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# BIOMECHANICAL ASPECTS OF PERTHES DISEASE (MATHEMATICAL MODELING)

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A geometric model with muscles functionally related to the hip joint was created. We studied the effect of muscles on the vector of the net effect when changing the position of the limb: passive lifting and adduction. During passive hip flexion, stretching occurred in gracilis, adductor magnus, gluteus maximus, biceps femoris, semitendinosus, semimembranosus. The net force vector initially decreases, and at maximum bending it increases. When increasing the effort of muscles m. gluteus maximus – the angle of co-action is reduced, and m. gracilis, adductor magnus, biceps femoris, semitendinosus, semimembranosus –is increased.

Adduction of the lower limb leads to passive stretching of the muscles: mm. rectus femoris, gluteus medius, gluteus minimus, tensor fascia latae, biceps femoris, semitendinosus, semimembranosus. The greatest elongation is determined in m. tensor fasciae latae, and the greatest efforts were found in m. gluteus medius. With simultaneous bending and adduction of the lower extremity, mm gracilis, adductor magnus, gluteus maximus, gluteus medius, tensor fasciate latae, biceps femoris, semitendinosus were subjected to passive stretching, which causes an even greater deviation of the resultant force vector from the normal than when the limb is flexed or adducted.

**Key words:** Perthes disease, hip joint, muscles, modeling

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## БІОМЕХАНІЧНІ АСПЕКТИ ХВОРОБИ ПЕРТЕСА (МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ)

Створена геометрична модель з м'язами, що функціонально пов'язані з кульшовим суглобом. Вивчали вплив м'язів на вектор рівнодіючої при зміні положення кінцівки: пасивного підняття та приведення. При пасивному згинанні стегна розтягування відбувалося у gracilis, adductor magnus, gluteus maximus, biceps femoris, semitendinosus, semimembranosus. Вектор рівнодіючої сили спочатку зменшується, а при максимальному згинанні – збільшується. При збільшенні зусиль м'язів m. gluteus maximus – зменшують кут рівнодіючої, а m m. gracilis, adductor magnus, biceps femoris, semitendinosus, semimembranosus – збільшують. Приведення нижньої кінцівки веде до пасивного розтягнення м'язів: mm. rectus femoris, gluteus medius, gluteus minimus, tensor fasciate latae, biceps femoris, semitendinosus, semimembranosus. Найбільше подовження визначається в m. tensor fasciae latae, а найбільші зусилля виявилися в m. gluteus medius. При одночасному згинанні і приведенні нижньої кінцівки пасивному розтягуванню піддалися mm. gracilis, adductor magnus, gluteus maximus, gluteus medius, tensor fasciate latae, biceps femoris, semitendinosus, що спричиняє ще більше відхилення вектору результуючої сили від нормалі, ніж при згинанні або приведенні кінцівки.

**Ключові слова:** хвороба Пертеса, кульшовий суглоб, м'язи, моделювання

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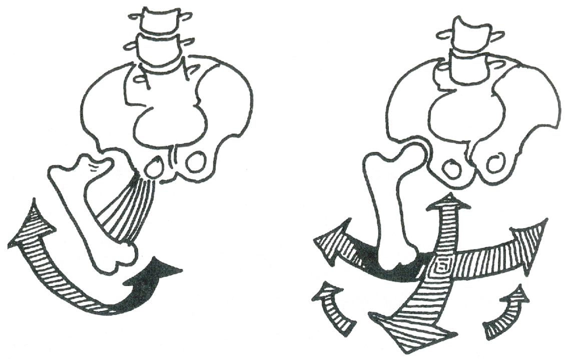
Legg-Calve-Perthes disease (LCPD) is a severe and long-term orthopedic disease of the hip joint (HJ) of childhood, which often ends with the development of early coxarthrosis and disability [6, 7, 9].

One of the early manifestations of the complicated course of Perthes' disease is the limitation of rotational movements followed by the development of flexion-adduction intra-rotator contracture of the HJ [6]. Such a position of the hip, in the conditions of reduced mechanical strength of the femoral head (FH) in LCPD, "contributes" to the formation of the deformation of the IRCHJ, which develops gradually and is not accompanied by a pronounced pain syndrome at the stages of formation (Fig. 1 A, B, C).
Previously performed biomechanical studies on the finite-element model of the HJ permitted to study the stress-strain state of the joint components in cases of different localization of the destruction of the femoral head due to LCPD with damage from 25 % to 75 % of its volume [1, 2, 10].

