BIOMECHANICS OF THE TAKE-OFF IN RUNNING

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In this article we tried to resolve three basic problems. The first was related to determination of the major joints and muscle groups in the support leg of the sprinter during the starting acceleration and during the run. In other words, which extensor muscles (hip or knee joint) determine the increase in speed of the sprinter's center of gravity (CG)?

We know that movement is most effective when there is maximum use of muscle contration force and that muscle force depends on initial muscle length. This means that the sharper the joint angle at the beginning of movement, the greater the duration and force of the muscle. Also, the pathway over which force is applied is increased. In the starting acceleration, especially at its very beginning, the angles in all the joints of the support leg as it is positioned on the track are approximately equal and lie within the limits of 90-110°. The working range of these angles is large enough for the muscles to exert their maximum force. Since the increase in the hip joint angle is in the order of 70°, which is significantly greater than in the knee and ankle joints (approximately 45°), then obviously the hip joint muscles are dominant in the starting acceleration.

As far as running the distance is concerned, the picture is different. From analysis of cinematograms, we found that when the leg is first placed in support, the angle in the knee joint is equal to approximately 140°; in the hip joint the angle is even greater, approximately 170-180°. Consequently, the length and force of the leg extensor muscles are almost minimal. Meanwhile, the angle in the ankle joint in the amortization (shock-absorbing and getting ready) phase is quite small, approximately 90-100°. Is it possible that in the take-off only the plantar flexor muscles are used to a maximum degree?

The second problem was that of support leg extension in the knee joint during the take-off. This evoked stormy arguments in the course of which the theory that the support leg must be fully extended was defeated. In looking at cinematograms of the world's best sprinters, however, it was apparent that at the end of the take-off, the angle in the knee joint of the support leg is equal to 160-165° (see photo). Also, commentators on the cinematograms delicately avoided this fact, evidently so as not to disagree with the generally accepted theory of sprinting. Therefore, is extending the support leg a defect or a virtue?

We gave ourselves the "rebellious" question: Could we not get along without full extension of the leg in the knee joint without sacrificing speed? The question is far from lacking importance since additional energy and time are required to extend the knee joint from 165 to 180°. Also, after the take-off, extension in the knee joint must immediately change to flexion in order to decrease the moment of inertia of the leg and facilitate its rapid movement forward. This means that the additional time required for full extension of the leg is now doubled!

The third problem was related to the power of a single take-off. Should it be maximal in the sprints? Common sense answers: Yes, of course! The more powerful the take-off, the greater the speed of the take-off, the longer the stride length and the better the result. But, if this is so, why do sprinters not run with jumps (although in training there are such exercises)?

These are problems arising from practical experience and correct resolution of them is most important. Descriptions of the take-off mechanism are used not only in formation of running technique, but they also determine the selection and amount of training methods.

We will now present some experimental facts which were determined by us and which are necessary for understanding the take-off mechanism in sprinting. The study was carried out in the Track and Field Department, together with a group of biomechanists from the Lenin Institute of Physical Culture, directed by Prof essor Zatsiorski.

