OPTIMIZATION OF THE KINEMATIC CHAIN IN HUMAN MOVEMENT AS IT RELATES TO TRAINING

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The theory of the kinematic chains which was first referred by Beyer in 1925, was mostly supported by Bernstein. It starts from the relationship that exists between "the total" and its separate links, as this relationship is appearing in such an obvious way in the biological organisms.

These mechanical movements of the biological system are significantly limited, if besides their mechanical determination, they are also determined biologically, as well as in relation with the purpose of the movements of the above system, in such a way that they lead to the creation of a new quality of movements.

DEFINITION OF THE KINEMATIC CHAIN

Hochmuth defines the kinematic chain as " a system in motion consisted of separate links which are connected by joints", while Donskoi determines it as " the one after the other or the branched joints of a series of kinematic pairs".

According to our opinion both definitions are not biomechanically sufficient to characterise the function of the biokinematic chains.

Both writers do not refer to the drive systems of the kinematic chains. And we all know that the kinematic chains are not activated by external forces, but by the drive systems of the chain itself.

For this reason we would like to refer to the following definition, which according to our opinion, characterises in a better way the kinematic chain."Kinematic or bio-kinematic chain is called a self-moving (biologically) system consisted of kinematic units. Each kinematic unit has two links which are connected with a joint and are moving by (muscular) self-acting drive systems".

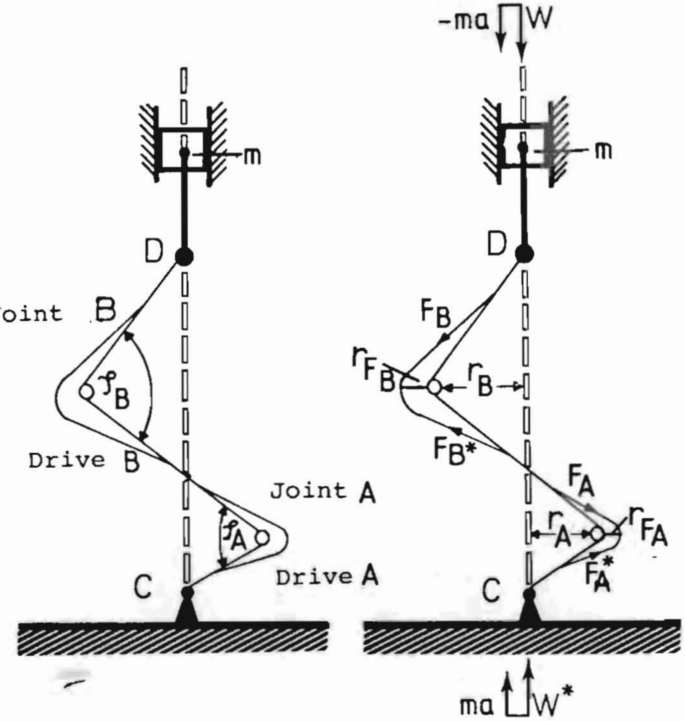


Figure 1. Mechanical model of a biokinematic chain.

ACTION OF THE KINEMATIC CHAIN

If someone wishes to comprehend the rules,wnich determine the mode of action (coordination) of the kinematic chains and consequently the coordination of the whole system, must,first of all, investigate the biological and mechanical conditions, as well as the functional relationships of the system.

From what has already been stated, we come to the conclusion that,for our Science, it is indispensable to investigate the structural particularities of the kinematic chain, their mutual functional influence and interdependence, as well as the influence exerted by Sports training.

The purpose of the present study is the investigation of the bio-kinematic chain mode of action of the lower extremities and specifically the mutual influence of the kinematic units in the kinematic chain, during the performance of a vertical jump without introductive movement under laboratory conditions.

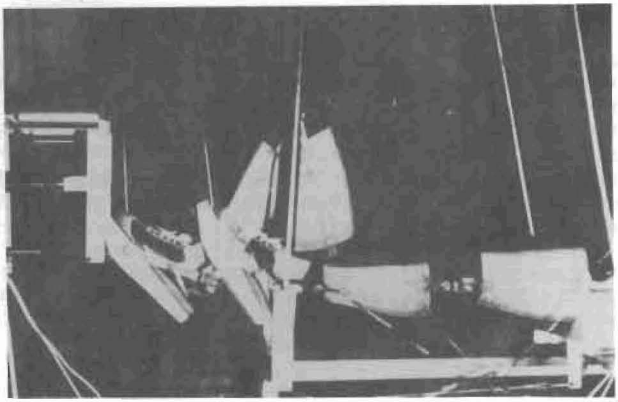


Figure 2. Methodology to determine the acceleration work for the separate and linkaged modes of action of the biokinematic chain.

