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Sagittal plane kinematics of triple jump: A review

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Abstract:
Background*: This review study is mainly focused on identifying sagittal plane kinematic factors that affect the triple jump performance and the purpose of this review study is to provide essential guidelines to coaches and athletes to identify the performance criteria of triple jump in the field of kinematics.*
Materials and Methods*: The all the original data in this article were collected under the topic of biomechanics & kinematics of triple jump, from previously published articles in authorized journals. Thirty five (35) articles were assessed, Eighteen (18) were included in this systematic review. Five (5) articles were recognized in the field of kinematics of horizontal jumps, nine (9) articles were recognized in the field of biomechanics and two (2) books also were included in this systematic review. Important kinematical factors in each phases of triple jump were analyzed from the recognized articles and books.*
Results*: Many researches were conducted in the field of kinematics of triple jump, those results are included in this review to find out the factors that affect the performance of triple jump. As expected, various kinematical variables influence the triple jump performance. Important variables are outlined based on the phases of triple jump with appropriate evidences.*
Conclusion: *In Particular, special awareness ought to have in step phase, preservation of horizontal velocity, take-off height, vertical velocity and touchdown phase.*
Key Word*: Biomechanics; Kinematics; Triple jump performance.*

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I. Introduction

Triple jump is one of the critical event in track and field in athletics, it consists of difficult movement patterns by bodily, mechanically and coordinately[2]. The major objective of this event is to achieve the maximum horizontal displacement which is the total of three successive movements (Hop, Step & Jump) from the take-off board[6]. It has been divided into four distinct phases for the purpose of analyzing, by James G. Hay. They are approach run, three take off phases, three flight phases & landing phase[8].

Kinematic variables seem to have a crucial influence on results in sporting disciplines. In sagittal plane, there are many kinematic variables influencing the triple jump performance (2D plane). Frequency of stride, length of last two strides before the take-off, take-off distances, flight distances, landing or touchdown distances, height of center of gravity (CG), take-off angle in three take-offs, distance of hop, step & jump, distance lost in take-off and contact time of hop, step & jump are important kinematic variables that affect the triple jump performance according to the modified theoretical model in Figure 01[7]. Therefore, each phases have important role in determining performance.

In jumping discipline take-off phase is considered as a critical phase. To initiate the take-off phase, approach run plays an important role and especially in triple jump the approach run is performed in different manner to prevent horizontal velocity loss during three take-offs[8]. Mainly athletes focus on generating maximal controllable velocity during the approach run. In order to produce vertical velocity at take-off phase athletes make some adjustment in their body position and they focus on the conversion of horizontal velocity into vertical velocity[3].

Once approach phase has been performed, then take off parameters will determine the distance of hop, step and jump. Height, velocity and angle of the CG and take-off distances at take-off are the important kinematic variables that influence the performance of flight phase. Here, velocity and the angle of CG at take-off phase depend on the horizontal and vertical velocities interaction at touch down and their changes in during take-off[3]. The unnecessary decrease in horizontal velocity due to excessive vertical velocity that lead the athlete to allow more ground contact time during the 3 take-off stages is the crucial factor that limits the athlete's performance[5]. In triple jump athletes use two most popular techniques, the Russian technique where the hop distance greater than the jump distance and other one is Polish technique where the jump distance is greater than the hop distance[7].