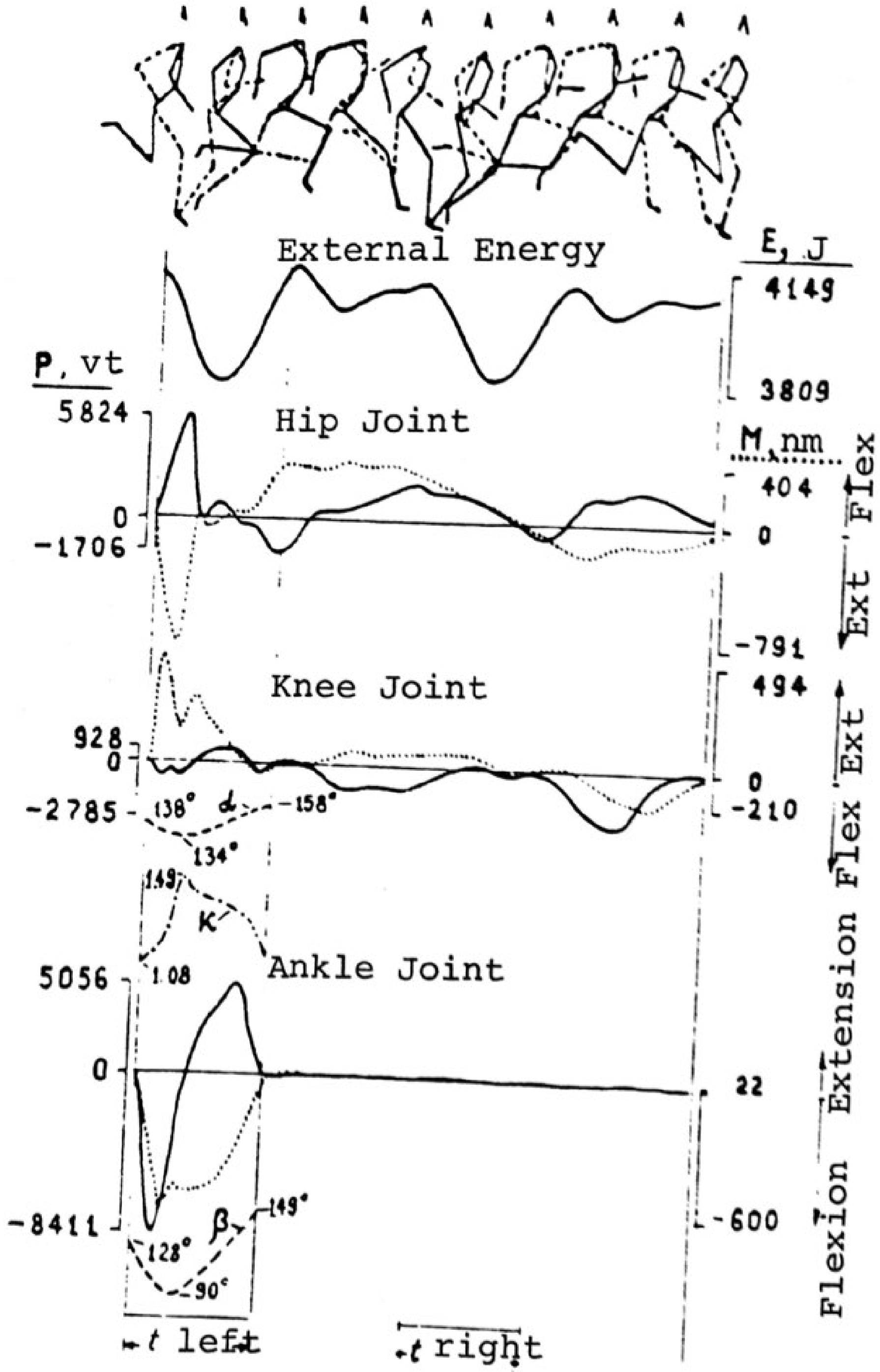
To resolve the first problem precisely, we used a method of computing the moments of muscle forces and joint power. We must remember that the moments of joint forces reflect quantitatively the extent to which tension of one group of muscles exceeds the tension of the antagonist muscle group of the same joint. This, in the last analysis, determines the change in the joint angle. Joint forces are computed simply: They are the product of the moment of force on the angular velocity in the joint. Note that a positive force develops when the muscles do overcoming (concentric) work and a negative force develops when they are lengthened (eccentric contraction).

In the starting acceleration, the greatest instantaneous power is developed by the extensor muscles of the hip joint, the gluteus maximus, the biceps femoris muscle and others. The extensor muscles of the knee joint and the plantar flexors of the ankle joint develop lesser instantaneous power, but they work longer. During the support period, the hip joint works at 64 J, and the knee and ankle joints at 72 J each. As we can see, in the starting acceleration, all joints of the support leg make an approixmately equal contribution to the acceleration of the center of gravity. The distribution of their work is characteristic.

In the beginning of support, the push-off is due predominantly to the muscles of the hip joint and, in the second half, to the knee and ankle joints. Also characteristic is that the greatest demands made of the hip joint extensor muscles are made at this point. When the leg is placed in support behind the line of gravity (vertical projection of the CG) during the starting acceleration, it is possible to include the hip joint in the push-off.

