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Research Article

The Magnitude of the Additional Encumbrance by Centrifugal Forces Arising in the High Jump (On the Example of the Jumps of Olympic Champions Anna Chicherova (London, 2012) and Mutaz Barshim (Tokyo, 2020)

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Abstract

In previous publications, we have carried out a detailed revision of the current paradigm of the driving forces of running and jumping [1,2]. In these articles, we pointed out the aberrations of the muscular-contractile understanding of the mechanics of jumping and running and concluded that the contractile work of actomyosin, based on central nervous impulses and the biochemical energy of creatine phosphate, is not able to give the body the necessary impulse for a vertical take-off speed of 5 m/s. Our analytics led us to the conclusion that the energy generator for the vertical takeoff of the jumper is the tendon strain energy.

At the same time, one of the key points in this analytics was our mention of the action of centrifugal forces, which exceeds 350 kg. Of course, with such an additional load on the athlete's musculoskeletal system, not only is it impossible for an athlete to take off with a vertical speed of more than 5 m/s, but even a simple extensor action of the push leg is a big question. It should be noted that the recorded record value of the vertical take-off speed of an athlete during a high jump is 5.217 m/s; the ex-record holder in the high jump 2m, 39 cm Ju Jianhua (China) - 1984.

However, it is difficult for practitioners who have "grown up" in their skills on explosive muscle contraction to abandon the muscle-contractile paradigm. Therefore, they probably have a suspicion about the objectivity of information. In this regard, there is a need in more detail, as they say with a pencil in hand, in manual mode, to calculate the action of centrifugal forces, which will convincingly testify to the impossibility of using the muscular-contractile paradigm for the athlete to acquire a high vertical take-off speed (more than 5 m/s). The fact that there is such a large external additional load (more than 350 kg) will "cross out" the muscular-contractile paradigm in their minds. But on the other hand, the "presentation" of this force from the standpoint of a deforming factor will put everything in its place and open up new ways for the progress of athletes.

In this regard, we conducted a study of the magnitudes of the action of centrifugal forces, the tasks of which were:

1. Determine the magnitude of the centrifugal forces that arise when running along the takeoff arc;
2. Determine the magnitude of the action of centrifugal forces when performing swing movements with the legs and arms;
3. Calculate the total value of the additional encumbrance of the action by centrifugal forces in the high jump using the Fosbury flop method.

Keywords: *Arcuate Trajectory Running; Leg and Arm Swing; Centrifugal Forces; Deformation Forces*

Introduction

And so, we repeat: in our understanding, the driving force in the high jump from a run is not the contractile work of the muscles, but the force of deformation. It should be noted that the tendons, neither by themselves nor by command from the motor centers of the cerebral cortex, will not stretch. This means that there must be some external force that will deform (stretch) the tendons, after which a return action will occur. This external force is the centrifugal force that occurs during the run along the arc (Figure 1).

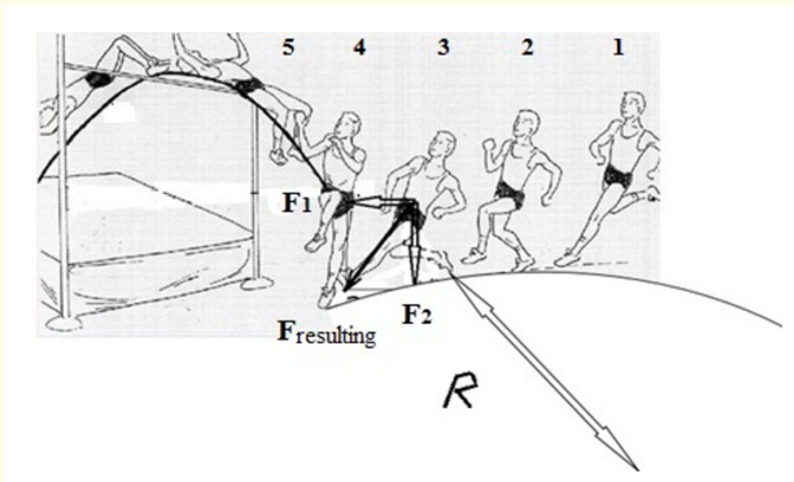

Figure 1: *The action of centrifugal force during takeoff in an arc.*

The action of centrifugal forces was mentioned by V. M. Dyachkov, A. P. Strizhak as a characteristic of a high jump, interconnecting forces, with the radius of the arc and the speed of the run, acting on the jumper [5,7]. However, in the scientific and methodological literature, this issue has been ignored.

