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Modeling the work of the muscles of the lower extremity in conditions of flexion-adduction contracture of the hip joint and flexion-extension contracture of the knee joint

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Large joint damage often leads to inability to work and disability that requires long-term treatment. The development of osteoarthritis is accompanied by changes in the muscles and special rehabilitation measures are needed to restore their strength, symmetry of the load during standing and steps during walking. Objective. To determine the most vulnerable muscles of the lower extremities in the conditions of osteoarthritis of the hip and knee joints using a mathematical model. Methods. Three mathematical models were created in the OpenSim system. Model 1 (normal): extension/flexion — 10°/0°/45°; removal/adduction — 5°/0°/12°; rotation — 3°/0°/3°, foot turning — 5°. Model 2 with flexion-adduction contracture of the hip: flexion setup — 20°, adduction setting — 10°, foot turning — 10°, shortening of the femur by 2 cm. Model 3: flexion contracture of the knee joint — 0/20°/50°. Results. With combined hip contracture, the isometric strength of the muscles decreases by almost 60 %. In the case of flexion contracture of the knee joint, the rectus femoris muscle is more stretched and requires 3.5 % more force to extend the knee. In the presence of adductor contracture of the hip joint, the thigh's thin muscle is in a contractile state, which reduces its strength by almost 90 %. In the case of knee contracture, this muscle is primarily in a stretched state, so more force is required to extend the knee — in our model, by 6 %. With changes in the lower extremity due to the development of hip contracture, the gastrocnemius muscle can lose up to 78 % of its strength, and the knee muscle — up to 5%. In conditions of knee joint contracture, the most vulnerable muscles are the pelvic stabilizer muscles (m. tensor fasciae latae) — a decrease in strength of up to 44.4 %, and the knee (m. semimembranosus) — up to 54.5 %. Conclusions. Contractures of the hip and knee joints lead to a loss of muscle strength of the lower limb, which negatively affects its functioning and recovery after arthroplasty.

Ураження великих суглобів досить часто призводить до непрацездатності й інвалідності та потребує тривалого лікування. Розвиток остеоартрозу супроводжується змінами в м'язах і необхідні спеціальні реабілітаційні заходи для відновлення їхньої сили, симетричності навантаження під час стояння та кроків — під час ходьби. Мета. За допомогою математичної моделі визначити найуразливіші групи м'язів нижніх кінцівок у разі остеоартрозу кульшового та колінного суглобів. Методи. У системі OpenSim створено 3 математичні моделі. Модель 1 (норма): розгинання/згинання — 10°/0°/45°; відведення/приведення — 5°/0°/12°; ротація — 3°/0°/3°, вигін стопи — 5°. Модель 2 із згинально-привідною контрактурою кульшового суглоба: згинальна установка — 20°, установка приведення — 10°, вигін стопи — 10°, укорочення стегнової кістки 2 см. Модель 3: згинальна контрактура колінного суглоба — 0°/20°/50°. Результати. За комбінованої контрактури кульшового суглоба ізометрична сила м'язів знижується майже на 60 %. У разі згинальної контрактури колінного суглоба прямий м'яз стегна розтягнутий дужче та для розгинання коліна використовуватиме на 3,5 % більше зусиль. За наявності привідної контрактури кульшового суглоба тонкий м'яз стегна перебуває в контрактильному стані, що зменшує її силу практично до 90 %. У випадку контрактури колінного суглоба цей м'яз первинно знаходиться в розтягнутому стані, тому необхідна більша сила для розгинання коліна — в нашій моделі на 6 %. За змін у нижній кінцівці внаслідок розвитку контрактури кульшового суглоба кравецький м'яз може втратити до 78 % своєї сили, колінного — до 5 %. За умов контрактури колінного суглоба найбільш вразливими є м'язи-стабілізатори таза (m. tensor fasciae latae) — зменшення сили до 44,4 %, та коліна (m. semimembranosus) — до 54,5 %. Висновки. Контрактури кульшового та колінного суглобів призводять до втрати сили м'язів нижньої кінцівки, що негативно впливають на її функціонування та відновлення після ендопротезування. Ключові слова. Колінний суглоб, кульшовий суглоб, контрактура, сила м'язів, математичне моделювання.