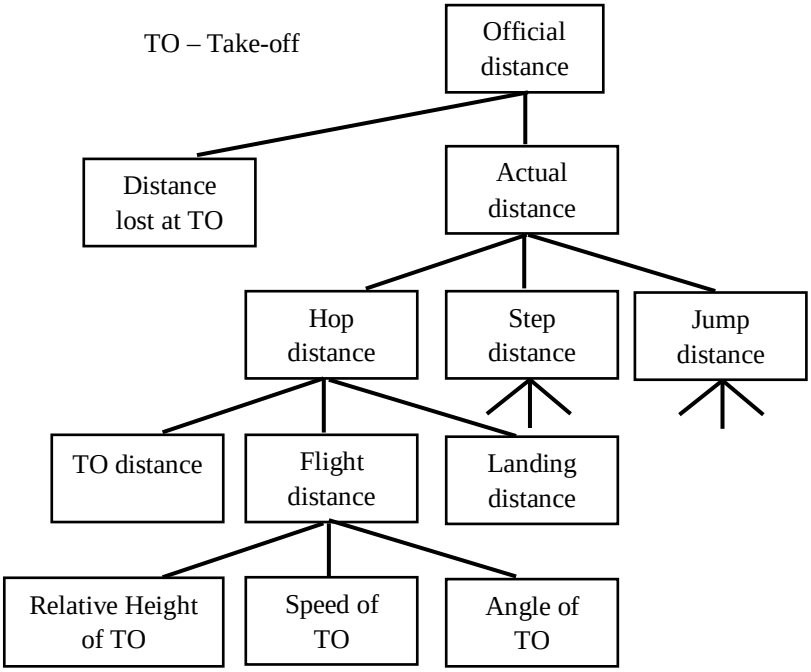

Figure 01: Modified hierarchical model from theoretical model of Triple jump[7]: Variables under the hop distance are same for Step & Jump distances

The aim of this review study is to provide essential guideline to athletes and coaches in order to emphasize the technique based on the scientific theory and to provide knowledge about kinematic variables that influence the triple jump performance.

II. Material And Methods

The framework for this systematic review was developed based on the previously published article and findings. All of the original data in this study came from research gate, Journal of human kinetics, International Journal of Sport Biomechanics, Journal of sports sciences, Journal of sport Biomechanics, Journal of applied Biomechanics, International Journal of Modern Trends in, Engineering and Research, IAAF and books. Published articles were searched under the topic of "Biomechanics of Triple Jump" and "Kinematic of Triple Jump" through google scholar, research gates and science direct.

The papers collected were reviewed, false journals and papers which did not meet the requirements were excluded. After a thorough review of the abstract, introduction, findings, and conclusions, the best papers were chosen. References were used to locate additional articles in order to obtain more information and data. According to phases of triple jump (Approach, 3-Take-offs, 3-Flights & Landing/touchdown) articles were categorized after review of articles. Then each phases were categorized into sub groups according to important kinematic variables.

III. Results

Initially thirty five (35) articles were assessed to see whether it does satisfy the requirement of data or not. Eighteen (18) articles were selected from those collections & others did not meet the requirement. In eighteen (18) articles, six (7) were in the field of kinematics, nine (9) were in the field of biomechanics and rest of were books related to the biomechanics and horizontal jumps. Results and findings from those seventeen (17) articles discussed through the distinct phases of triple jump.

Approach phase

Usually elite level triple jumpers have 35-50m run up distance (17-26 strides), and within 4-6 strides athletes should have gained their maximum horizontal velocity with static or dynamic (a moving) start but some studies show that this may be incorrect [6,2]. In order to facilitate the vertical velocity athletes make several adjustments in their body position. From the kinematical point of view these changes are made in stride

frequency, stride length and by lowering the CG of athlete at last 2-3 strides[6]. The last stride prior to the take-off is called as penultimate stride.

Frequency and Stride Length

At the last 4-8 strides from the take-off board, the frequency of stride increases while athletes straightening the trunk position[16]. The last two steps must be faster than the previous ones, so that there would be an improvement in rhythm[13]. Many studies on frequency and length of stride have been conducted over the years and stated that they strongly affect the conversion of horizontal velocity into vertical velocity. Timothy Koh has found that there is correlation between the last stride distance and hop distance ($r = 0.53$) and between Hop distance and effective distance ($r = 0.60$). This suggests that athletes may use large last stride distance in order to generate the vertical velocity[10]. However the purpose of last stride in triple jump is to gain vertical velocity to project CG and to reduce the loss of horizontal velocity. Therefore, Last stride compared to the long jump's last stride should be shorter to allow fast lift of the CG and to utilize the vertical velocity[2].

Changes in Height of Center of Gravity

The purpose of lowering the CG of athlete at last two or three strides is to generate vertical velocity during take-off. Some studies showed that during last three strides CG changes and during the penultimate stride CG lowers to a greater extent. An observation showed that athletes lower their CG approximately 11cm than their normal approach height of CG during penultimate stride until touch the take-off board. The analyzed result of 12 finalist at 1991 World Student Game, Lees found that athletes at the time of touch down of board lower their CG approximately 2cm which caused them to have small negative velocity of $-0.04ms^{-1}$. This shows athletes must ensure that there is zero vertical velocity or minimal negative vertical velocity when they reach take-off board. This allows athletes to generate vertical velocity positively and to jump efficiently[11].