One of the components of the surgical treatment of the complicated course of LCPD is soft tissue decompression of the HJ, which includes adductor myotomy, subspinal myotomy, Z-shaped decompressive plastic of the broad fascia of the thigh on the lateral surface of the HJ, lengthening of the tendon of the iliopsoas muscle in the area of the trochantin [5, 9, 11], etc. These soft tissue interventions are often performed empirically, based on clinical data and the experience and intuition of the surgeon, without sufficient biomechanical justification.



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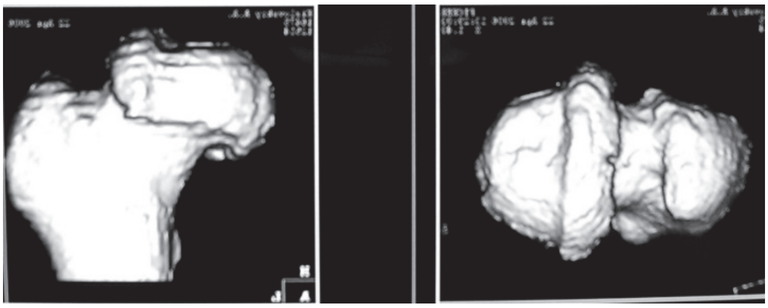


C

Fig. 1. A – scheme of movements in the HJ in normal conditions and under the condition of the development of flexion-adduction contracture of the joint and the formation of deformation of the HJH; B – a photoprint of a radiograph of the right CS with LCPD in the stage of an impression fracture with the formation of a deformation of the HJH, the area of its lesion is 75 %; C – computer tomogram: 3D reconstruction of the right HJ of the same patient: pronounced saddle-shaped deformation of the HJ is determined (photographs from our own archive).

At the same time, at the current stage of the development of orthopedics as a science, great importance is attached to the mathematical modeling of HJ: biomechanical characteristics in the "pelvis-thigh" system in congenital hip dislocation, aseptic necrosis of HJH in adults have been studied in detail [6, 9, 11]. One of the promising directions for obtaining new knowledge and substantiating the methods of surgical treatment of Perthes' disease is the application of biomechanical modeling using the grapho-analytical method.

**The purpose** of the study was to investigate the influence of passive muscle efforts and anatomical features on the deviation of the net force vector in the hip joint in Perthes' disease. with the help of the created grapho-mathematical model.

**Materials and methods.** A geometric model was created in the biomechanics laboratory of the State University "Sytenko Institute of Spine and Joint Pathology National Academy of Medical Sciences of Ukraine" in which the attachment points of the muscles functionally related to the HJ are coordinated [2] (diagram of the geometric model presented in Fig. 2.)

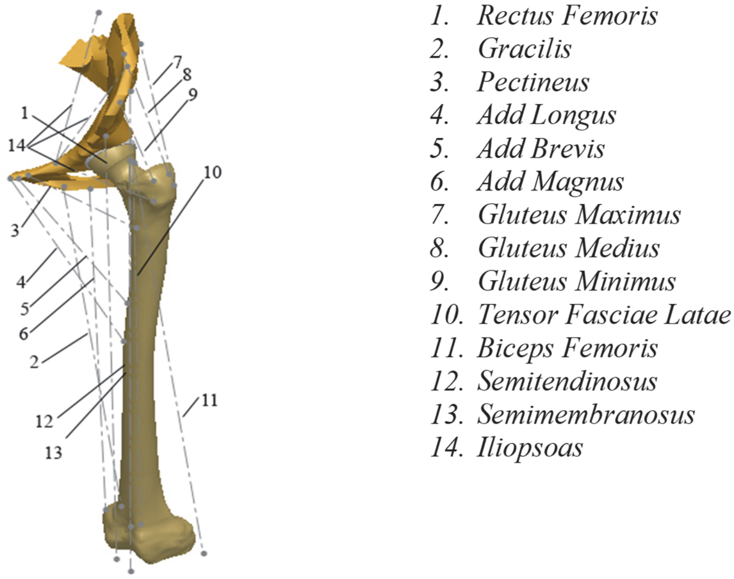



Fig. 2. Diagram of the geometric model "thigh — pelvis" with coordinated points of attachment of muscles that are functionally related to the HJ.