Key words. Knee joint, hip joint, contracture, muscle strength, mathematical modeling

Introduction

In recent years, the problem of osteoarthritis has acquired great medical and social importance, which is due to the significant prevalence of the disease, the rapid development of functional disorders, the increase in indicators of temporary and permanent disability, and a sharp decrease in the quality of life of patients. In case of damage to large joints in the early stages of the disease, it is recommended to change the lifestyle, perform physical exercises, use adaptive devices, and prescribe medications; later stages require surgical treatment [1]. Despite the existing protocols for the treatment of osteoarthritis, most doctors continue to follow an expectant approach with the use of conservative methods. This leads to an increase in the number of patients with severe forms of the disease at the late stages, when the effectiveness of surgical treatment is significantly reduced, and the recovery results are unsatisfactory.

The long course of osteoarthritis is characterized by the formation of a persistent pain syndrome and contractures (muscle spasms), which causes reflex distortion of the pelvis, curvature of the spine, and increased walking asymmetry [2]. Distortion of biomechanical parameters of large joints is manifested in the asymmetry of weight loads on the feet, acceleration of oscillations of the general center of gravity of the body, reduction of step length, violation of the rhythmicity of walking [3]. In case of progression of the disease, patients are forced to use auxiliary means of support, such as a stick or crutches. Under these conditions, lameness becomes not just a bad habit, but an adaptive reaction of the body. With an increase in the duration of the disease and the formation of an adaptive pattern of the body, the recovery process becomes much more complicated [4, 5]. The pathogenic basis of the specified changes in the biomechanical parameters of large joints is the development of secondary changes in the muscles. Initially, there is an isolated decrease in the strength, endurance and normal functioning of a certain group of muscles in the projection of the affected joint with the formation of a contracture, afterwards the muscles of the affected limb, trunk, neck, and shoulder joint are involved in the pathological process with a violation of the biomechanics of movement. Therefore, a change in the biomechanics of the lower limbs completely affects the functioning of the entire human body [6]. Accordingly, the return to a physiologically normal state is not limited to the elimination of joint contractures. Changes in the muscles, especially long-term ones, require a lot of time, special rehabilitation measures to restore their strength, symmetry of the load on the feet while standing and steps while walking. At the same time, it is necessary to understand which muscles are the most vulnerable. Of course, it is impossible to evaluate the changes that occur in the muscles of the whole body within the limits of one study, so let us dwell on the assessment of the work of the muscles responsible for the work of the hip and knee joints at the same time.

Purpose: using a mathematical model to determine the most vulnerable muscle groups of the lower extremities under the conditions of osteoarthritis of the hip and knee joints.

Material and methods

Parameters were studied and evaluated in OpenSim 4.0, an open source system for biomechanical simulation and analysis. The software package provides tools for conducting research on biomechanics of movement. OpenSim was created by the NIH Center for Biomedical Computing at Stanford University, which provides leading software and computational tools for physically oriented modeling and modeling of biological structures [7].

The modeling is based on anatomical changes occurring in patients with a long course of degenerative diseases of the hip and knee joints. The gait2394 model is taken as the base model. This is a 3D model with 23 degrees of freedom in the human musculoskeletal system. The gait2392 model includes 76 muscles of the lower limbs and trunk [7] and is the basis for modeling any conditions of the human musculoskeletal system. The non-scale version of the model is an object with a height of 1.8 m; with a body weight of 75.16 kg.

3 mathematical models were created in the OpenSim system [7]:

– Model 1, norm: extension/flexion — 10°/0°/45°, abduction/adduction — 5°/0°/12°, rotation — 3°/0°/3°, foot flexion — 5°.

– Model 2, with flexion-adduction contracture of the hip joint: extension/flexion — 0°/20°/45° (flexion setting 20°), abduction/adduction — 0°/10°/15° (adduction setting 10°), foot bend — 10°, femur shortening — 2 cm.

– Model 3: flexion contracture of the knee joint — 0°/20°/50°.

Models 2 and 3 simulate the severe condition of the hip and knee joints. Changes in the muscles of the right lower limb were studied; estimating the maximum magnitude of their force required at the time of the step. The maximum value of the force was fixed without taking into account the phase of the step. Mostly, the peak of the greatest muscle tension occurs at the phase of maximum hip extension and separation of the toes from the support. Changes in muscle strength were evaluated as a percentage of the norm (model 1) [8]. The anatomy and functioning of muscles are taken from the specialized knowledge base «Physiopedia».

Results and their discussion

The muscles that are simultaneously responsible for the mobility of the hip and knee joints include: *mm. rectus femoris, gracilis, sartorius, tensor fasciae latae, semimembranosus, semitendinosus, biceps femoris-long head*. Let us discuss their work.

