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# Biomechanical analysis of running in the high jump

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## Annotations:

The aim of this paper is to analyze the biomechanics of running at high jump. To this study was realized a bibliographic revision. The running phase is the one which starts when the athlete is set in movement for the jump until the moment that he touches the ground with the takeoff foot in front of the bar, this phase can be divided into two parts: the running in straight line and the running in curve. On the other hand, for better understanding and due to a biomechanical complexity, the running in curve will be divided into three other parts: the three last strides, the two last strides and the last strides. Besides that, we could mention important factors for an efficient approach run: the radius of the curve, the distance and length of the takeoff run.

**Леите В. Биомеханический анализ разбега в прыжках в высоту.** Цель этого исследования – проанализировать биомеханические особенности разбега в прыжках в высоту. В реализации исследования использовался анализ публикаций по теме статьи. Фаза разбега – начинается с движения и до отталкивания спортсмена от опоры. Эта фаза может делиться на две части: бег по прямой линии и бег по кривой. С другой стороны, для лучшего понимания и благодаря биомеханической сложности, бег по кривой будет делиться на три другие части: три последних больших шага, два последних больших шага и последние большие шаги. Кроме этого, отмечаются важные факторы для эффективного разбега: радиус кривой, расстояние и длины пробег взлета.

**Леите В. Биомеханічний аналіз розгону в стрибках у висоту.** Мета цього дослідження – проаналізувати біомеханічні особливості розгону в стрибках у висоту. У реалізації дослідження використовувався аналіз публікацій за темою статті. Фаза розгону – починається з руху і до відштовхування спортсмена від опори. Ця фаза може ділитися на дві частки: біг по прямій лінії і біг по кривій. З іншого боку, для кращого розуміння і завдяки біомеханічній складності, біг по кривій ділитиметься на три інші частки: три останні великі кроки, два останні великі кроки і останні великі кроки. Крім цього, наголошуються важливі чинники для ефективного розгону: радіус кривої, відстані і довжини пробігу зльоту.

## Key words:

high jump, running, biomechanics, takeoff, athletics.

прыжок в высоту, бег, биомеханика, взлет, атлетика.

стрибок у висоту, біг, біомеханіка, зліт, атлетика.

## Introduction

The high jump is one of the most technical and complex proof of the athletics, this proof can be divided into three parts: the approach run phase, the takeoff phase, and the flight or bar clearance phase. The most important and critical phases of the jump are the approach run and takeoff, the bar clearance is a direct consequence from previous phases. In all the jumping events in athletics, there is a direct correlation between the execution of the approach run and the performance of a jump. The more consistent and more technically correct the approach run and takeoff, the better the jump performance [9].

In present day high jumping, the Fosbury-flop is the sole technique used by world-class high jumpers. This technique appeared in the mid-1960's [4]. Two major characteristics of the technique are a curved approach run and a back layout position for crossing the bar [6]. The Fosbury-flop technique is not easy to learn and perform, since it requires some unusual attitudes. Its mechanic and dynamic analysis reveals movements of an exceptional difficulty that cannot be so easily assimilated by most jumpers. Certain "time" of execution (particularly those made over the bar) requires a psychomotor control and an extreme sensibility that is not reached by everyone [7].

The aim of this paper is to analyze the biomechanical of approach run. The running phase is the one which begins since the moment when the athlete is set in movement to jump until the first instant in which he makes contact with the front leg towards the bar [10-1]. The purpose of the run is to set the appropriate conditions for the beginning of takeoff phase [2], developing a consistent approach run that allows for gradual acceleration, beginning with the first stride and ending with maximum controlled velocity at takeoff [9]. During this phase, the jumper builds up running velocity to between 7 and 8m/s [5]. This way, the

form, the technique of execution, the number of strides, its length and the rhythm of running happen in order to achieve these goals.

The approach run is divided into two phases: the straight run in progressive rhythm and the running in a curve keeping the pace gradually. The pursuit of progressive impulse of the run is classified in three levels: progressive speed, progressive entry into the curve of impulsion, the progressive increase in the frequency of the backups [7].

To the segmental analysis of the phases of the approach running, all of the technical information, pictures, tables and coaching points will be offered for a left-footed jumper approaching the bar from the right side.

