. Based on the current understanding of the biomechanical and structural analysis of the pole vault, the expected results have been achieved by defining the relevant factors that best explain the importance of certain parameters essential to successful pole vault technique and at the same time the best result.

By comparing the length of the last step with all three pole vaulters, it can be seen from the table that the values are approximately the same, however the length of the penultimate step is the lowest in S. Bubka and measures 211 cm in length in the analyzed jump, while the length of the penultimate step for the remaining two jumpers is significantly longer / 225cm for S. Zagorac and 220cm for I. Horvat. Gudelj et al. (2015) received roughly the same results in the sample of the European Junior Championships 2009. By analyzing the horizontal speed of the two last steps before the take off, it is notable that S. Bubka develops the highest horizontal speed of 9.9 m/s at the last and penultimate steps, while the other two jumpers achieved a lower horizontal speed Horvat 9.58 and 9.35m/s, and S. Zagorac achieved the lowest speed of 8.5 m/s. It is important to note that I. Horvat had a noticeable drop in speed in the last step relative to the penultimate step.

Based on the results of the horizontal speeds the last two steps before the take off, it can be seen that these kinematic variables significantly determine the difference between the three jumpers. Zagorac has the lowest personal best of 5.15 m compared to Bubka and Horvat, and the lowest value of the achieved horizontal speed of the last two steps of the take off.

Comparing the values of the kinematic variable / GHT / to conclude that there is no difference between the three jumpers. Height of body mass at begining of take the off not only depends on the technical performance of the jump phase but also on the morphological characteristics of the jumper. The height of the pole grip after take off is highest in S. Bubka (240 cm) while for the other two jumpers this height is significantly lower (230 cm). Regarding the variables of the height of the body's center of mass before and after take off, in all three of the obtained values they are approximately the same. A variable that significantly differentiates a jumper is the duration of take off. The pole vaulter with the lowest personal best S.Zagorac has the longest take off duration, which ultimately results in a lower value achieved of the maximum height of body mass during the jump. Take off angle after last contact with the ground for I. Horvat is 18 °, while for S. Bubka that angle is 21 °, or for S.

Zagorac 17°. So, in this variable the jumpers are different. The lowest take off angle of the center of body mass is the jumper with the lowest personal best. If the jumper takes off too far under or too far back, there will be a significant loss of horizontal speed and the upper hand will block or prevent the jumper from easily generating vertical speed. Thus, parameters such as the distance from the take off position from the end of the box, the tilt of the trunk, take off duration, and the horizontal distance between the upper arm and the front part of the take off leg can help identify the jumper's position during planting of the pole in the box.

Finally, to ensure that the jumper provides efficient energy transfer into the pole, the jumper must stay as rigid as possible in the take off position. The results of maximum pole bend are 85 to 86 degrees in all three jumpers. With a stronger and faster take off, the pole vaulter should be able to maximize propulsion forward with a goal of converting stored kinetic energy into potential energy by shortening the actual length of the pole.

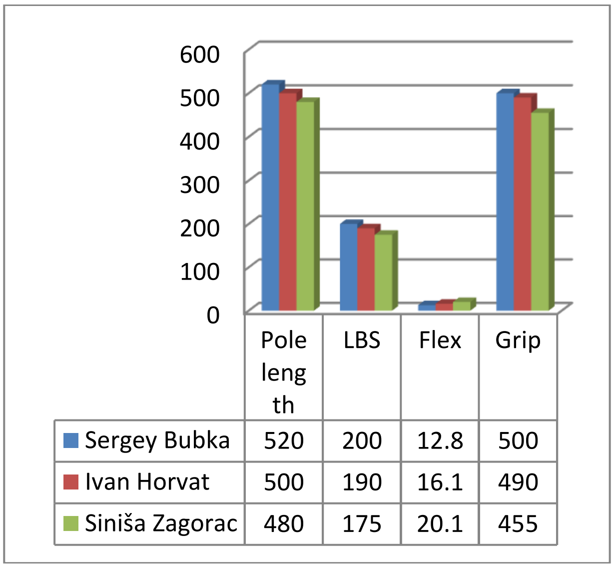

Figure 1. Characteristics of the pole vault.

Allmann (according to Gudelj, 2015), states that at the point of maximum bending, the tetiv length is approximately 70% of the rest of the pole. The faster bending of the pole or its maximal shortening will store inside the pole more potential energy that will be utilized by the jumper achieve a higher center of mass over the crossbar. Pole vaulters that use stiffer poles, a higher grip and have a stronger take off will also perform a faster bending of the pole, which will be advantageous for achieving better results. It should also be noted that faster bending and deeper penetration of the body into take off can also have negative consequences, with the possibility that the jumper body is located deep in the angle of the pole bend, thus reducing the impact of the pole.

Table 2. Results of the obtained kinematic parameters.

Variable abbreviation	Sergey Bubka 5.90m	Ivan Horvat 5.80m	Siniša Zagorac 5.15m
LLS	195	198	198
LPS	211	225	220
HLS	9,90	9,53	8,58
HPL	9,90	9,31	8,56
GHT	2,20	2,22	2,20
GHET	2,43	2,30	2,30
HBMBT	1,08	1,09	1,06
HBMET	1,28	1,29	1,25
TD	110	116	133
TALCG	21	18	17
MPB	85	85	86
TMPB	0,57	0,58	0,59
PUT	0,40	0,48	0,49
MHBM	6,12	6,00	5,38
TMDBM	0,52	0,64	0,53
DMHCJ	90	110	70

Conclusion

A total number of sixteen kinematic parameters were recorded in this study to determine the difference in technical characteristics of the three pole vaulter with different successful results. The jumps that were taken for this research were filmed during the training process and during pole vault competitions. The subjects analyzed for this research are: Sergey Bubka, Ivan Horvat and Siniša Zagorac. The age of the subjects ranges from 23 to 27 years, and the range of their best personal results ranged from 5.15m to 6.15m.

Ivan Horvat 5,76m, Siniša Zagorac 5,15m and Sergey Bubka 6,15m. Based on the current understanding of the biomechanical and structural analysis of the pole vault, the expected results have been achieved by defining the relevant factors that best explain the importance of certain parameters essential to successful pole vault technique and at the same time the best result. From the observed kinematic parameters analyzed in this study, it can be concluded that the subjects differ mostly in the variable velocity that is achieved at the end part of the run up prior to take off, the angle of ascent of the body, the duration of the take off and the difference of the height of the pole vaulters grip on the pole and the height that is cleared. Achieving a greater horizontal speed and maintaining that speed into the take off, a powerful take off and an optimal take off position of the body with a fast bending of the pole will accumulate a large amount of kinetic energy into the pole that will ultimately provide a better performance and result. Result efficiency in the pole vault is primarily determined by variables defined by motor abilities as well as by indicators for which jumping technique has been determined. The results of the research can be used by sports coaches in the programming of the training process.

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