In the presented study, we took the elastic modulus of muscle tissue from the literature [10] due to the fact that it is necessary to perform rather complex experiments to determine it. The cross-sectional area is also obtained from the literature, we determine the length and elongation of the muscles through the construction of a geometric model. Data on the angles of inclination of the muscle forces lines of action, of the length of the muscles, as well as their cross-sectional area are taken both from the literature [8] and obtained independently as a result of the measurements (according to NMR and CT data). In order to move away from "absolute values", a system of reduced units was built: the length of muscles and their cross-sectional area are normalized. The unit of measurement is length and cross-section of m. rectus femoris (data on the muscles of interest are given in Table 1).

Table 1

**The length of the muscles and their cross-sectional area in normal**

| + | Reduced length | Reduced area |
|---|---|---|
| *m. rectus femoris* | 1.00 | 1.00 |
| *m. gracilis* | 0.82 | 0.14 |
| *m. pectineus* | 0.25 | 0.20 |
| *m. adductor longus* | 0.36 | 0.39 |
| *m. adductor brevis* | 0.30 | 0.37 |
| *m. adductor magnus* | 0.29 | 1.69 |
| *m. gluteus maximus* | 0.33 | 2.50 |
| *m. gluteus medius* | 0.20 | 1.78 |
| *m. gluteus minimus* | 0.12 | 0.81 |
| *m. tensor fascilate latae* | 0.18 | 0.21 |
| *m. biceps fermoris* | 0.83 | 1.00 |
| *m. semitendinosus* | 0.83 | 0.40 |
| *m. semimembranosus* | 0.83 | 1.04 |
| *m. iliopsoas* | 0.29 | 1.29 |

We divided this study into two stages:

I. Modeling of the muscles' passive action on the deviation of the net force vector in HJ, that is, the study of the effect of individual muscles on the net vector in the event of a change in the position of the limb: passive flexion and adduction, this corresponded to the state when the child is in a lying position, its m The ligaments are not tense, and the researcher raises (bends) or adducts the straight limb.

II. Modeling the active action of muscles on the deviation of the net force vector in the HJ – the results of this stage of the study will be presented in our further works.

**Results of the study and their discussion.** Thus, with regard to the first stage of our study, we assumed that if the muscle becomes longer, that is, it stretches, then, considering the muscle as an elastic body (like a rubber band), we can determine the resulting forces using the formula:

$$F = k\Delta l \qquad (1)$$

where k is muscle stiffness; Δl is the change in its length.

In the case of a decrease in the length of the muscle, internal forces do not arise in it. Each muscle has its stiffness coefficient, which depends on its length, area and mechanical properties (modulus of elasticity E). We will obtain the formula for calculating the stiffness coefficient through the values that can be measured. Consider a muscle as a uniform rod with a constant cross-sectional area and a linear relationship between deformations and stress. Then the force that occurs in the muscle can be calculated by the formula:

$$F = \sigma N \qquad (2)$$

where σ is the internal stress; N is the cross-sectional area.

The value of internal stresses is defined as:

$$\sigma = E\varepsilon, \qquad (3)$$

where E is the modulus of elasticity (Young's modulus), ε is the strain.

The amount of deformation is calculated according to the formula:

$$\varepsilon = \frac{\Delta l}{l} \qquad (4)$$

where Δl is the change in muscle length, l is its initial length.

Sequentially substituting the parameter values from formula (4) into formula (3), (2) and (1), we obtain:

$$k = \frac{EN}{l} \qquad (5)$$

That is, to determine the forces of a stretched muscle, we need to know the modulus of muscle tissue's elasticity, its length and cross-sectional area.

Analysis of the results showed that in the case of passive hip flexion, stretching occurred in the following muscles: gracilis, adductor magnus, gluteus maximus, biceps femoris, semitendinosus, semimembranosus. In fig. 3 A graphs of changes in muscle effort of these muscles are presented. As you can see, the greatest efforts under passive stretching conditions occur in m. adductor magnus – 940 N.