But is this ignorance so harmless? Recall the school experience with the rotation of a bucket of water, demonstrating the action and magnitude of centrifugal force. Even with a slow rotation of a bucket of water, we see that the water does not spill [4]. And this means that the weight of water of 5 - 10 kg is easily balanced by a force that presses it to the bottom, the value of which at least exceeds the same 5 - 10 kg (Figure 2). We get the same effect by rotating the bucket in the horizontal plane.

This allows us to state that when running along an arc, the athlete also experiences the action of centrifugal force, which can be very significant. To compensate for this force, the athlete is forced to tilt inside the arc (Figure 1), and this, in turn, burdens the jumper's motor apparatus with an additional load. Moreover, the higher the speed of running along the arc, the greater the additional burden. The question is whether the athlete needs these burdensome kilograms of additional load, because the centrifugal force can "press down" the athlete at the moment of the so-called repulsion.

But this is contradicted by the research data of A.P. Strizhak's complex scientific group, which determined the fact of high take-off speeds among ex-world record holders Patrick Sjoberg, Rudolf Povarnitsyn, Zhu Jianhua and world record holder Stefka Kostadinova [7,8]. Here, quite logically, another bewilderment arises: what made the inventor of this jump method, Dick Fosbury, use an arcuate run?

Figure 2: *Demonstration of the action of centrifugal force during the rotation of a bucket of water [4].*

After all, we just decided, the arcuate run creates centrifugal force and burdens the jumper with additional kilograms? However, the fact is that after more than 50 years, no one has improved the run-up by straightening the trajectory and eliminating the burdensome effect of centrifugal force. This implies the assumption that the arcuate run, even if it burdens the jump, but it clearly carries some special mission! There are no fundamental studies of the centrifugal force and its magnitude arising during the takeoff run in the scientific and methodological literature.

Methodology, Research Results and Discussion

To achieve the objectives, we conducted a study in which the following research methods were used:

1. Video analysis:
   a) A screenshot;
   b) Scaling video frames:
      i. Spatial scaling;
      ii. Time scaling (calibration of time intervals);
      iii. Object-oriented spatial scaling.
   c) Curvimetry.
2. Mathematical processing of results.

Description of research methodology

The study of the magnitude of centrifugal forces in the high jump by the Fosbury-flop method, Olympic champion (London 2012) Anna Chicherova. The study of the magnitude of centrifugal forces in the high jump using the Fosbury flop method was carried out on the basis of a video recording of Anna Chicherova's performance at the 9th stage of the Diamond League in Lausanne (Switzerland) in July 2015

[3]. In the Fosbury flop high jump, the action of centrifugal forces occurs during an arcuate run along an arc and when performing swing movements with the leg and arms. Before starting work with video recording, first of all, preliminary research was required:

1. Determine the algorithm for frame-by-frame video playback on the monitor.
2. Calibrate the time interval between freeze frames during frame-by-frame playback.
3. Scale linear dimensions.

The magnitude of the centrifugal force (F) was determined by the formula:

$F = mV^2/r$ (1),

Where m is the mass of the body, or part of the body, v is the speed of the body, or part of the body, r is the radius of the trajectory of the body, or part of the body [6]. In accordance with this, in order to fill this formula with data, it was necessary to determine the initial indicators:

- The speed of movement of the center of mass of the fly leg when performing the swing;
- The speeds of movement of the centers of mass of the left and right hands when performing the swing;
- The radius of the trajectory of the center of mass of the fly leg during the swing;
- The radius of the trajectories of movement of the centers of mass of the left and right hands;
- Weights of the jumper's left (right) hand;
- The mass of the fly leg of the jumper.

Description of the frame-by-frame video playback algorithm

The algorithm for frame-by-frame video playback on the monitor consisted of the following command actions (Figure 3):

Figure 3: *Algorithm for setting frame-by-frame video playback.*

- Enable video recording;
- Press the "pause" button on the required fragment of the video;
- Using the right button to open the window and find the "Additional features" function;
- Left-click to move the cursor and click on the "Additional features" function. A new window will open, where the function of interest to us "Setting the playback speed" will appear;
- Move the cursor to the command line of frame-by-frame playback; -using the left button, using the arrows "left", "right" to work with the video.