MECHANICAL MODELS OF THE BIO-KINEMATIC CHAIN

An observation of the functional conditions in a simplified mechanical model of the lower extremities kinematic chain, can easily show the interdependence of two kinematic units as well as the mutual influence of the internal (torques of force) and external (torques of loading) forces.

In figure 1 we can see the structure of a mechanical model, which is composed of the kinematic units A and B. The joint of these units have only one rotatory degree of freedom around the transverse axis, so that the drive systems of the chain are able to cause the transposition of the angles φA and φB from 0^{o} to 180^{o}. The weight W of the mass m acts vertically on the joint A, in the distance rA (resisting arms A), while on the joint B it acts in a distance rB (resisting arms B) and it causes the torques (torques of load).

The drive systems of joints A and B act vertically on the rotation axis, in the distances rA and rB (force arms) respectively and they cause the torques (force torques) FA · rFA and FB · rFB which have an opposit direction from that of the load torques.

The purpose of the action of the kinematic chain has, in any occasion, to be the attainment of the largest possible value of the vertical final velocity. From the view of Biomechanics this means that in relation with the resistance of the environment, the largest amount of mechanical work acceleration must be developed. The relationship between the work acceleration and the increase of the amount of the energy is given by the following equation:

$$\text{Fav} \cdot \text{Sa} = \frac{m}{2} \cdot (V_2^2 - V_1^2)$$

According to this equation the two factors the Fav and the acceleration distance Sa are equivalent. This equivalence exists in fact only when Fav is independed from the acceleration distance, which means that the acceleration distance does not lower the force.

The acceleration distance of the kinematic chain is determined by the bending of the separate links of the chain in the joints. When the angles φA and φB become smaller, the acceleration distance of the kinematic chain is respectively increasing. Also the resisting torque of each joint is depended upon the bending position of the parts chain. Consequently, there is a relationship between the acceleration distance and the resisting torque.

An interdependence of the dynamic influence among the units of the kinematic chain should be also noted. Both kinematic units (A and B) can not (according to action and reaction) develop or transmit acceleration torques independently.

It is important to know how the separate kinematic units of the kinematic chain correspond to the development of an acceleration torque.

In the above case we have the following dynamic equilibrium conditions:

Kinematic Unit B:

$$(m \cdot a + B) \cdot rB = FB \cdot rFB \qquad \text{and}$$

Kinematic Unit A:

$$(m \cdot a + B) \cdot rA = FA \cdot rFA$$

From the above equation we can assume the equilibrium conditions of the kinematic units A and B as follows:

$$\frac{FB \cdot rFB}{rB} = \frac{FA \cdot rFA}{rA}$$

It is obvious that in order to set the kinematic chain in action the quotient of the force torque ($FB \cdot rFB$) of the drive system B and the arm torque rB of the joint B must be equal to the quotient fo the force torque ($FA \cdot rFA$) of the drive system A and the arm torque rA of the joint A. So, it can be concluded that among the force torque (developed by the drive systems and the relative load arms of the kinematic chain) the following relationship exists:

$$\frac{rA}{rB} = \frac{FA \cdot rFA}{FB \cdot rFB}$$

It is apparent that the analogy of the load arms is equal to the analogy of the force torques:

$$rA : rB = FA \cdot rFA : FB \cdot rFB$$

when i.e. the analogy of the arms ($rA:rB$) is changing the analogy of the torques $FA \cdot rFA : FB \cdot rFB$, namely the acceleration torque, must change accordingly. So, there is an interdependence among the separate kinematic units when the kinematic chain is in action.

Consequently, the kinematic chain under examination, can transmit on the point C only the acceleration torques that the weakest kinematic unit of the chain can develop.

If we assume that the kinematic units of the chain are able to develop equal torques of force ($FA \cdot rFA = FB \cdot rFB$) during the acceleration distance hat mas m covers, the arm torques must behave accordingly, in other words they always have the same value.

But the hypothesis $rA=rB$ is not realizable during the whole acceleration distance, because of the geometrical order of the links of the drawn kinematic hain. That means that only a concrete part of the acceleration distance should be utilized. And that is the part that secures the hypothesis $rA=rB$. So, it is generally acceptable that, under these circumstances, the kinematic chain could never produce a maximal acceleration work.