An altogether different mechanism is observed in the course of the sprint when maximum speed is attained. In running at top speed, there is a braking phase due to the placement of the foot ahead of the line of gravity. However, in the starting acceleration, there is an increase in speed of the CG with every support step. A sprinter 178±6 cm tall, weighing 68±8 kg, and running at 8.36±0.85 m/sec loses 1.23±38 J of external energy and 0.129±0.08 m/sec of speed during a braking time of 0.05±0.007 sec. In order to maintain an average uniform speed, these losses must be compensated for in the take-off phase 0.071±0.008 sec long by energy and speed corresponding to 155±32 J and 0.195±0.09 m/sec (as determined in studies with 98 sprinters).

From Figure 1 it is very clear that the basic shock-absorbing function is carried out by the ankle joint. Why? Simply because the shock-absorbing decrease in the angle of the knee joint is significantly less than that in the ankle joint (4° as against 38°). As a result, the extreme negative force (eccentric) of the extensor muscles of the knee joint is 8% of the negative force of the foot plantar flexors (679vt against 8411). When this happens, 227 J are expended on muscle lengthening while only 16 J is expended on stretching the extensor muscles of the knee joint.



Thus, if the ankle joint and the plantar flexor muscles are the main ones in the braking phase, then is it obvious that they must also be the main ones during take-off? Actually, this is the case. During take-off, external energy increases by 340 J. If the knee joint muscles do only 31 J of work, then the foot plantar flexors do 192 J, or more than 6 times as much. Therefore, the main driving link in running with maximum sustained speed is the foot.

What, then, is the role of the hip joint? In the take-off with steady running speed, the hip joint of the support leg does not take an active part since contraction of the extensor muscles ends at the moment the support leg becomes vertical. After this, the hip flexor muscles work in a yielding (eccentric) regime. (Figure 1) During the starting acceleration in the second half of the support period, the same phenomenon is observed. Thus, the eccentric work of the hip flexor muscles of the support leg is necessary in the take-off phase to keep the trunk from dropping backwards. Also, the preliminary stretching (tension) of these muscles strengthens the forward carry of the thigh after the take-off.

Now for the second problem concerning extension of the support leg in the push-off. Resolution of this problem exceeded all expectations. It seems that the anatomic structure of the knee joint is such that when the leg is extended from 164-168 to 180°, the distance between the hip and ankle joints is not only not increased, but is even decreased by 8 mm. This occurs with the roll of the joint surface of the tibia on the part of the joint surface of the femur which has a greater radius of curvature (when seen from the side). Thus, extension of the leg in the knee joint from 164-168° to its full capacity is a useless movement since it does not lengthen the leg as a biokinematic link during the push-off phase. For this reason, the angle in the knee joint at the end of take-off in running at maximum speed should not exceed $165 \pm 8°$.

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(Continuation from Volume 19, Number 1)

Now we will examine the power of the take-off. Leaving the starting blocks leaves no room for doubt. The less the time for push-off, the more powerful it is, and the greater is the speed of take-off, which in a number of cases, reaches 3.5 m/sec. In subsequent strides, running speed increases due to an increase in average power of take-off and stride length with a decrease in take-off time (total stride time does not decrease).

Thus, Borzov (1978) is right in advising runners not to "hurry in the first strides during starting acceleration." This conclusion refers to the individual share of each running stride. It is a different matter if we compare the starting acceleration of various sprinters at the third stride. Why at the third? Because at the end of this stride, after 0.8-1.1 sec from the beginning of movement in the starting blocks, there is maximum external work done in the longitudinal direction per unit of time over a unit of track distance.

Also, with this stride, the main quantitative difference in power production shows up between highly qualified sprinters and all others. Our studies (68 sprinters) showed that at the third stride those who stand out develop the highest stride frequency, take-off with greater force, spend less time in support and accomplish more significant work during the stride.

Stride length in itself is not an informative index. Thus, every single push-off in the starting acceleration must be as powerful as possible. The force of the push-off can serve as an informative index in a comparison of various sprinters or in repeated testing of a single athlete during an extended period.

In going over to a biomechanical analysis of running over the distance, we expected similar results (107 sprinters running at maximum speed participated in the study). The force of the push-off, however, both in absolute and per 1 kg of sprinter mass, had an extremely low correlation with running speed. A case was even recorded where a member of the national team developed less power than a Class II runner! What was going on?