Tare the time interval between freeze frames in frame-by-frame playback

To determine the time parameters, we tared the time interval between freeze frames. To do this, we used the time counter located in the left corner of the video recording (Figure 4). Taking the readings of the time counter from 00:03s as the beginning of the frame count. and up to the time of 00:04s., counted the number of clicks of freeze frames produced that “fit” in this second. It turned out 24 frames. Therefore, the time interval between freeze frames was 0.041s.

Figure 4: *Taring of time intervals between freeze frames.*

Thus, knowing the value of the time interval between freeze frames, we can, by multiplying it by the number of intervals, determine the execution time of the motor action of interest.

Scaling linear dimensions

The determination of linear values was carried out by scaling, in which all the indicators obtained during the measurements were "tied" to the reference length, which was used as the length of the foot - 0.3m.

Determination of the speeds of movement of the centers of mass of the fly leg, left hand, right hand

The determination of the speed of movement of the centers of mass was carried out in two stages. At the first stage, we determined the lengths of the trajectories of the fly leg, left and right arms. At the second stage, having the values of the trajectories of the movement of the fly leg and arms, we determined the speed of movement of their centers of mass.

Determination of the length of the trajectory of the movement of the fly leg and arms

The length of the fly trajectories of the limbs was determined in two ways.

First way: Based on the available video, using the screenshot function, three frames were copied and saved:

- Setting the left push leg on the support in the repulsion phase;
- Vertical phase;
- The moment of the end of the repulsion (preceding the separation from the track).

With the help of "Paint" the selected frames were superimposed on each other. The foot of the jogging leg served as the common point of combining frames. We got the following scores:

- The length of the path of movement of the center of mass of the right fly leg was 4.07 relative units, which, when multiplied by the length of the foot (0.3m.), is 1.14m;
- The length of the path of movement of the center of mass of the left hand - 2.5 relative units = 0.7m;
- The length of the path of movement of the center of mass of the right hand - 2.1 rel. = 0.6m.

Second way: The length of the trajectory of the movement of the fly leg, or arms, was measured using a cartographic roller - a curvimeter (lat. - "curved"), the mechanism of which consists of a measuring wheel connected to an arrow. When the wheel moves along the measured line, the arrow of the device indicates the distance traveled (Figure 5). We compared the obtained data with the scale of the figures.

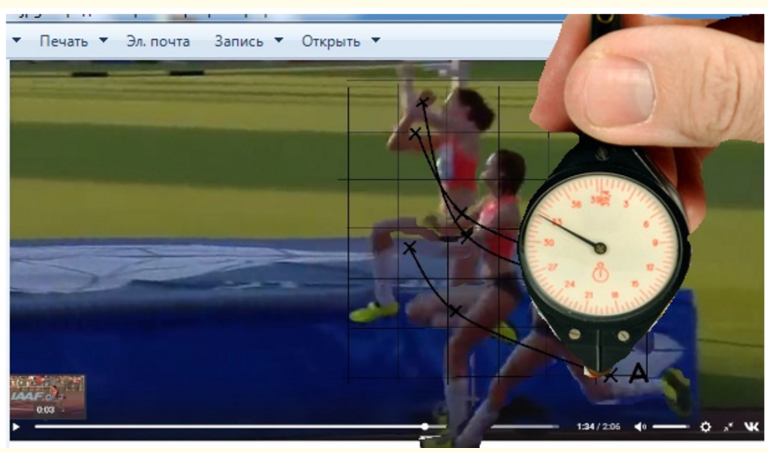

Figure 5: *Determining the length of a curved path using a curvimeter.*

Determination of the speeds of movement of the centers of mass of the fly leg, left hand, right hand

The data obtained were entered in table 1 and using the formula for finding the speed (V): V = S / t (2), where S is the length of the path, t is the duration of the movement, we determined the speeds of movement of the centers of mass of the fly leg and arms.