Take-off Phases

Take off phase is considered as a critical phase in all jumping events, because, it has a great influence in performances. The difference between triple jump and other jumping event is there are three sub maximal effort determine the performance. During the take-off phases in hop, step & jump take-off parameters determine the performance. Measuring actual distance of triple jump is sum of the take-off distance, flight distance & landing or touchdown distance of each hop, step & jump phases[15]. In take-off phase, take-off distance, take-off height, take-off angle and take-off velocities (Horizontal & vertical) are the important kinematic variables in take-off phase that affect the distance of each hop, step & jump phases (figure 02).

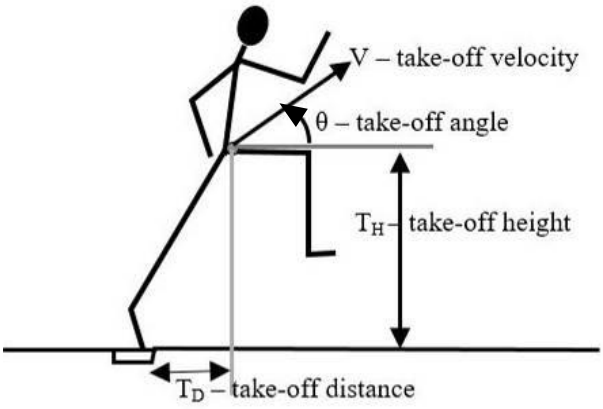

Figure 02: Take-off parameters

Take-off Distance

It's the horizontal distance from the toe of take-off foot to the CG of athlete. Maher Al-Kilani found the correlation between the take-off distance and the distance of each phases to be strongest for both the hop and the jump phases (hop, $r = 0.76$; step, $r = 0.10$; jump, $r = 0.76$)[1]. Fukashiro et al (1981), cited by (Graham-Smith, 1999), reported that take-off distances of 0.65m (11.5%), 0.70m (15.3%) and 0.62m (12.2%) contribute the performance of 5.65m hop, 4.59m step and 5.09m Jump distances respectively according to the table 01. This states that, more in take-off distance result in higher actual distance[6]. In 1984 Hay found a negative correlation ($r = -0.62$; $p < 0.10$) between take-off distance in jump phase and official distance. It means less take-off distance in jump phase results in greater official distance[7]. It was opposing our belief. After investigation of other variables related to the take-off distance, he concluded that more effort during step phase and more

vertical effort at take-off in the jump phase result in greater jump distance. Karayiannis (1987), cited by smith (1999), also reported that take-off distance determined by not only technique but also the height of athlete and the length of lower limb[7].

Table 01: Take-off distances7

Take off distance	Mean	SD
Hop	-0.65	0.07
Step	-0.70	0.06
Jump	-0.62	0.06

Take-off Height

Here, take-off height means the vertical height of athlete's CG from the ground at the exact time at which athlete leaves the ground. It has a great contribution on flight distance with combination of landing height of CG (relative height of take-off). Hay and Miller reported the mean values of take-off height of each hop, step & jump phases 1.20m, 0.95m & 1.03m respectively[7]. This suggested that "high low medium" pattern was used by ten athletes among twelve in his experimental group. In all athletes take-off height of step phase was lower than all other phases. Bruggeman (1990), cited by Graham-Smith reported that take-off height in hop phase relatively lower than long jump take-off height, net change in height of CG increased by 0.16m for hop phase and for 0.29m long jump. In hop take-off the take-off height increased 0.07m from their standing height of CG. There are some evidences ensuring that if athletes may raise their CG at step take-off, they may gain longer step distance (r = 0.906, R2 = 82%). In Jump take-off, take-off height increased about 0.15m from their standing height[6].