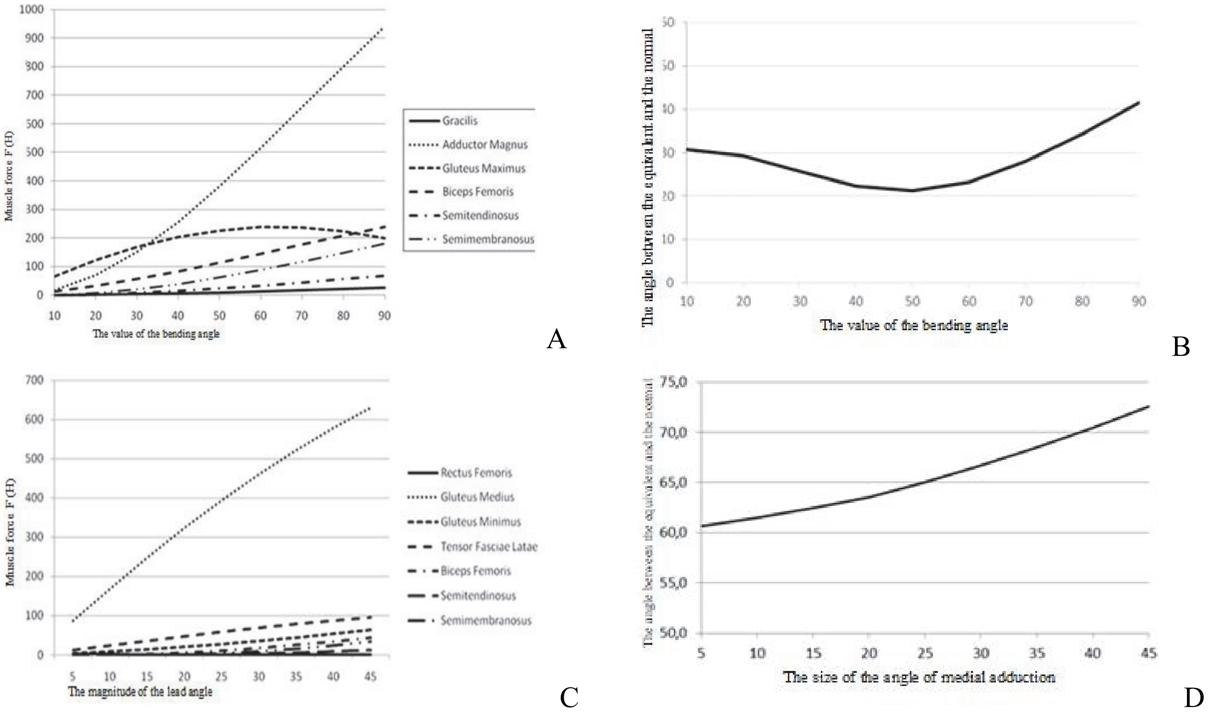



Fig. 3. A Graphs of the dependence of muscle effort on the angle of passive bending of the lower limb in HJ; B. Graph of the dependence of the angle between the resultant force and the normal under the conditions of passive bending of the lower limb. C. Graphs of the dependence of muscle effort on the degree of passive adduction of the lower limb in HJ. D. Graph of the dependence of the angle between the resultant force and the normal under the conditions of passive adduction of the lower limb.

That is, under the conditions of hip flexion, the resultant force in the case of normal muscle tone moderately deviates by approximately 10º in the direction of decrease, and then by 10º in the direction of increase.

We determined the resulting deviation under the conditions of a stepwise increase in force from the initial force to 1000 N with an interval of 200 N under the conditions of maximum adduction of the limb. Calculations based on our model show that additional muscle efforts, which are lengthened in the case of hip flexion, have different effects on the direction of the resultant force in the HJ: m. gluteus maximus – reduce the angle of co-action, and m. gracilis, m. adductor magnus, m. biceps femoris, m. semitendinosus, m. semimembranosus – increase.

The next step was to calculate the action of the muscles under the conditions of bringing the straightened lower limb into the HJ from 0º to 45º with a step of 5º (Fig. C). It was established that the following muscles underwent passive stretching: mm. rectus femoris, gluteus medius, gluteus minimus, tensor fascia latae, biceps femoris, semitendinosus, semimembranosus. M. tensor fasciae latae underwent the greatest elongation. – 3 cm, and the greatest efforts under passive stretching conditions were found in m. gluteus medius – 631 N.