On the contrary, if we suppose that the kinematic unit B develops higher force torques than the kinematic unit A, namely :

$$FB \cdot rFB > FA \cdot rFA$$

then the unit B will determine the value of the acceleration torques, pressuposing that the load arms rA and rB are equal in every single moment of the motion.

So, considering that the kinematic units have a different potential ($FB \cdot rFB \neq FA \cdot rFA$) we ask how a kinematic chain must act in order to produce the maximal possible acceleration work and which are the conditions that the kinematic system of the chain must follow in order to achieve its goal.

In that case, the kinematic chain of the figure has the following two possibilities of action:

1. To transform the load torques, which act contrary to the acceleration torques in such a way that the kinematic units of the chain be able to develop acceleration torques of the same value. That is to say to reduce the load torques for the weakest kinematic chain(A)and increase them for the strongest one(B).The most extreme case is noted when the carrier of the acceleration force goes through the joint A and consequently the load arm rA of the kinematic unit A is zeroed.
2. To place a mechanism of stabilization in the weakest kinematic unit A (block of the joint) in such a way that the strongest kinematic unit (B) can produce the maximal possible torques of the force, in the minimum possible load torques, without causing any trouble to the function of the kinematic unit A.

It is apparent that this second case is more appropriate for the fulfilment of the aim of the action, because the "block of the joint" helps, as we have already said, the kinematic chain to develop the maximal possible force torques,in the minimum possible load torques, without exerting a significant influence on the production of the acceleration work of the kinematic unit A.

It is also obvious that the successive order of the dynamic action of chain kinematic units is determined by the potential of the drive systems, namely by the intensity of the forces of the kinematic units. In the first case, the two kinematic units act at the same time, while in the second case they act successively. It should be noted that the stabilized joint with the weakest drive system must transmit the acceleration torques of the strongest kinematic unit, that is to say to produce static work.

From the theoretical analysis of a kinematic chain action, we come to the conclusion that this way of action is depended upon the dynamic conditions of the separate kinematic units, as well as upon the negative influence of the torques which follow the load torques that act contrary to the force torques of the kinematic units.

It can be noted that the conclusion which concern the purposeful action of the kinematic chain cannot be directly applied without taking into consideration the biological conditions of the human kinematic system.

BIOMECHANICAL CONDITIONS AND THE ACTION OF THE BIO-KINEMATIC CHAIN IN THE LOWER EXTREMITIES

For the research of the biomechanical factors which influence the performance of the kiokinematic chain during its action, a methology should be applied which would permit the evaluation of the kinematic units of the chain during both actions: separate and connected (Fig. 2).

We know that in most sports we aim at the realization of "citius- altius - fortius". This from the biomechanics view means that in relation with the enviornmental resistances, the possible amount of the mechanical acceleration work has to be produced.

The two factors, force (F) and acceleration distance (Sa) are equivalent in the production of the acceleration work. The value of the force which in the biokinematic chain is given by the muscle force which is defined by the training conditions of the athlete, while the acceleration distance of the kinematic chain is given by the flexion of the different links of the ankles.

If we examine the muscle system of the kinematic chain of the lower extremities, we will see that the kinematic unit of the knee joint has a much more developed muscle system (drive system) than the one of the ankle joint.

Studies where the kinematic units of the biokinematic chain of the lower extremities have been measured separately, have proved that the knee kinematic unit can exert its maximal acceleration forces (Tsarouchas 1971,1983)(Fig. 3). Figure 4 showsthat the linked mode of action permits the biokinematic chain to reach its maximal performance. This means that the hip and ankle kinematic units have a positive influence upon the performance of the biokinematic chain of the lower extremities because they contribute to the improvement of the acting conditions (reduce the load torques) especially those of the knee kinematic unit.