The straight muscle of the thigh (m. rectus femoris) is a component of the quadriceps and crosses the hip and knee joints. Therefore, it extends the knee and also helps the iliopsoas muscle *(m. iliacus)* to bend the thigh. Results of the calculations (Table) show that in a complex contracture of the hip joint (adductor and flexor at the same time), the isometric strength of the rectus femoris muscle decreases by almost 60 %. This is due to the fact that in the presence of a flexion contracture, the muscle is in a contracted state, that is, it becomes shorter, and uses more effort to do the necessary work to flex the hip. On the contrary, in the presence of a flexion contracture of the knee joint, the rectus femoris muscle is stretched more and will use 3.5 % more effort to perform knee extension, which is associated with the limitation of the extension angle (work to overcome the contracture).

The thin muscle (m. gracilis) belongs to the group of medial muscles of the thigh. It attaches to the tibia and flexes the knee joint, adducts the hip, and internally rotates the tibia relative to the femur. So, in the presence of an adductor contracture of the hip joint, the thin muscle is in a contractile state, which reduces its strength to almost 90 %. During hip adduction, the muscle does not need to perform this work due to the presence of an adduct contracture. But in the case of a contracture of the knee joint, the muscle is initially in a stretched state, so a greater force is needed to extend the knee — in our model by 6 %.

Tailor's muscle (m. sartorius) is a thin, long, superficial muscle in the front of the thigh. It runs the entire length of the thigh through the hip and knee joints and is the longest muscle in the human body. In the hip joint, it bends, adducts and turns the thigh to the side, in the knee joint, it bends the leg, and when the knee is bent, it rotates it inwards. This muscle plays an important role in stabilizing the pelvis. Due to changes in the lower extremity due to the development of contracture of the hip joint, the tailor muscle can lose up to 78 % of its strength, and the knee muscle can lose up to 5 %. This is due to the fact that in the case of the formation of flexion contractures in the hip or knee joints, the muscle changes its vector of action and enters a contractile state, that is, it decreases its length compared to the physiological norm.

The tensor fasciae latae (TFL), despite its small size, works with several muscle groups: medium and small gluteal muscles — to rotate inward and abduct the hip; rectus femoris muscle — to bend the hip.

The TFL is an accessory flexor of the knee when it is bent more than 30°; stabilizes the knee along with the tibia when it is in full extension. Another important function of the muscle is to prevent the pelvis from dropping on the side of the leg being carried. Therefore, disturbances in the work of this muscle lead to an imbalance of a number of limb functions. According to the simulation results, in the case

Table

Isometric force of the muscles of the lower limb in contractures of the hip and knee joints

Muscle	Function	Maximum isometric force (H)				
		model 1	model 2 (hip joint)		model 3 (knee joint)	
			force	%	force	%
M. rectus femoris	Flexion of the hip joint, extension of the knee joint	1169.00	469.82	–59.81	1210.13	3.52
M. gracilis	Flexion and adduction of the hip joint, extension of the knee joint	162.00	19.79	–87.78	171.69	5.98
M. sartorius		156.00	34.39	–77.96	149.16	–4.38
M. tensor fasciae latae	Flexion, adduction and internal rotation of the hip joint	233.00	111.30	–52.23	129.56	–44.40
M. semimembranosus	Extension and adduction of the hip joint, extension of the knee joint	1288.00	431.70	–66.48	586.49	–54.46
M. semitendinosus		410.00	159.92	–60.99	541.23	32.01
M. biceps femoris-long head		896.00	315.31	–64.81	799.56	–10.76

of contractures of the hip and knee joints, the TFL loses strength by almost 50 %. This can be explained by the fact that during flexion contractures of both joints, the muscle acquires contraction, i. e. contractility, and it needs less energy to maintain such an antological position.

Semimembranous (m. semimembranosus) and *semitendinosus (m. semitendinosus)* muscles belong to the group of popliteal tendons. Their main function is hip extension and knee flexion. They also play a significant role in stabilizing the knee joint while standing and bending the knee. The semimembranous muscle under conditions of flexion contractures of the hip and knee joints loses strength (about 65 %) due to its more posteromedial location, as a result of which the tension of the muscle decreases due to the reduction of the distance between the attachment points. The semitendinosus muscle loses its strength due to hip joint contracture (in particular, the adductor muscle — up to 60 % of normal), and with knee contracture, on the contrary, its strength increases by 30 %. This is due, most likely, to the fact that the lower edge of the muscle is a continuation of the deep fascia of the lower leg, and therefore the flexion contracture leads to an increase in the distance between the points of attachment of the muscle.