Part of the body	The length of the path of the swing movement of a body part (m.)	The duration of the swing (s)	The speed of movement of the body part (m/s)
Swing leg	1,14	0,123	9,26
Left hand	0,7	0,123	5,69
Right hand	0,6	0,123	4,87

Table 1: *Data for the path length, execution time and speeds of the centers of mass of the flywheel links.*

Determination of the radius of the arc of the trajectory of the movement of the fly leg, right arm and left arm

To determine the radius of movement of the flywheels, we used a table of segmentation of human body parts. The radius of the arc of movement of the flywheel was equal to the joint of the shoulder (or greater trochanter of the femur) to the cent of the masses of the arm (leg). In accordance with this, the following indicators were used as values for the radius of the flywheel links: The length of the radius was also measured with a curvimeter. Based on the constructed curves, drawing perpendiculars and measurements with a curvimeter, the following results were obtained:

- rt.s. - The value of the radius of movement of the leg (from the center of the trochanter of the femur) = 0.5m.;
- rt.p.r. - The value of the radius of movement of the right hand = 0.2m.;
- rt.l.r. - The value of the radius of movement of the left hand = 0.2m.

Determination of the repulsion duration

To find this parameter, the frames of the moment when the leg was put on the repulsion (Figure 6, position 1) and the moment of the end of the repulsion (Figure 6, position 2) were selected.

Figure 6: *Determining the duration of the repulsion phase.*

By counting the number of intervals between the selected frames (3 freeze frames) and multiplying them by the calibrated time standard (0.041s), we determined the time of support in repulsion, which was 0.123 seconds.

Determination of the masses of the fly leg, left and right hand

To determine the masses of the fly leg, left and right hand, we used the table of segmentation of body parts [131] (Table 2).

Segment	Relative segment weight (%)	Total segment weight (%)	Segment weight (kg)
Shoulder	3/%	Total arm weight - overall 6%	3,42
Forearm	2/%		
Brush	1/%		
Hip	12/%	Total leg weight - overall 19%	10,83
Shin	5/%		
Foot	2/%		

Table 2: *Determination of the mass of the fly leg and arms using segmentation of body parts.*

Knowing the athlete's weight (57 kg), we calculated the weight of the fly leg, left and right arms.

Calculation of the impact force of centrifugal forces that arise when performing a swing with the foot, swing with the left and right hand

Thus, having all the data on speed, mass, radius and using the formula F = mv2/r, we obtained the final value of the action of centrifugal forces (Table 3).

Part of the body	Mass of the body part (kg)	Speed of movement of the body part (m/s)	Length of the radius of angular rotation of the body part (m)	Value of the centrifugal force (kg)
fly leg	10,8	9,26	0,5	186,55
Left hand	3,4	5,69	0,2	56,16
Right hand	3.4	4,87	0,2	41,14
Total: 283,85 kg				

Table 3: *A summary table of the magnitudes of the action of the centrifugal forces of the fly leg and the left and right hands (kg).*

This value of the action of centrifugal force when performing swing motor actions with the legs and arms was 283.85 kg.

Determining the speed of running along an arc and calculating the magnitude of the action of centrifugal force

To determine the speed of running in an arc:

- With the help of a screenshot, we selected the frames of the beginning and end of the run-up step and, using paint, combined them on a single picture (Figure 7).
- Using the applied scale grid, we determined the distance traveled on the video recording and calculated the actual length of the running step, based on the reference foot size (0.3m.), Which was 7 relative values, or 2.1m.

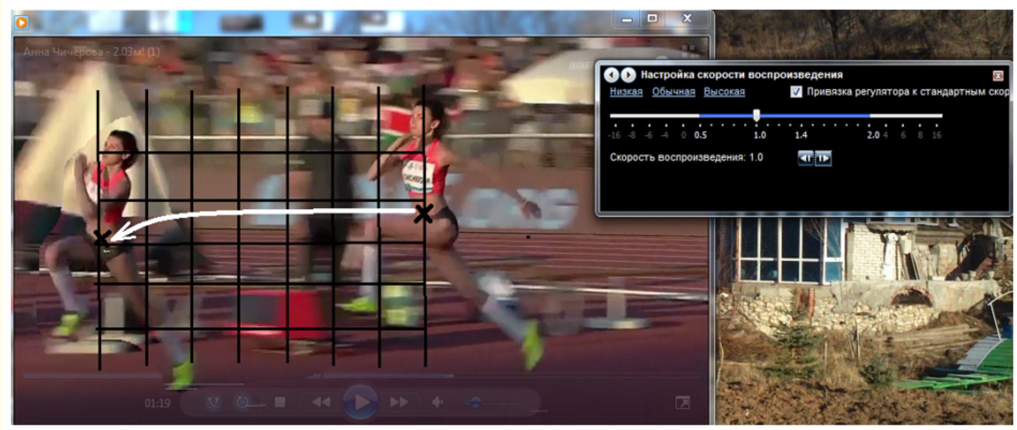

Figure 7: *Determination of the horizontal take-off speed.*

- Counted the number of freeze frame intervals 6x0.04 = 0.24s.
- That is, a path equal to a step length of 2.1m. Was overcome in 0.24s. Consequently, the speed of running along the arc was V = 8.75 m/s.