Take-off Angles

Take-off angle is an important parameter that determine the flight duration and distance of an object in a projectile path, and it's a dependent variable on interaction between horizontal and vertical velocities. It's the angle of CG of an athlete to the horizontal line. The absolute projection angle of an object to travel maximum distance with fixed velocity is 45^o, but obtaining this angle in horizontal jumps is much difficult and that will lead to excess loss in horizontal velocity especially in triple jump[2]. The take-off angle for hop phase can be 14^o-21^o, 11^o-21^o for step phase & 17^o-28^o for jump phase (jump dominated technique). It may differ with athlete's techniques. In Athletes who use hop dominated technique, the take-off angle of hop phase will be higher than take-off angle of jump. However the angle of take-off in step phase will be lower than other take-off phases because, if the take-off height of step phase is much higher, negative vertical velocity on touchdown of jump phase will cause excessive loss in horizontal velocity[4, 5, 12, 14]. Strong positive correlation was found between distance of hop phase and take off angle (r=0.873)[17].

Table 02: Take-off angles taken from authors

Authors	Take-off angle(°)		
	Hop	Step	Jump
Milan Čoh & Otmar (2011)	19.20	14.90	27.50
Panoutsakopoulos & Kollias (2008)	15.4 -19.5	10.2 -14.2	17.8 -24.3
Mendoza & Nixdorf (2009)	14 - 16	13 - 16	19 - 26
Abeer Eissa (2014)	20.5	21.50	23.25
Zerf Mohammed (2015)	16	13	26
Santhosh R & SJ Shabu (2019)	13 - 16	12.85	18 - 23

Take-off Velocities

Another important parameter that influences overall performance of horizontal jump is take-off velocity. It's the velocity of center of gravity of athlete. It can be further divided into two, horizontal and vertical velocities. Both horizontal and vertical velocities are strongly correlated with triple jump performances[1]. In order to gain vertical velocity athletes need to loss horizontal velocity. There is a strong linear correlation between loss in horizontal velocity and gain in vertical velocity (r = 0.95)[2]. Hui (2015) found regression equation for longest actual distance obtained using optimal phase ratio and it showed that the greater horizontal velocity & the lesser downward vertical velocity at approach run result in longer actual distance[9].

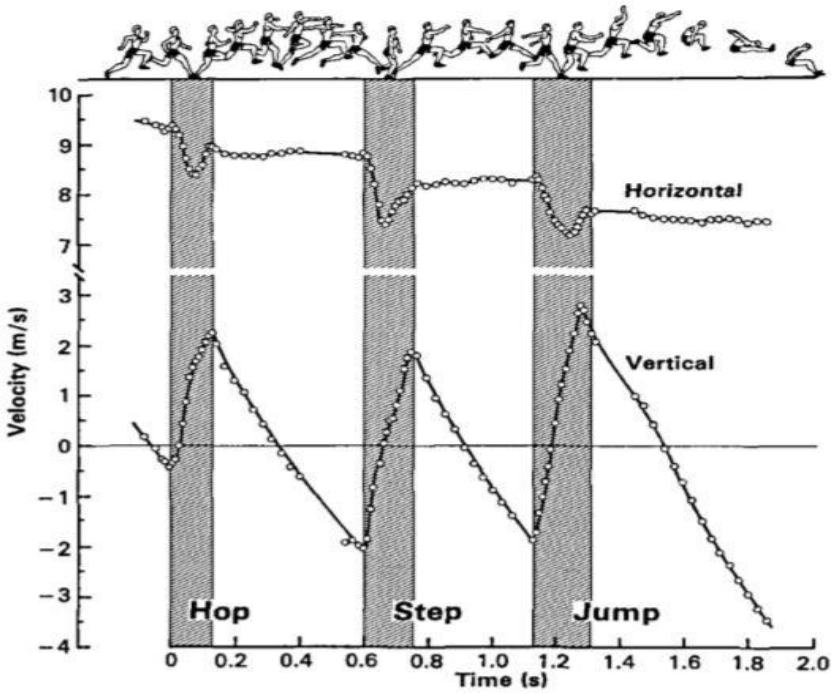

Figure 03: The horizontal and vertical velocity of the center of gravity of an athlete vs time, during the performance of a 15.33-m triple jump[8].