After examination of the mechanical model of the kinematic chain we came to the theoretical conclusion that the successive

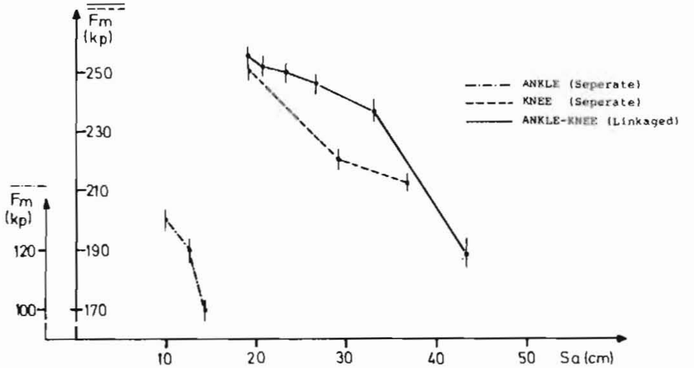


Figure 3. Mean acceleration force (Fm) in different acceleration distances (Sa).

order of the dynamic action of the kinematic units are the most important. We will be able to verify this phenomenon during training.

According to actio and reactio the kinematic unit of the ankle, which is the weakest unit of the chain, must transform the acceleration torques of the stronger kinematic units to the direction of the supporting point. Namely it must produce a proportional work.

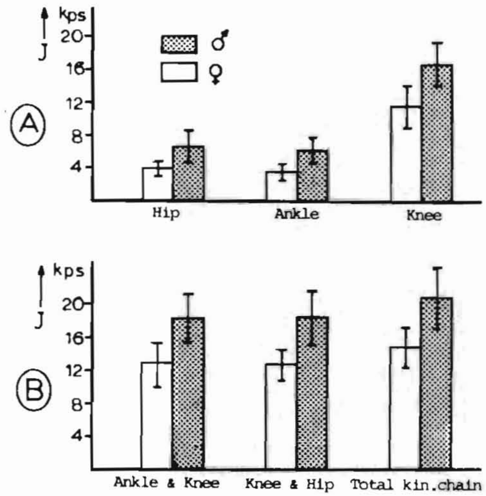


Figure 4. Mean and standard deviations of vertical impulse for the separate (A) and linkaged (B) modes of action of the kinematic chain.

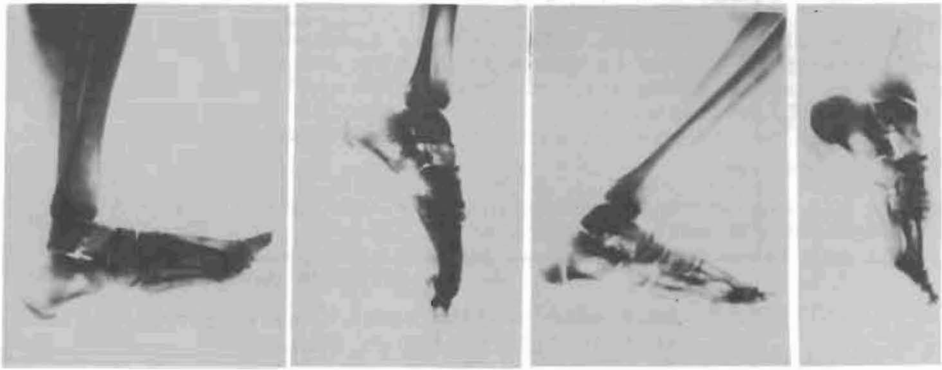


Figure 5. Range of motion of the ankle.
(A-woman , B-man).

A special case, related to the pursued stabilization of the joint, appears in the ankle joint. As the following x-rays plates show, a "block of bones" is created during the bending of the ankle joint (Fig. 5).

The same x-rays plates also show that the range of joint motion differs from man to man. This difference is not due only to the active system (muscle system, ligaments e.t.c.), but also to the anatomy of the skeletal system.

We have already mentioned that from the point of the kinematic units potential, the kinematic unit of the knee is, in comparison with the kinematic unit of the ankle, the basic one. This means that the kinematic unit of the knee is the basic factor in the production of the acceleration work. But in order to ensure this conclusion, the influence of the different kinematic units of the chain upon the total acceleration distance must be examined.

In figure 6 we can see the quantitative contribution of kinematic units of the hip, knee and ankle to the total acceleration distance. The knee kinematic unit can produce 72%, while 17% is produced by the hip kinematic unit and 11% by the ankle unit. So, the knee kinematic unit produces over 70% of the total acceleration distance of the kinematic chain.

It should be noted that although the hip kinematic unit acts on the trunk of the body, which contains more than 50% of the total body mass, only 17% of the total acceleration distance is produced.

The ankle kinematic unit contribution of 11% to the total acceleration distance is impressive. Because the foot length , which in this case is the accelerated segment of the ankle kinematic unit and constitutes the radius of the point of action, is much smaller than the radius of the trunk, which is the accelerated segment of the hip kinematic unit.