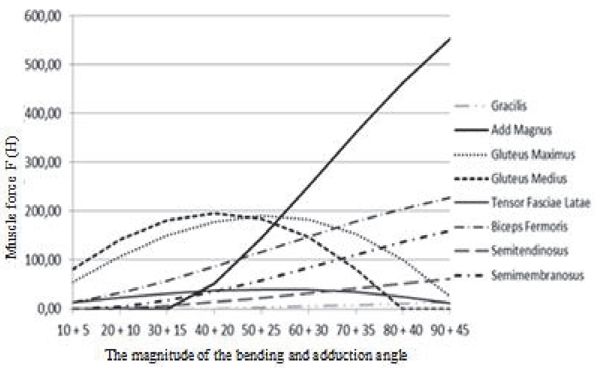
The change in VRF in HJ when the limb is adducted is presented in the graphs (Fig. 3 D). In the case of adduction of the lower limb from 0º to 45º, the angle between the resultant and the normal increases by 12º, which is slightly different from the situation of bending.

The next step was to examine the deviation of the resulting force under the conditions of a gradual increase in force from the initial force to 1000 N with an interval of 200 N. In the case of applying additional force to the studied muscles, it was established that m. gluteus minimus and m. tensor fasciae latae reduce the angle of deviation of RFV in HJ from the normal, and m. rectus femoris, m. gluteus medius, m. biceps femoris, m. semitendinosus, m. semimembranosus – increase.

The third variant of the calculations was performed for simultaneous bending of the lower limb from 0º to 90º with a step of 10º and its bringing from 0º to 45º with a step of 5º. The analysis of the results showed that in this situation the following muscle groups underwent passive stretching: m. gracilis, m. adductor magnus, m. gluteus maximus, m. gluteus medius, m. tensor fasciate latae, m. biceps femoris, m. semitendinosus, m. Semimembranosus (Fig. 4 A).

As we can see, the greatest efforts under the conditions of passive stretching occur in m. adductor magnus – 551.8 N (graphs of changes in muscle effort are presented in Fig. 4 A). M. gluteus maximus and m. gluteus medius are characterized by an increase in effort with an increase in the bending angle to 40º–

50º and adduction to 20º–25º. A further increase in these angles leads to a decrease in effort in these muscles.

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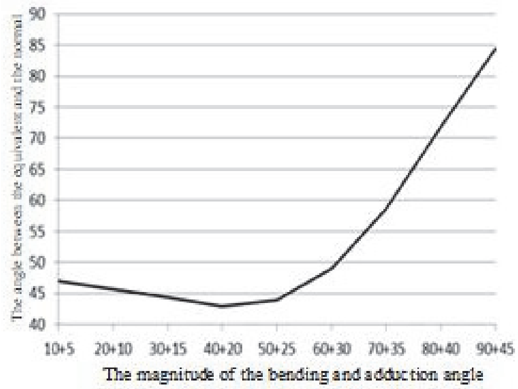


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Fig. 4. A Graphs of the dependence of muscle effort on the degree of passive flexion and adduction of the lower limb in the hip joint; B. Graph of the dependence of the angle between the resultant force and the normal during passive bending and adduction of the lower limb.

After analyzing the influence of passive stretching, it was found that simultaneous bending and adduction of the lower limb in the hip joint causes an even greater deviation of the resultant force vector in the HJ from the normal than in the case of bending or adduction of the limb (Fig. 4 B). So, the maximum value of the angle between the resultant and the normal is 84.7º (72.5º – in the case of reduction). In the case of flexion and adduction of the limb, there is a significant displacement of the VRF in the HJ to the outside, in contrast to exclusively bending or exclusively adduction.

The next step was to examine the deviation of the resulting force under the conditions of a gradual increase in force from the initial force to 1000 N with an interval of 200 N. Under the conditions of providing additional forces to the muscles in the case of simultaneous bending and adduction of the lower limb, it was established that m. gluteus maximus and m. tensor fasciae latae (provided large angles of the limb's deviation) reduce the angle of deviation of the VRF in the HJ from the normal, and m. gracilis, m. adductor magnus, m. gluteus medius, m. biceps femoris, m. semitendinosus, m. semimembranosus – increase.