## Biomechanic analysis of the running

### - Running in straight line

To start the approach run, some athletes walk a few strides and then start running; others make a standing start [2]. A successful approach run is dependent on the consistency of the first two or three strides. It is here that the rhythm of the run is developed. If the run is inconsistent, it is usually because of the inconsistency in the speed and length of the first two or three strides. During the first part of the approach run the jumper should look straight ahead [9].

On the straight part, the athlete runs with metatarsal support, leaving the ground with the heel in a high position. It always seek a full extension and reaches up until 180° to the knee and the ankle to return with a circular movement in which the heel near the buttocks. From here, the leg surpasses the hip dislocating the knee to the front and slightly raised, later, we extend it progressively turning to the ground in the front side and in the back side seeking the traction. The torso, in this first part of the run, is always bent forward, allowing the alignment of the axis-standing hip-shoulder and the arms acting coordinated and alternate with the legs. All these actions allow the reach of

large amplitude, the abolition of all types of lock and loss of speed [10-1].

The development of impulse early in the run is necessary to set up correct mechanical execution later in the approach. This impulse must be developed early, because shorter ground contact times at higher speeds give us less opportunity to apply force and generate impulse. A drive phase is the tool of choice to develop this impulse. This drive phase is characterized by long ground contact times. The drive phase in the high jump is considerably less radical than in the horizontal jumps. The initial forward lean established at the start is less exaggerated, and the process of increasing body angle to erect posture is practically complete by the fourth stride [8].

In this straight phase of run, in the stages of flight, the only force acting on the athlete is the terrestrial attraction, corresponding to their body weight, whereas in periods of contact with the ground, besides the athlete's weight there is a supporting force that allow them the rectilinear movement forward and overcome the terrestrial force of attraction [10]. In the early part of the run, the athlete should follow a gradual progression in which each stride is a little bit longer and faster than the previous one. After a few strides, the high jumper should be running pretty fast, with long, relaxed strides, very similar to those of 400/800m runners [2].

The first part of the run is the phase of acceleration and covers 7-11 strides of balance. The mechanic execution in this phase, such as the position of the torso forward and later, the back to the erect posture and a slight lateral inclination helps a higher speed, up to 8m/s in high level athletes. According to Tellez [9], the transition from running the straight line into the curve should be gradual enough so that acceleration is continued.

#### **- Running in curve**

The jumpers who use the Fosbury-flop technique have a curved approach running. One of the main purposes of the curve is to make the jumper lean away from the bar at the start of the takeoff phase [2]. According to Velez

Blasco [10], the curved part of the run could have three or, in most cases, more than five strides. The standard is to do three to five strides on the curve, more than five strides is difficult to find in elite jumpers.

As the jumper increases his speed and enters in the curved part of the run, besides the gravity force, he is subjected to the action of the centrifugal force (tangent to the curve) always increasing. This way, he resists creating a centripetal force (towards the center of the curve) every time his free leg, outside the curve, keeps contact with the ground. This action gives an "inclined" course to the approach run (figure 1), especially in the last strides [7-10].

The resultant force (RF) between the support force (SF) and the centripetal force (CF) has its origins in the foot support, to neutralize the angular moments, this resultant force must be directed to the center of the gravity (c.g.) of the athlete. This way, in the curved part of the run, the c.g. is closer to center of the curve than the support foot. Here, the lateral inclination, characteristic of the athlete towards the interior of the curve in the Fosbury-flop, produced instinctively to maintain balance and speed, may exceed 30° on the vertical axis, mainly in the leg support inside the curve. This lateral inclination causes dip slope side of the c.g. of the athlete. In the case of inclined 20-30°, it ranges between 6 and 13% of the height of the c.g. the jumper ( $\Delta H$ ) [1]. The resultant force of the centripetal force and the support force must be directed in a way that can go through c.g. of the athlete to avoid moments of rotation, which could cause balance problems and could block it to keep increasing its speed.