Applying the formula (1) $F = mV^2/r$, 57kg x 8.752/8 = 48.5 kg, we determined that the magnitude of the centrifugal force when running in an arc is 55.66 kg.

Determination of the resultant from the action of centrifugal force and the action of gravity of the jumper

And so we determined that the jumper at every moment of her run along the arc is burdened by the action of centrifugal force equal to 55.66 kg. But the jumper is also affected by a gravitational force equal to the weight of the athlete - 57 kg. The action of centrifugal force occurs in a horizontal plane, and the action of gravity is directed strictly vertically downwards. Thus, in the presence of two forces, on the basis of which, it is possible to build the resulting vector (Figure 8). It will be the final value of the additional load acting on the jumper.

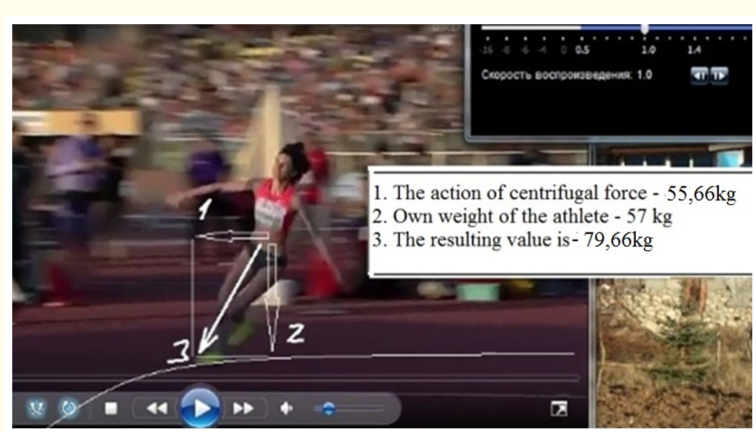

Figure 8: *The action of centrifugal force, gravity and the resulting force during the takeoff in an arc.*

Using the law of geometry for finding the hypotenuse: "the square of the hypotenuse is equal to the sum of the squares of the legs" (3) calculated the value of the resulting force (L3), which amounted to 79.66 kg.

Thus, summing up the magnitude of the action of centrifugal forces that arise when performing swing movements, equal to 283.85 kg and the resulting centrifugal force acting when running along an arc, which is 79.66 kg, we obtain a total value of the action of centrifugal forces equal to 363.51 kg!

The action of centrifugal forces has not previously been covered in the scientific and methodological literature. However, our study showed that, for example, the Olympic champion, country record holder Anna Chicherova, the total value of these forces is 363.51 kg!

Determination of the magnitude of the action of centrifugal forces arising in the high jump of the Olympic champion (Tokyo, 2020) Mutaz Barshim

The next stage of the study was to determine the magnitude of the action of centrifugal forces in men. For the object of study, we took the jump of Mutaz Essa Barshim, the silver medalist of the Olympics in Rio de Janeiro (2016), the 2017 world champion in London, the Olympic champion (Tokyo, 2020) Mutaz Barshim [5] (Figure 9).

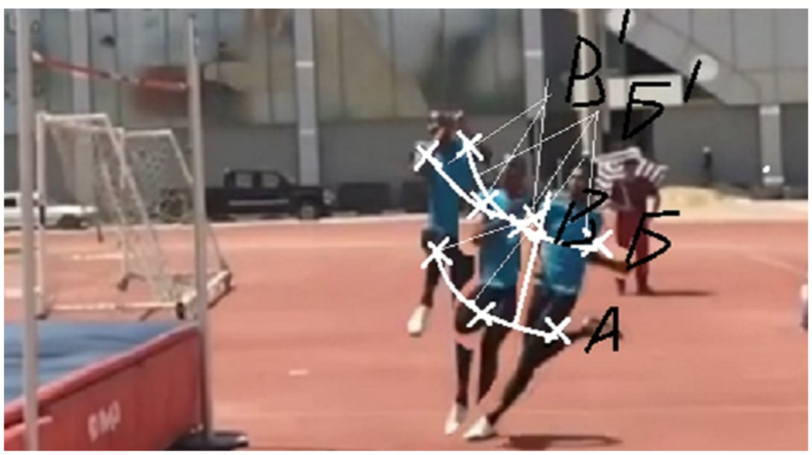

Figure 9: *Finding the length of the path and the radii of the trajectory of the movement of the flywheel links of the legs and arms of M. Barshim in the repulsion phase.*