The biceps femoris muscle (m. biceps femoris) is a muscle of the back of the thigh, located in the posterolateral part and belongs to the group of popliteal tendons. The long head of the muscle is located superficially relative to its short head. The function of the long head of the biceps femoris is to bend the knee joint, extend the hip, and laterally rotate the lower leg with the hip extended. The short head is solely responsible for bending the knee and rotating the lower leg, it is not considered in our article. Therefore, during flexion contractures of the hip and knee joints, as a result of the reduction of the distance between the attachment points, the muscle loses a significant part of its strength: up to 65 % in the case of a combined contracture of the hip joint, up to 10 % in the flexion knee joint.

Discussion

The changes in the muscles of the lower limb highlighted in the article based on the results of mathematical modeling can be taken into account when planning rehabilitation measures to restore the functionality of the lower limbs after endoprosthetic repair or injuries followed by a long period of immobilization or limitation of the use of the limb. At the same time, it should be noted that the model cannot take into account all accompanying contractures, functional disorders and the impact of pain syndrome occurring due to degenerative diseases and injuries. In addition, the contracture of one of the joints causes a violation of the biomechanics of the others. For example, a flexion contracture of the hip joint leads to a functional shortening of the affected limb and tilting of the pelvis in its direction, and an adductor contracture results in tilting of the pelvis in the opposite direction [9–11]. Then there are two options for the development of the impairment. In one case, in order to maintain balance, a person is forced to bend the trunk and extend the heel-shin joint. At the same time, the knee joint remains fully functional. Otherwise, the flexion contracture is compensated by the formation of minor flexion angles of the trunk, knee, and supracalcaneal joints. The consequences of this can be different: for example, the presence of contracture of the knee and supracalcaneal-tibial joints without bending the trunk, or bending of the trunk and significant extension of the supracalcaneal-tibial joint without the formation of flexion of the knee. Sometimes balance compensation requires bending the knee joint of the opposite limb, which should be taken into account during rehabilitation measures [12, 13].

The long-term degenerative process affects all joints of the body to some extent, therefore their mobility is impaired, and even a slight imbalance of one joint causes a violation of the biomechanics of all others. Moreover, all muscles work in a complex and balanced manner, that is, there are agonists and antagonists for each. If one element of the system is weakened, there is an imbalance in others.

Endoprosthetic repair, as one of the radical methods of treating osteoarthritis of large joints in the late stages, makes it possible to eliminate pain and functional contracture, but the reduced strength of the muscles responsible for the mobility of the limb of the joints does not contribute to their full recovery. For example, the antagonists for the rectus femoris are the biceps, semimembranous and semitendinosus, that is, the muscles of the posterior and posteromedial groups.

In the case of a combined contracture of the hip joint, we observe a weakening of the entire complex of muscles, that is, a violation of the function of both flexion and extension of both joints. Under conditions of flexion contracture of the knee joint, the results of mathematical modeling revealed an increase in the strength of the semitendinosus muscle, which can lead to medialization of the knee (valgus).

So, with the help of a mathematical model, we investigated the work of the muscles that are simultaneously responsible for the function of the hip and knee joints, but contractures affect all muscles of the body. The further studies will be devoted to these issues.

Conclusions

Contractures of the hip and knee joints lead to a loss of muscle strength of the lower limb, which negatively affects the ability to restore the full functioning of the joints after endoprosthetic repair and injuries.

Mathematical modeling determined that flexion-adduction contracture of the hip joint changed the work of the muscles around it. Significant changes in the work of the medial group of hip stabilizer muscles were established. The adductor muscles of the thigh turned out to be the most vulnerable: the force of the thin muscle decreased up to 89 %, and that of the tailor's muscle up to 78 %.

Under the conditions of modeling the knee joint contracture, the stabilizer muscles turned out to be the most vulnerable: the strength of the tensor of the broad fascia of the thigh decreased to 44.4 %, and that of the semimembrane to 54.5 %.

The obtained results can be taken into account during the planning and implementation of rehabilitation measures to restore joint function after endoprosthetic repair. Taking into account the fact that during the contracture of the joints of the lower limb, changes occur in almost all muscles of the body, it is possible to outline the prospects of these studies for the rehabilitation of orthopedic patients.

Conflict of interest. The authors declare no conflict of interest.

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MODELING THE WORK OF THE MUSCLES OF THE LOWER EXTREMITY IN CONDITIONS OF FLEXION-ADDUCTION CONTRACTURE OF THE HIP JOINT AND FLEXION-EXTENSION CONTRACTURE OF THE KNEE JOINT

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