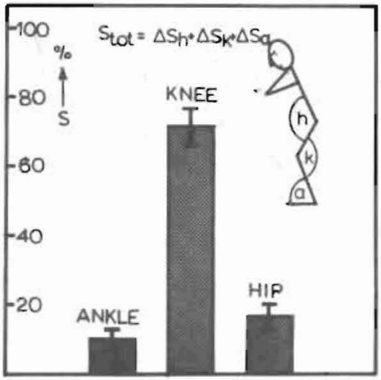


Figure 6. Contribution percent of the different drive systems to the total acceleration distance of the center of gravity.

The proportion of the space that these two accelerated segments take up. namely the foot and the trunk, is 1:4, while their quantitative contribution to the total acceleration distance is 11% nad 17% respectively, that is to say 1:1,5.

It can be concluded that the knee kinematic unit is the main unit of the lower extremities kinematic chain that produces acceleration work. Nevertheless, both kinematic units (hip and ankle) influence the performance of the kinematic chain of the lower extremities, because they both contribute to the improvement of the action conditions (reduce of the load torque e.t.c) mainly of the knee kinematic unit. They also help the funtion of the kinematic chain as a whole.

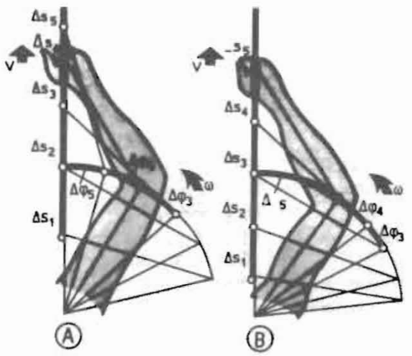


Figure 7. Function process of the linear velocity (V) of the point of action with respect to the angular velocity of the kinematic units during the extension of the kinematic chain of the lower extremity (A-constant angular displacement, B-constant linear displacement) (Donskoi, 1975)

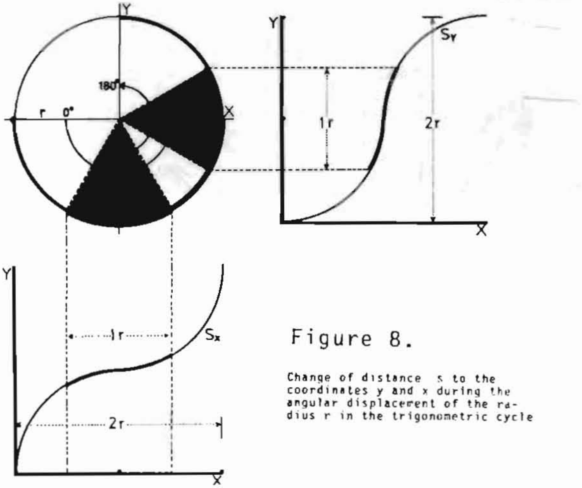


Figure 8.

Change of distance s to the coordinates y and x during the angular displacement of the radius r in the trigonometric cycle

INFLUENCE EXERTED ON THE ACTION OF THE BIO-KINEMATIC CHAIN BY THE GEOMETRICAL ORDER OF THE CHAIN LINKS

The movements of the links in the chain joints can be considered as rotatory ones. For this reason, in a movement of a link we must distinguish the angular velocity of this link from the linear velocity of its point of action. For the kinematic chain, the point of action is determined as the point of contact of two successive links, while for the biokinematic chain, the points of action are usually localized on the joints, which connect the neighbouring chain links.

Due to the fact that the linear velocities of the points of action, are not relative to the angular velocities of the links around the joints, i.e. in the extension of the biokinematic chain of the upper extremities,with two links, where the first link is moving with a steady angular velocity (ω), the linear velocity (v) of the point of action is reduced (Figure 7).

That means that in order to achieve a steady linear velocity (v) a high increase of the angular velocity (ω) is necessary, because the relationship between the linear and the angular displacement in a regular rotatory movement of the points of action of the links is determined by the following equation:

$$\Delta s = r.\sin\varphi$$

where Δs = linear acceleration distance
r = the length of the rotatory link, namely the radius of the cycle and
φ = the angular displacement of the accelerated link of the chain

For a better comprehension of the above relationship we examine a regular rotatory movement of a point of action of the chain in the trigonometric cycle (Fig. 8).