According to Velez Blasco [10], this position inclined to the center of the curve is one of the advantages of this technique. In the stages of the flight, the c.g., in spite of dislocating on the curve, it creates a straight line. This line is tangent to the point where the support was left, in a way that we can see a curve drawn on the ground on which we put different supports. Only when there is contact with the ground, the c.g. moves itself upon the curve line, however

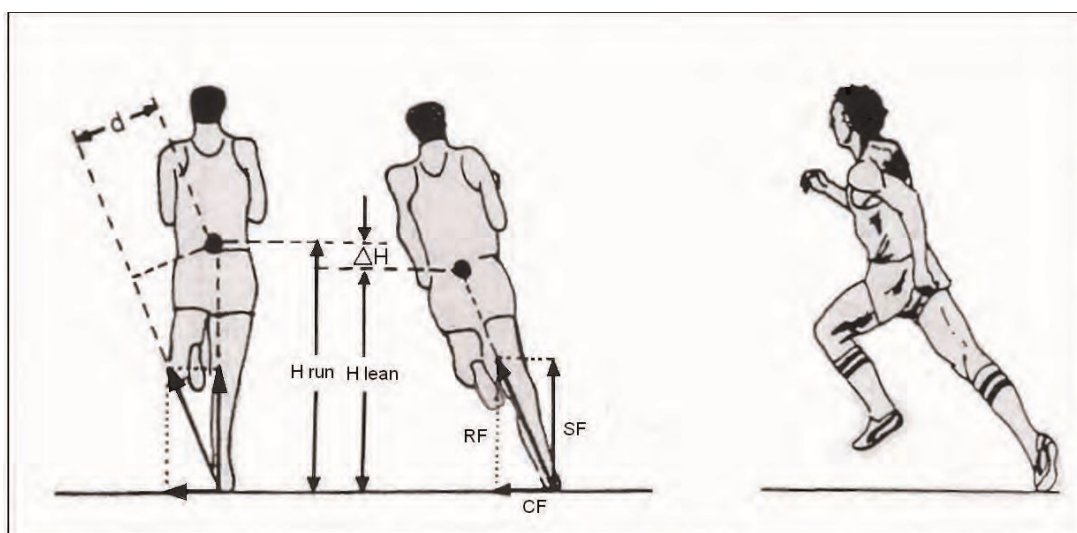


Figure 1. Lateral inclination of the athlete in the curved run.

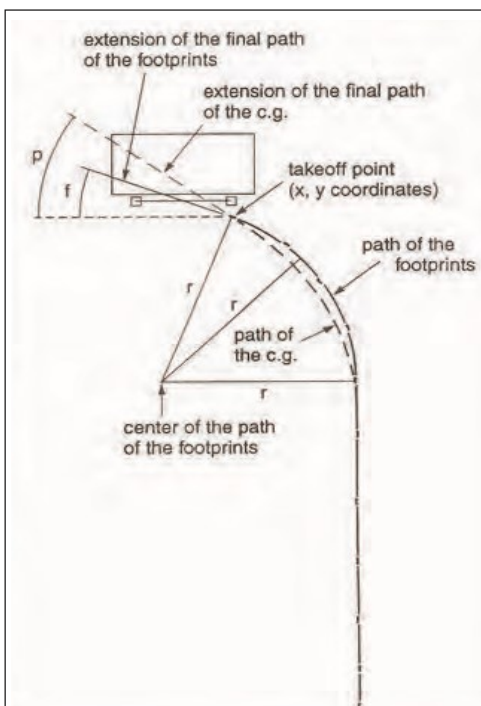


Figure 2. Trajectory and extending support and the center of gravity.

Table 1. Trajectory of the center of the gravity in the end of the run.

Direction of the last stride	Trajectory of the c.g.		
	Second to last stride	Last stride	Phase of flight
$29 + 5^\circ$	$51 + 5^\circ$	$40 + 5^\circ$	$36 + 5^\circ$

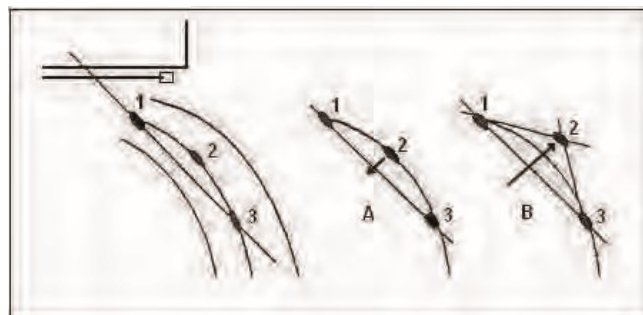


Figure 3. Projection of the last three supports of the running.