A comparative analysis of the data obtained by us with the data of other studies shows a general tendency towards similarity with the difference in previously performed studies [2, 3, 10] studied the influence passive muscle efforts on the deviation of the resultant force vector in the hip joint in normal in adults and in other pathological conditions (deforming coxarthrosis and aseptic necrosis of the femoral head) – calculations were made taking into account the mean weight of an adult, and muscle efforts also differed from childhood. Therefore, we consider it not quite correct to make a direct comparison of the obtained data with the data of other authors.

Confirmed data [4, 9], that the muscles surrounding the hip joint play a decisive role in the processes of forming overload in certain areas of the femoral head, which in turn can lead to the development of deformations and significantly disrupt the function of the HJ.

The obtained data deepen and expand the previously obtained knowledge [1, 3, 7] regarding the anatomical and functional features of the hip joint elements in Perthes' disease.

The performed study permitted to determine that in the case of passive hip flexion, stretching occurred in the following muscles: gracilis, adductor magnus, gluteus maximus, biceps femoris, semitendinosus, semimembranosus. At the same time, the vector of the resultant force initially decreases, and under the conditions of maximum bending of the limb, it increases (deflecting outwards) by 10º. The gradual increase in muscle strength in the case of hip flexion has a different effect on the directionality of the resultant force in the HJ: m. gluteus maximus – reduce the angle of co-action, and m. gracilis, m. adductor magnus, m. biceps femoris, m. semitendinosus, m. semimembranosus – increase.

Bringing the straightened lower limb into the HJ leads to passive stretching of the muscles: mm. rectus femoris, gluteus medius, gluteus minimus, tensor fascia latae, biceps femoris, semitendinosus, semimembranosus. M. tensor fasciae latae underwent the greatest elongation – 3 cm, and the greatest efforts under passive stretching conditions were found in m. gluteus medius – 631 N.

When the lower extremity is simultaneously bent and brought, muscle groups are subjected to passive stretching: m. gracilis, m. adductor magnus, m. gluteus maximus, m. gluteus medius, m. tensor fasciate latae, m. biceps femoris, m. semitendinosus, m. Semimembranosus, which causes an even greater deviation of the vector of the resultant force in the HJ from the normal than in the case of flexion or adduction of the limb. Applying additional effort to the muscles in the case of simultaneous bending and adduction of the lower limb leads to the fact that m. gluteus maximus and m. tensor fasciae latae reduce the angle of deviation of RFV in HJ from the normal, and m. gracilis, m. adductor magnus, m. gluteus medius, m. biceps femoris, m. semitendinosus, m. semimembranosus to passive stretching – increase.

The acquired knowledge should be the basis for the justification of the algorithmic concept of treating children with Perthes disease depending on age, the degree of damage to the femoral head and the existing pathological changes in the soft tissues of the hip joint, primarily in the muscles.

## Conclusions

1. A comparative analysis of the results of the calculations obtained on the grapho-analytical model revealed regularities in the influence of hip position and muscle strength on RFV deviations in HJ:

– under the conditions of passive hip flexion, m .adductor magnus is stretched most of all., under the conditions of adduction — m. gluteus medius;

– the angle of deviation of the RFV from the normal shifts (increases) slightly in the case of passive flexion and significantly increases in the case of passive adduction of the limb as a result of the occurring muscle tension;

– under the conditions of passive bending, the outward deviation of RFV is determined by m. gracilis, m. adductor magnus, m. biceps femoris, m. semitendinosus, m. semimembranosus. In the case of passively driving the deviation outward, the RFV cause m. rectus femoris, m. gluteus medius, m. biceps femoris, m. semitendinosus, m. semimembranosus. The greatest deviation of RFV occurs under conditions of simultaneous hip flexion and adduction.

– m. iliopsoas does not significantly affect the deviation of the RFV angle in the HJ.

2. The results of the performed study allow us to state that even with a passive change in the position of the hip (adduction and bending at different angles, which is noted in cases of Perthes disease complicated by flexion-adduction contracture of the HJ), there is a redistribution of stresses in the segments of the HJH and a change in the vector of the resultant force in these joint models.

*Prospects for further research It requires further study of the stress redistribution's features in the segments of the HJH and the change in the vector of the resultant force in the case of active loading of the HJ muscle groups, which determine the pathological position of the limb in the case of a complicated course of Perthes' disease, and a comparison with the state of passive loading, which will be reported in our next studies.*

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