In the case of the vertical displacement (Δs)of the point of action , we are examining only the range of the angular displacement , from the lowest to the highest place ($0°-180°$). In other words we are examining the linear displacement Δs of the point of action on the axis y.

We observe that the more the point of action is getting closer to the horizontal axis x, the more the displacement of Δs becomes longer (in proportional sections of angular displacements), while the more it gets closer to the axis y, the more the increase of Δs is getting smaller. That means that, with a constant contractive velocity of the muscle and consequently a constant angular velocity of the link, different linear velocities of the point of action are achieved. Thus, the area of the angular displacement around the axis x is considered as the ideal area of the cycle for the linear displacement, in other words for the increase of the linear velocity.

So it is proved that the relationship between the angular and the linear displacement is generally influenced by the geometry of the motion.

The following example shows the geometrical order of the links of a biokinematic chain of the lower extremities during a vertical jump (Fig. 9).

In the case that every link of the chain can move independently from all the others, with a steady angular velocity, the angular displacement $\Delta\varphi$ is the same for each of the above links. On the contrary, for the linear angular displacement of the links we notice different values. F.i. for the links which are found in the horizontal axis x (links1,3)we notice high , while for the links near the vertical axis y (links2,4)low changes, because Δs is changing according to the sine of the angle ω.

In a simultaneous motion of the links 3 and 4 and under the condition that the contractive velocity of the kinematic units, during the extension remains the same, the point of action of link 3 overtakes link 4, because it covers a longer vertical distance Δs, that is it is moving with a higher vertical velocity, wich results in prevention of the extension of the link 3. In other words, an opposit movement is caused between the two links (3 and 4), something that in Sports everyday practice should be avoided because it diminishes the final result. So, it is clear that the movements of kinematic chain links are also determined by their geometrical order.

Reffering to the geometry of the link movements, we have come to the conclusion that in the vertical displacement the advantageous links are those which act around the horizontal axis, while in the horizontal displacement, those which act around the vertical axis. However regarding the vertical movement it is noticeable that in that position which from geometrical point of view has been characterized as advantageous, higher load torques appear (from the dynamical point of view the same position is interior). For this reason in the case of the vertical movement the application of the above conclusion should be conducted carefully and specificly. On the other hand in the horizontal movement the above conclusion could be indispensably applied and the purposeful athletic technique could be adapted to it.

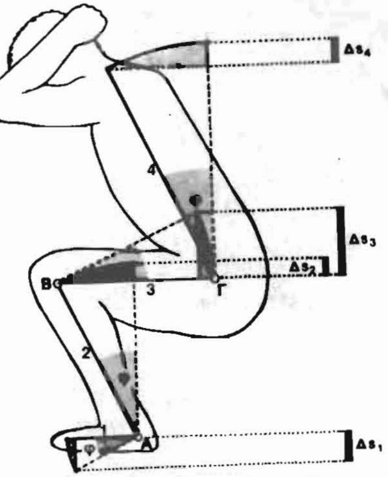


Figure 9. Part acceleration distance (Δs) of the biokinematic chain of the lower extremities with constant angular displacement.

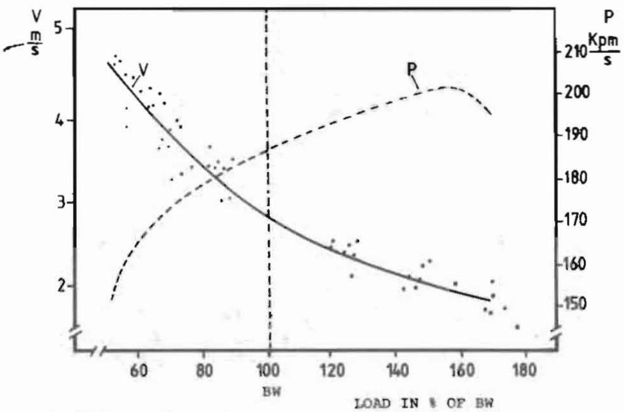


Figure 10. The velocity and the mechanical power output of vertical jumping as a function of load in percent of body weight.

Finally, the general conclusion can be drawn that the effective links movements are those whose point of action is found around the axis (level) which is vertical to the main direction of the body movement.

The chain mode of action must also depend upon the purpose of the motion, because this purpose determines the geometrical order of the chain links.