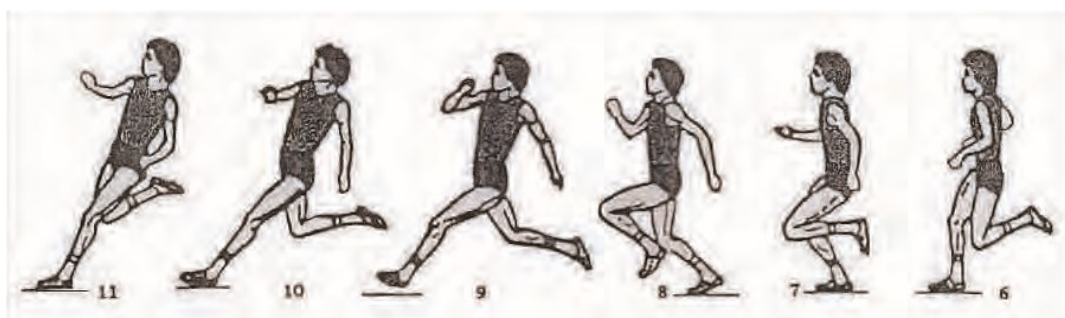


Figure 4. Technical gesture in preparation for takeoff.

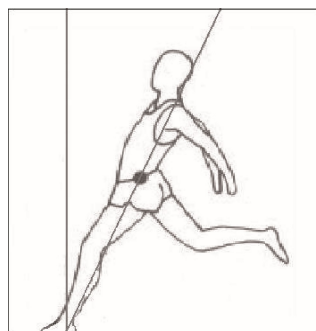


Figure 5. Previous inclination of the body in the last stride.



Figure 6. Performance of centrifugal force in the vertical center of gravity during the takeoff.



in the air phases this displacement is rectilinear (picture 2, table 1). At the end of the curve, the paths of the c.g. and of the footprints converge, and this puts the c.g. more or less directly above the left foot by the end of the takeoff. A consequence of the convergence of the two curves is that the final angle of the e.g. path (p) is always larger than the corresponding angle of the footprint' path (f) [3].

According to this, athletes who have a big length of legs, therefore large amplitude of strides, in the air phases, will have much more rectilinear route than curvilinear ones in relation to athletes with a smaller leg length and will enjoy less than the short ones the advantages of the run in curve, since they will have less essential movements to the jump. There are very tall jumpers that create part of the jump movement by introducing the arm, since the running did not cause enough speed to jump effectively [10].

According to Bravo, Ruf e Velez [1], the run in curve causes, besides the lateral inclination of the athlete to neutralize the angular moment, an increase of frequency of the strides which are produced fundamentally by a reduction in time of flight (specially in the last strides). As a result, we have a tension of the extensor musculature of the legs, like a sharp pushup of the leg in inner curve (picture 4, frame 7) elements that later favor a more dynamic answer during the takeoff.

#### **The last three strides**

Here, the culminant moment of the jump starts, where the athlete does series of actions that will transform the horizontal speed of the c.g. in vertical speed during the impulse and where the angular movements for passing the bar will be formed. The quality of the jump depends on the form in which the antepenultimate takes place (left foot) to the penultimate support (right foot, picture 4, frame 6) and the penultimate support to the takeoff (left foot, frame 11) [1].

The last three supports have a fundamental role in the jump. It is very important to emphasize that, as the athlete technique evolves, these three supports will be performed much closer to the same axis (picture 3, frame A). This action avoids a premature rotation on the longitudinal axis of the athlete and a bigger oscillation of the free leg, as well as a great extension before placing the leg thrust. This is a problem of the beginner jumper, who opens the penultimate support to the outside of the curved line (right foot, frame B), to allow the fast step of the takeoff leg and cause earlier the longitudinal rotation of the back towards the bar [1].

According to Velez Blasco [10], this action makes the hips go forward, although without the speed and the impulse force that they could have if this support really was on the running line. Thus, we have a premature rotation on the longitudinal axis. Running on the race line, all forces that the athlete generates on the ground will pass directly the c.g. and it will not be a projection of these forces, as it happens as the support is opened. The reason to open the penultimate support, besides helping the longitudinal rotation, is that the musculature of the athlete can not be able to support the extension forces that will increase the forces of pressure in the following support.

Dapena [2] says that an athlete should learn how to run faster and lower the c.g. in the final strides, and then try jumping using a run that is faster and lower than the athlete's usual run. If the athlete jumps well with the new run, a run that is even faster and lower should be tried. According to the author the athlete must be careful with the use of a faster and lower run, because it will put a greater stress on the takeoff leg, and thus it may increase the risk of injury if the leg is not strong enough. Therefore, the adoption of a faster and lower run may require some extra strengthening of the takeoff leg, to withstand the increased impact that will be produced when the takeoff leg is planted at the end of a faster and lower run. Therefore, this faster and lower running requires a bigger number of efforts and training. But, consequently, a faster running is good for increasing the vertical force exerted during the takeoff phase.