Based on the conducted graphical analysis, similar to the study described in the algorithm for calculating the action of centrifugal forces by Anna Chicherova, the following data were obtained:

- Duration of support in repulsion (4 frames of 0.041s) - 0.164s;
- The length of the path of the fly leg - 1.44m.;
- The length of the trajectory of the movement of the left hand - 0.7m.;
- The length of the trajectory of the movement of the right hand - 0.7m.;

- The radius of the trajectory of the movement of the fly leg - 0.55m.;
- The radius of the trajectory of the movement of the left hand - 0.25m.;
- The radius of the trajectory of the movement of the right hand - 0.25m.

M. Barshim's own weight is 65 kg. So according to the table of segmentation of masses of parts of the human body [13]:

- Hand weight - 3.9 kg;
- Weight of the fly leg - 12.35 kg.
- Foot length 0.32m.

Based on the obtained values, the speeds of movement of body parts were determined when performing swing movements (Table 4).

Part of the body	The length of the path of the swing movement of a body part (m.)	The duration of the swing (s)	The speed of movement of the body part (m/s)
Fly leg	1,44	0,16	9,0
Left hand	0,7	0,16	4,375
Right hand	0,7	0,16	4,375

Table 4: *Data of the path length, execution time and speeds of the centers of mass of the flywheel links.*

Applying formula (1): $F = mV^2/r$, we have obtained the total value of the action of centrifugal forces when performing swing movements with the legs and arms (Table 5).

Part of the body	Mass of the body part (kg)	Speed of movement of the body part (m/s)	Length of the radius of angular rotation of the body part (m)	Value of the centrifugal force (kg)
Fly leg	12,35	9,0	0,5	204,15
Left hand	3,9	4,375	0,25	30,46
Right hand	3.9	4,375	0,25	30,46
Total: 234,61 kg				

Table 5: *A summary table of the magnitudes of the action of the centrifugal forces of the fly leg and the left and right hands.*

To obtain data on the action of centrifugal forces when performing an arcuate run, we also used the algorithm of actions described in the study of Anna Chicherova's jump.

With the duration of the running step (9 freeze frames x 0.041) - 0.369s and the length of the running step (45 mm) - 2.88m, we got a running speed of 7.8 m/s (Figure 10).

Figure 10: *Determination of the takeoff speed by M. Barshim.*

Using the previously mentioned formula (1): $F = mV^2/r$, received the magnitude of the action of centrifugal force when running along an arc of 51.94 kg. Adding the acting forces (centrifugal and gravitational) - formula 3, we got the magnitude of the resultant force = 84.5 kg, Adding the centrifugal force resulting from the performance of swing movements (234.61 kg) and the resulting force from the action of centrifugal forces when running in an arc (84.5 kg), we got the final value, which was - 319.11 kg.

Conclusion

1. As a result of the analytics and mathematical calculations, we obtained the following indicators of encumbrance by the actions of centrifugal forces when performing a run in an arc, as well as when performing a swing with the legs and arms:
    1) The resulting value of the action of centrifugal forces that occur when running along the takeoff arc for Anna Chicherova is 79.66 kg;
    2) The resulting value of the action of centrifugal forces that arise when running along the takeoff arc for Mutaz Barshim is 84.5 kg;
    3) The total value of the action of centrifugal forces when performing swing movements with the legs and arms of Anna Chicherova is 283.85 kg;
    4) The total value of the action of centrifugal forces when performing swing movements with the legs and arms of Mutaz Barshim is 234.61 kg.
2. The final value of the encumbrance by the action of centrifugal forces: Anna Chicherova is 363.51 kg; Mutaz Barshim is 319.11 kg.
3. Such a colossal additional burden (363.51kg and 319.11kg) of the athletes' pushing leg completely crosses out the muscular-contractile paradigm of the driving forces that give the athletes lifting power, but shows the deformation mechanics of jumping locomotions, which makes it possible to achieve high speed (more than 5 m/s) vertical departure.

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