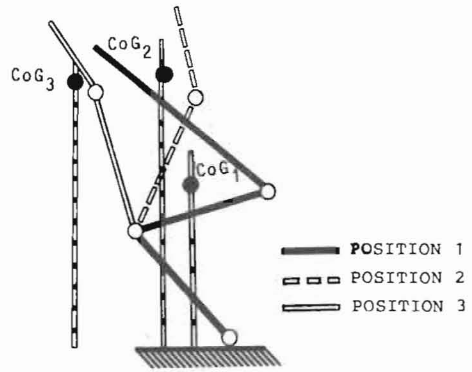
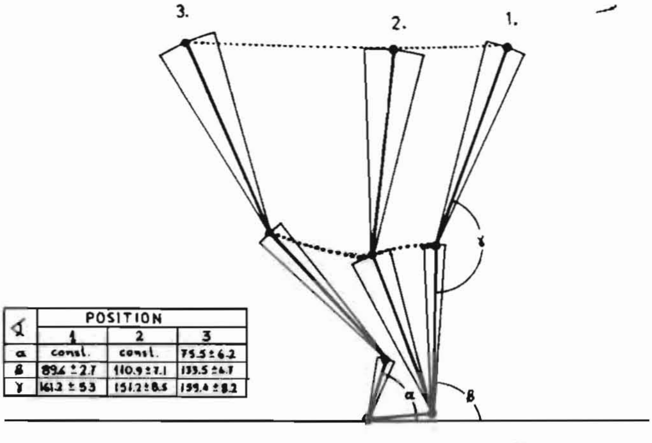


Figure 11.Position of the CoG of different joints angles.

In the example of the figure 10 the purpose of the kinematic chain must be the vertical acceleration of the body Center of Gravity. Thus the chain mode of action of the lower extremities is determined by the body equilibrium conditions. For this reason the movements of the kinematic units must be performed in such a way that the carrier of the resulting muscle force which is applied in the Center of Gravity always passes through the supporting point.

Finally, the purpose of a movement in general nad especially the purpose of a movement in Sports, namely the athletic technique, forces the biokinematic system of man to act in a concrete way.



∢	POSITION		
	1	2	3
α	const.	const.	75.5 ± 6.2
β	89.6 ± 2.7	110.9 ± 7.1	133.5 ± 6.7
γ	161.2 ± 5.3	151.2 ± 8.5	159.4 ± 8.2

Figure 12.The mean values of three geometrical positions of twelve sprinters in different links of the biokinematic chain.

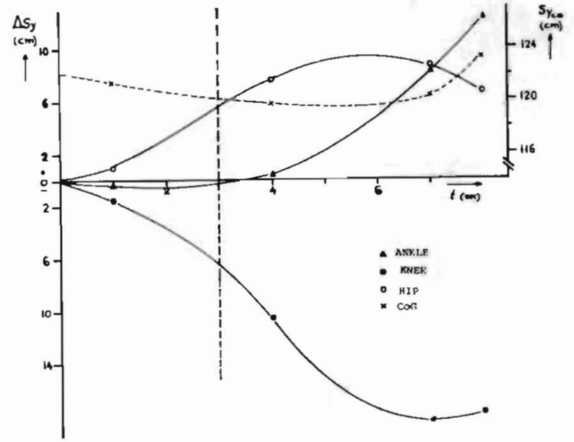


Figure 13. Differences of vertical distance of CoG and various links of the lower extremity biokinematic chain for a sprinter.

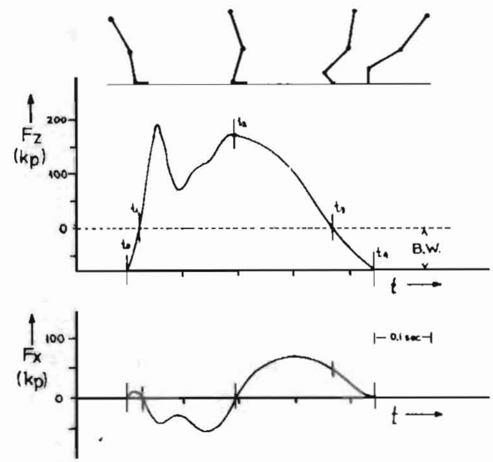


Figure 14. The F-t-diagram for the vertical (Fz) and horizontal (Fx) forces in a take off phase of a sprinter.