According to Velez Blasco [10] in the last three strides (preparation to the takeoff) we modify the position of the torso, increasing the inclination towards the center of the circle (20-30°) to offset the centrifugal force and try to keep the horizontal speed. The speed reached in the last strides of the run, in men, is of 7,7–8,7m/s. And in women it is from 6 until 7,5m/s. It is important that we could not have great loss of speed between the antepenultimate and the ultimate stride.

#### **The last two strides**

The last part of the run, the last two strides, is the most important one, since here is where the athlete changes the horizontal speed to vertical speed that will be used in the takeoff. The maximum height that reaches the c.g. is, mainly, due to the vertical speed of the impulse. The step from the antepenultimate to the penultimate support becomes very important, the athlete starts to do series of actions which will allow him a profitable impulse in order to get the maximum height of the c.g. during the flight [10].

The right foot contact, in the penultimate support, is the same as the previous ones, of metatarsal, it is made with all the foot sole and we put it forward the vertical axis of the knee (figure 4, frame 6). The torso is found a little bit inclined forward or almost vertical, keeping the lateral inclination. The focus is on the bar. At this time, the hip must be relatively high and forth. The left leg (back) after flexing by the knee goes fast forward without approximating much the heel and the buttocks. The arms help actively and may act in different ways [1].

During the first part of this support (damping) the jumper accumulates energy to, in continuation (acceleration) release it actively pushing it forward, putting the force to the quadriceps (frame 8-9). According to Velez Blasco [10], the way to enhance the quality of the penultimate support (frames 6,7,8) which is considered crucial for the takeoff, the time in which last the dumping phase and the time that last the acceleration phase are biomechanically studied (concentric phase in relation to the quadriceps). The best athletes have double time in the concentric phase than in the eccentric one, in other words, in the extension phase than in the flexion phase.

In the penultimate support, by ending the dumping

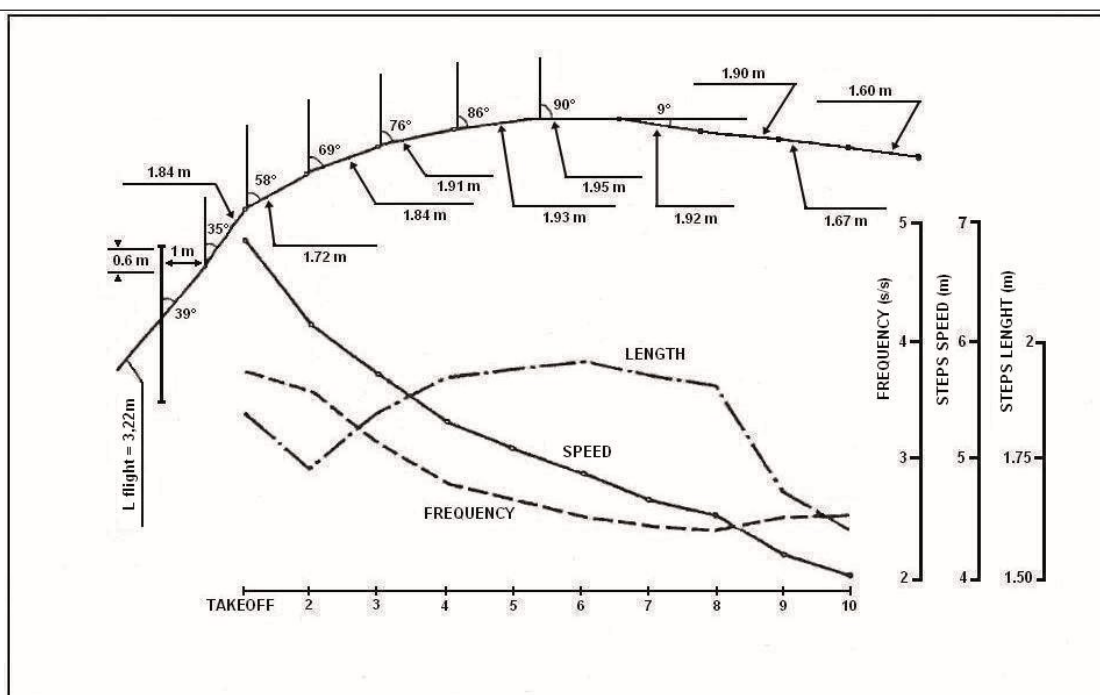
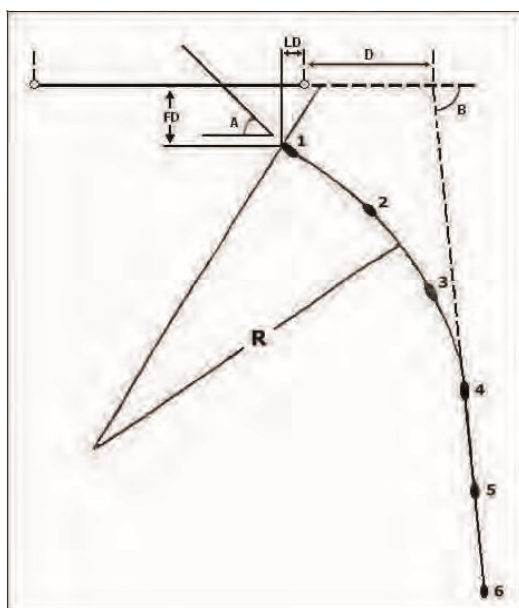