Naturally, at the beginning we did not believe the data and placed all the "blame" on the tensiometric platform (true frequency was only 60 hz). It became necessary to repeat the tests using a tension platform (force plate) which had high metrological qualities (frequency not less than 200 hz). However, the results were the same as before.

It was at this point that we recalled the comparison of running at maximum speed and jump running. We remembered and hypothesized: Can it be that in running it is not that important to have a very forceful drive of the body in single take-offs? Can it be that the resultant speed is summarily determined by a series of take-offs in a unit of time and that the push-offs are not as powerful as they are more frequent? If this is so, then this informative indice (speed) should be served by the power of the take-off multiplied by stride frequency. It was shown that this was the case. In other words, running speed is determined by the optimal combination of power and stride frequency.

Besides this, it was shown that when there is an increase in running speed, there is a decrease in the angle of flight of the CG, the dependence of which is almost functional. For this reason, running with very powerful take-offs but with long stride time and, consequently, a large angle of flight, is not favorable. The sprinter "hovers" in the air longer than necessary. Instead of this, he should quickly begin the next push-off.

After revealing similar relationships, we returned to evaluate the starting acceleration. In this case, the power of the push-off multiplied by stride frequency had greater informativeness than before. The final conclusion was that in the starting acceleration a high stride frequency and a very powerful push-off are necessary.

A question arises: In evaluating running speed, why did we not use an indice such as external work executed in the horizontal direction during the stride time? This indice is frequently mentioned in scientific research. It appeared, however, that with strict inter-individual analyses this indice is not sufficiently informative.

How do the biomechanics of the push-off change before the finish, as for example, in the 400m run? The influence of fatigue is expressed first of all with a significant decrease in the power of the take-off and work executed during stride time. This leads to a drop in running speed: Stride frequency decreases primarily due to an increase in support time. Because of this, its relationship to flight time (coefficient of running activeness) significantly decreases from 1.076-0.09 to 0.951-0.08.

An increase in flight time leads to an increase in the angle of take-off. The force of the braking, stride length and work when calculated according to units over the race track decreases but is not statistically significant. However, during the run to the finish the most informative indice of the interaction with support is mean power of the take-off multiplied by stride frequency. It decreased from 113.8-24.3 wt/kg/sec to 57.7-31.3 wt/kg/sec.

Thus, some basic results: 1) The start and the first steps of the beginning acceleration are provided for basically by the overcoming (concentric) work of the muscles of the support leg. All the joints make approximately the same contribution in accelerating the body.

2) In running with maximum speed, the ankle joint appears to be the main amortizer and mover of the body. The support leg muscles work in the eccentric-concentric regime. One of the main factors of the push-off is the spring-like properties of the foot.

3) In the concluding portion of the race, the limiting factor of running speed is fatigue of the hip joint muscles, especially the flexors. As a result, the slower speed of bringing the swing leg forward leads to decreased preliminary stretching of the muscles, especially the plantar flexors of the foot, which decreases power of the push-off.

4) One of the basic criterions of running speed over the entire distance appears to be the product of stride frequency on mean power of take-off.

5) Extension of the support leg in the knee joint should be no more than 165°.

We will now go into the bases for selecting specialized exercises. Before giving recommendations, however, it is first necessary to understand the work regime of the major muscles used in running at one or another portion of the short distances.

Starting movement is made possible by the concentric work of the leg muscles. On the successive strides of the beginning acceleration, the support leg muscles continue working in the concentric contraction regime but they now begin to make use of preliminary stretching. Approximately with the 5-7th stride, according to the degree of body straightening and placement of the foot further in front of the projection of the CG, the phase of amortization appears with its inescapable loss of speed and external energy. This leads to amortization in the knee joint and to a further increase in the ankle joints' angles.

From here we derive a principle for selection of exercises. They must have a concentric muscle work regime within the working range of the joint angles which correspond to a certain segment of the starting acceleration.

After moving into maximum running speed, external work executed during stride time substantially decreases. At this moment, the metabolic sources of energy in the muscles are mostly exhausted. However, the external power of the push-off not only does not decrease, but even increases. This means that in running with maximum speed, supplementary and other non-metabolic sources of energy are used. Which?