The amount of force and power that a muscle can develop, depends not only on its histochemical properties but also on its mechanical ones. One of the most fundamental dynamic properties of skeletal muscle is the force-velocity relation, which was first established by A.V. Hill in isolated muscle (Hill, 1938). This relation has also been confirmed for intact human muscles (Cavagna, 1968; Dern, 1947; Komi, 1971; Wikki, 1950).

Figure 11 presents the individual as well as mean values of the take-off velocity of vertical jumps at different loads. It also depicts the product of velocity and load, which is power. It is apparent that the load-velocity relationship, obtained from a total body movement and used in the kinematic chain of lower extremities, has the same pattern as desctribed previously for the mammalian muscle.

It evident that there is a wide range of movements over which the kinematic chain of the lower extremities can produce power close to maximal levels. This slow rate of power increase may be explained by the biomechanical conditions in the kinematic chain (see figure 3).

The maximal velocity of the moving body is the result of the application of the acceleration forces, which are produced by the shortening of the muscles. The velocity of shortening is propor - tional to the angular velocity of the drive system. Therefore there is an interdependence between the geometrical order of the links of kinematic chain and the shortening velocity of the muscle. For this reason we believe that the mode of action of the biokinematic chain must influence the output of energy of the muscle system. The first results from the studies that have been carried out in our research institute have convinced us that the output of energy is influenced by the mode of action of the chain (Tsopanakis et al 1982; Tsarouchas et al 1981,1982).

THE PERFORMANCE OBJECTIVE AND THE BIO-KINEMATIC CHAIN

The general purpose of the athletic technique of a runner is to run a determined distance in the shorter possible time. From the Biomechanical point of view this means that the runner must perform the purposeful athletic technique which will help him to obtain during take off and thus during landing,either the maximal possible horizontal average velocity (Vxav) or the minimum possible vertical velocity (Vymin).

In order to evaluate the sprinter technique we examine the course of the Center of Gravity. However such an analysis gives us only the result of the whole body motion, without the causes of this result. After studies on the mode of action of the biokinematic chain of the lower extremities we have come to some conclusions regarding the quality of the technique as well as the level of the athletes physical conditions.

Figure 12 shows the mean average of the geometrical order of the kinematic chain links in the three main positions of the supporting phase, which have been determined by measuring 15 sprinters.

It can be seen that during the supporting phase all the links of the chain except the lower leg do not significantly change the position between them. It is apparent that the whole body of the sprinter is starting its rotation,first around the ankle joint , up to a certain point after which it continous rotating around the supporting point of the ball of the foot. In spite of the fact that the body is continously rotating forward, the curve of the point of action of the hip does not change accordingly. As seen when setting in balance by the separate movements of the other links of the chain it remains almost regular. It can also be noticed the important role that the ankle kinematic unit plays and especially the link of the foot that influences significantly the course of the whole body (Fig. 13).

The rate of the horizontal delay is influenced by the order of the ankle kinematic unit links during the landing of the athletes. The more the link of the lower leg is placed in front of the vertical position, the more energy must be consumed for the elevation of the point of action of the lower leg. This results in the reduction of the horizontal velocity of the body, because the whole body is following the motion of the lower leg, during this phase. This means that the duration of the supporting phase increases and thus the step frequence is reduced.

CONCLUSIONS

From the present study it has become obvious that the forces of the separate kinematic units of the biokinematic chains have a functional interdependence.

The knee drive system is the most important factor for the production of the acceleration work. For this reason we consider it the main drive system of the biokinematic chain of the lower extremities.

However, the mode of action of the total biokinematic chain is the best action to produce acceleration work, because the hip and ankle kinematic units have presumably a positive influence and optimise the torque and balance during the action of the link drive system.

Generally, the kinematic chain can develop only as much acceleration force as can be produced by the weakest drive system. Thus the functional capacity of the biokinematic chain is depended on the condition of the function of each drive system in the biokinematic chain.

Accordingly in order to improve the functional capacity of the biokinematic chain one must improve the condition of the muscle function through muscle force training. The muscle force training must be carried out in such a way that all the kinematic units obtain the functional capacity which is in accordance with the goal of the movement namely with the purposeful sports technique. Thus the investigation of each kinematic unit individually is an important method for determining quantitative results which can be used to increase the overall functional capacity of the biokinematic chain.

The kinematic chain and the whole kinematic moving system constitute a functional unit. The above point of view shall give the opportunity to well understand the function of the human kinematic moving system.

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