Figure 7. Example of approach run with frequency and length of strides, athlete's speed and angles of support (related to the bar).



- A: drive angle formed by extending the approach running in a curve and a line perpendicular to the bar;
- B: angle of the approach run formed by the prolongation of the run in a straight line and the line extended from the bar;
- FD: front drive away;
- LD: lateral distance of thrust;
- D: distance between the extension line of the run and the end of the bar.

Figure 8. Angles and distances measured during the jump.

Table 2. Reference values in determining the curve in the Fosbury-flop.

Group of jumpers	Radius of the curve (m)	Frontal distance of Takeoff (m)	Lateral distance of takeoff (m)
Beginner Women	3 – 7	0,5 – 0,7	0 – 1
Young people	6 – 10	0,6 – 0,9	
Men	8 – 12	0,9 – 1,1	

phase, the right leg reaches its maximum flexion in this support ( $120 \pm 15^\circ$  in the knee) starting from here, the active phase, staying the left thigh almost horizontal to the ground (frame 8). The right leg extends rapidly and almost completely ( $150 \pm 10^\circ$ ) leading the hip forth and staying the torso back (frame 9) [1]. Then, the knee and the foot extend totally they stay in dorsal flexion in order to keep active all the musculature and prepare for the takeoff (frame 9) [10].

#### **The last stride**

The strong horizontal impulse of the right leg and the fast extension of the left leg lead to a position of 'split' (figure 4, frame 9), also achieving an inclination to the backside before the takeoff. The step forward and below the left leg, getting together with the movement forward and above the right leg (frame 10) in the technical nomenclature is called the active movement of 'scissors'. We realize, therefore, the fact that the flight time of this support, is almost half of the previous ones [1].

In the moment in which the foot touches the ground, in the last stride, besides the lateral inclination, there is a clear back inclination. At this moment, the course of the takeoff is prolonged, the axis foot-hip-shoulders is formed going through the c.g. figure 5). During the support for the takeoff, it is essential that we do not have loss of speed reached during the running. The speed of the approach run should allow for maximum controlled velocity at takeoff enabling the jumper to convert horizontal speed into vertical speed. Moreover, the extensor muscle of the hip, the knee and the ankle are tense before the impact [9].

A fast approach run can help the athlete to exert a larger vertical force on the ground. This can happen in the following way: when the takeoff leg is planted ahead of the body at the end of the run, the knee extensor muscles try to resist against the flexion of the leg, but the leg is forced to flex anyway, because of the forward movement of the jumper. In this process the extensor muscles of the knee of the takeoff leg are stretched [2].

At the moment of placement of the takeoff foot, it has to be as the same line as the penultimate support. It favors a position rapidly displaced of the c.g., related to the support, towards the inner of the takeoff curve. During the time in which the jumper will spend to perform his takeoff, the action of the centrifugal force will put his c.g. in the vertical support (picture 6), allowing an ideal vertical takeoff [7].