The same mechanical energy of the sprinter's body which, in the phase of amortization, leads to stretching of tensed muscles, and which gives them a supply of energy in the form of resilient deformation. In the take-off phase, it again returns to mechanical energy strengthening the contraction of the muscles (this phenomenon was given the name energy recuperation).

The main group of muscles which accumulate external energy are the ankle joint extensors (plantar flexors). According to our data, the gastrocnemious muscle stretches 3-4 cm during this action. To do this, the amortizational decrease in the ankle joint must be 33.4-7°. This means that a faster run is possible with greater stretching of the ankle joint extensor muscles. Thus, a loss of external energy (and speed) in the phase of amortization is not necessraily an "unfavorable" thing. Without them, it is simply impossible to have preliminary stretching of the muscles which strengthen the push-off and increase running economy.

And now for the most interesting. According to data in the literature, the tendon portion of the triceps surae muscle accumulates 75-90% mechanical energy which is absorbed by the entire muscle. In other words, the belly of the muscle works almost in an isometric regime and lengthens mainly in the Achilles tendon.

From here, we have an extremely important conclusion for practice: It is necessary to improve the spring-like capabilities of the feet by all possible means. The higher the firmness of the muscle (especially its tendon portion), the less will be the diffusion of energy and the greater will be its accumulation, which is necessary for fast running. It is mainly because of this that the firmness of the triceps surae muscles in sprinters should be higher than in track athletes specializing in other events.

Five to six seconds after beginning the run, exhaustion of the metabolic sources of energy reserves is already completed. There is appearance of the fatigue factor and a decrease in running speed. Because of this, most important in practice is determination of the most vulnerable muscle group, which when fatigued, leads to a drop in running speed. Such "fine" links are the muscles surrounding the hip joints. They are the most power-consuming muscles.

Here is one example. Full mechanical work accomplished by the hip joint muscles in one running cycle is equal to 455 joules. At the same time, for the knee and ankle joints during the period of support, mechanical work is equal to 31 and 192 joules, respectively. During the forward carry of the knee joint, almost all the work time is in the eccentric regime. (Figure 1) It is known that in doing this, muscles expend approximately three times less energy than in the concentric work regime. In the forward carry, the ankle joint muscles work very little.

Besides this, the maximum energy recuperation possible in the hip joint is relatively less than in the distal joints. If the hip joint muscles during their stretching in the running cycle can accumulate 20% mechanical energy, the extensor muscles of the knee and ankle joints during support, accumulate about 50 and 100%, respectively. This means that the muscles in the hip joint work mainly from the metabolic sources of energy and tire earlier than the others.

What happens in fatigue? Our pictures of the 200m run showed the following: Running speed decreased from 9.05 to 7.19 m/sec and stride frequency from 4.68 to 3.55 strides/sec. Mean speed of thigh (hip) flexion at the beginning of the run was equal to 8.32 radians per sec and at the end, it decreased by 25%. Amortization in the ankle joint decreased from 20-35° and in the knee joint, from 11 to 1°!

Thus, stretching of the extensor muscles of the knee joint and ankle joint became less. As amortization time increased, speed of knee joint angle decrease dropped from 3.9-0.4 radians/sec and in the ankle joint, from 13.6-7.1 radians/sec. This quickly led to a worse push-off since the range of the increased angle in the ankle joint decreased from 52-46°.

It is characteristic that a supplementary mechanism to fatigue is expressed in increased extension in the knee joint from 24-28°. When this occurs (with the almost complete disappearance of amortization of the knee joint extensor muscles of the support leg) the extensors begin to work in the concentric regime.

This means that fatigue of the hip joint flexor muscles has an effect, making the biomechanical conditions of the take-off worse. It decreases amortization in the distal joints and the preliminary stretching of the muscles. This is an unfavorable condition for using the resilient properties of the muscles. From here we have a conclusion: Together with strengthening of the foot muscles, major attention should be given to developing local speed endurance of the hip joint muscles, mainly the flexors.

We will not carry out a repeat of the specialized exercises available from the rich contemporary arsenal of exercises. This depends on the creativity of each coach who can determine the most "lagging" portion of physical and technical preparation of each sprinter. It is important to only remember the principles of running technique and the muscle work regimes for the different distances. When this is known, specialized exercises which correspond closely can be selected.

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