In figure 03, the velocity change in each phases are clearly explained by Fukashiro et al (1981), cited by Hay J. G[8]. It shows that the horizontal velocity decreases through each support phases and vertical velocity in hop and jump take-offs shows similar values, while lower vertical velocity in step take-off. Maher A. Al-Kilani & Carol (1990) examined ten female athletes, found correlation between the horizontal velocity at hop, step, and jump take-offs and the total distance of the jump (r = 0.74, r = 0.81, and r = -0.32 respectively) and found low correlation between horizontal velocities of each take-offs and respective distance of phase (r = 0.53, r = 0.51 and r = -0.14). And he found correlations between the total distance of the jump and the vertical velocity at take-off to the each phases (r = 0.46, r = 0.82, and r = -0.09, respectively) and correlations between the vertical velocity at take-off to each phases and the distance of respective phases (r = 0.75, r = 0.73, and r = 0.64) (Table 03)[1].

Graham-Smith reviewed and found strong relationship between hop distance and horizontal and vertical velocity of CG, it indicated large hop distance correlated with greater gain in vertical velocity and greater losses in horizontal velocity. But in step take-off & jump take-off, lack of strong relationship were found between both velocity (Horizontal and vertical) and step distance and jump distance. Therefore he concluded that athletes should strive to maintain their horizontal velocity rather than focusing on gaining larger vertical velocity in each phases[6]. Santhosh R and SJ Shabu, found the positive relationship between average velocity and distance of hop phase (r=0.544) and strong positive correlation between distance of hop phase and horizontal velocity (r=0.876)[17].

Table 03: Correlation of take-off velocities[1]

Take-off velocity		Between total distance	Between each phase distance
Horizontal velocity at	Hop Step Jump	r = 0.74 r = 0.81 r = -0.32	r = 0.53 r = 0.51 r = -0.14
Vertical velocity at	Hop Step Jump	r = 0.46 r = 0.82 r = -0.09	r = 0.75 r = 0.73 r = 0.64

Flight Phases

Athletes need to shift their body weight in projectile path in three consecutive flight phases under the gravity. Flight phase determines the flight distance which is more important parameter that impacts the overall jumping performance. In triple Jump, flight distances are determined by take-off velocity, take-off angle and relative height of take-off. Due to the angular momentum conservation the center of mass of athlete cannot be changed in zero aerodynamic situation.

Flight Distance

In horizontal jump events, flight distance provide great contribution to total distance than either take-off height or landing distance. Hubbard (2001), cited by Wakai, M., & Linthorne, N. P., have given the mathematical equation for the flight distance for standing long jump. However, there are no kinematical differences in any horizontal jumps under the free flight situation. The equation for flight distance is d_{flight} in (equation 01)[18]. Here, h is the relative height of take-off.

$$d_{flight} = \frac{v^2 \sin 2\theta}{2g}\left\{1 + \left(1 + \frac{2gh}{v^2 \sin^2\theta}\right)^{1/2}\right\} \qquad (01)$$

From equation 01, the importance of take-off parameters and landing height to gain optimum flight distances are clearly understood. If the relative height equals zero (take-off height = landing height), flight distance will decrease ($d_{flight} = \frac{v^2 \sin 2\theta}{2g}$) [18]. Hay and Miller found significant correlation between flight distance for the step phase and official distance (r = 0.52), indicated that greater the flight distance of step phase, greater the official distance[7].