The horizontal speed of the c.g. of the athlete presents a great individual tendency. The elite jumpers manifest, in the end of the run, a horizontal speed ranging between 7,0 and 8,5m/s (women approximately 1m/s less). We do not have to confuse the horizontal speed of the c.g. of the athlete with the speed of the strides, result of the product of frequency and the length of the strides [1].

#### **Determination of the curve**

A difficulty in the approach run lies in determining the curve of the run. It has to be extremely individualized, since it depends on the approach of the jumper, his mass and his muscle possibilities [7], of the technical level and gender of the athletes (Table 2).

The radius of the curve ( $r$ ) has important relation with the run speed ( $v$ ), they both generates a centrifugal force that, on the other hand, induces the lateral inclination of the athlete ( $q$ ). The proportion between the square of the running speed and the radius of the curve used by an athlete determines how much the athlete will lean. This can be expressed by the formula  $q = v^2/r$ ; the larger the value of  $q$ , the greater the lean [3]. The radius of the curve should be tight enough to generate adequate centrifugal force to allow easy bar clearance [8].

There are three possibilities to influence the centrifugal force: acting on speed, radius, or both. For an equal centrifugal force: same speed, smaller radius; same radius, higher speed; bigger radius, higher speed. The last one seems to be more profitable for the purpose of seeking a higher speed useful to reach the maximum takeoff [7]. Other possibility to regulate the curve radius is doing more strides in the curved part of the run (5 strides) or opening, sufficiently, the rectilinear part of the run, reducing this way the exit angle that, usually, has between  $60$  and  $90^\circ$  in relation to the bar extension (Figure 8, angle B).

At an equal speed, the smallest radius of the curve is, the bigger inclination and tension are. Hence the importance of adopting a radius according to the athlete's physical abilities. In the best athletes, the frequency of the last step has values ranging between 4,3 and 5 strides/second (s/s) (in women, about 0,5 s/s to more) and increased from 1,0 to 1,2 s/s relative to the fourth step prior to takeoff [1].

#### **Takeoff distance**

The distance between the takeoff foot and the plane of the bar and the standards is called the "takeoff distance" (picture 8, distance FD, table 2). The value of this distance is very important, because it determines the position of the peak of the jump relative to the bar: if an athlete takes off too far from the bar, the c.g. will reach its maximum height before crossing the plane of the bar, and the jumper will probably fall on the bar; if the athlete takes off too close to the bar, there will be a larger risk of hitting the bar while the c.g. is on its way up, before reaching its maximum height. Different athletes usually need different takeoff distances. The optimum value for the takeoff distance of each athlete is the one that will make the c.g. of the jumper reach its maximum height more or less directly over the bar, and it will depend primarily on the final direction of the run and on the amount of residual horizontal speed that the athlete has left after the completion of the takeoff phase [2].

In general, athletes who travel more perpendicular to the bar in the final strides of the run will also travel more perpendicular to the bar after the completion of the takeoff phase, and they will need to take off farther from the bar. Also, athletes who run faster in the final strides of the run will generally have more horizontal speed left after the takeoff; thus, they will travel through larger horizontal distances after the completion of the takeoff phase than slower jumpers, and they will also need to take off farther from the bar in order for the c.g. to reach its maximum height directly over the bar [2].

Another important aspect is the angle of the athlete's

jumping in relation to the bar (picture 8, angle A). It is important to check the angle in that the athlete performs a jump execution. The ideal angle of approach running in the last support (takeoff) usually has between 25 and 35° from the bar.

### Length of running

The literature is inconclusive in relation to the ideal length of the approach run in the high jump, since it is influenced by several factors. The approach run should be as long as possible, depending on the experience of jumper, speed, ability of acceleration and mechanic of running. The length of the approach running will determine the amount of speed that is developed [9].

To Bravo, Ruf e Velez [1], the length of the running is from 16 to 18m and the number of strides goes from 8 to 12 strides. Dapena [2] says that the typical length of the run for experienced jumpers is over 10 strides. To Tellez [9], the length of the approach run should be between eight and twelve strides. In addition, the distance directly out from the bar should be between 14 and 16 feet (picture 8, distance D). When specifying the distance directly out from the standard, 14 to 16 feet, the jumper's anatomical height must be taken into account. Shorter athletes should be closer to 14 feet and taller athletes close to 16 feet.

In case of opposite wind or other unfavorable situations, the total length of the run reduces, keeping unchanged the number of strides and the rhythm of application [1].

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