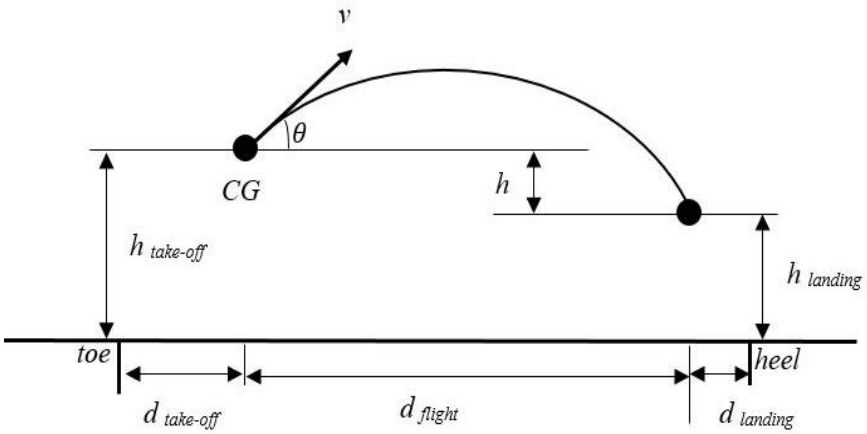

Figure 04: Contribution of total distance

Landing and Touchdown Phases

In triple jump, after take-off athletes need to touchdown the ground three times. Two times in take-off from step and jump phases and another one in landing. In first two touchdowns athletes focus on generating vertical velocity. In last touchdown, athletes focus on landing to achieve more distance. In landing and touch down phases, landing/touchdown distance influence the phase distances and landing/touchdown height of CG indirectly influences the flight distances of each phases[7].

Landing /Touchdown Distance

It's the horizontal distance from heel to CG of athlete while he touches the land. In triple jump, touchdown distance in hop and step phases & landing distance in jump phase will determine the official distance by distance wise of each phases. Hay and miller found the mean landing distance of hop and step (0.53m, 0.60m respectively), and he stated that this led to the difference in breaking duration of support phase which cause loss in horizontal velocity[7]. Koh and Hay (1990) stated the correlation coefficient (r = -0.61) between touchdown distance and loss in horizontal velocity. They stated large touchdown distances may lead to large losses in horizontal velocity. Also, he found the correlation coefficient (r = 0.44) between touchdown distance and effective jump distance and recommended large touchdown distance may lead to effective jump distance[10].

Hay and Miller (1985) reported the negative correlation (r = -0.62, $p < 0.10$) between landing distance of the jump and official distance, suggested that less the landing distance, better the official distance. This result extended to further investigation of correlation between landing distance and four variables (vertical velocity at

take-off, the angle of take-off, the flight distance, and the distance of the hop). They also were negative values, indicated that greater the variables determine the hop distance, less the landing distance of jump[7].

Landing/Touchdown Height

Hay and miller reported significant correlation between height of CG at instant touchdown at the end of the hop and step phase and official distance. (After hop phase; $r = 0.56$; $P<0.10$, after step phase; $r = 0.53$; $p = 0.10$), were unable to conclude this result with logical reason[7]. Graham-Smith stated "the height of the center of mass relative to standing height at touch-down, 62.0%, was greater than that observed in the long jump, 56.1%, ($P<0.000$, effect size = 2.06)" into step take-off, into the jump take-off, height of the center of mass relative to standing height at touch-down, was 59.3% due to large downward vertical velocity[6].

Distance Lost at Take-off

This is the distance of toe from where the measurements taken (foul line of the take-off board). May and Miller found the correlation coefficients for the distance lost at the board ($r = -0.51$). This negative correlation clearly states that minimize the less the distance lost at board, greater the official distance. He examined 6 individuals in 15 trials, mean distance lost at board was 20cm[7]. The accuracy of approach run is needed to minimize the distance lost at board.

IV. Conclusion

Scientific studies on triple jump were widely investigated by many authors to find out the science behind the event and to improve the performance through scientific knowledge. Even many studies have been conducted, still there are many limitations and critical things. The recommendation and correlation provided through this study have a comprehensive practical application, this will allow many coaches and athletes to organize the training plan according to the scientific theories. In Particular, special awareness ought to have in step phase, preservation of horizontal velocity, take-off height, vertical velocity and touchdown phase. Step phase is considered as a most difficult phase than other phases, researchers are often looking forward to improve the step phase performance. Another important variable contribute the triple jump performance is velocity during take-off phases. Even there are many variables contribute the performance, velocity in each phases correlated with other variables such as angle of projection, support time, flight time, phase distance and etcetera. Triple jump athletes must strive to minimize the loss of horizontal velocity rather than gain in vertical velocity. Take-off height has strong correlation with distance of hop and jump phases. During the last stride or touchdown prior to take-off athletes need to minimize the downward vertical velocity which cause them to loss their horizontal velocity. However, focusing on take-off parameters (take-off velocity, angle, height & distance) with more consideration of preservation of horizontal velocity rather than focusing on gain in vertical velocity and on approach phase accuracy will provide better result in overall distance. In future studies, other kinematical factors such as segmental position and angles of segments are going to be reviewed to optimize the performance.

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