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Study of the influence of the position of the tendon graft hamstring muscle on the stability of the knee joint under the conditions of plasticity of the structures of the posterolateral angle

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Damage to the posterolateral angle of the knee joint is an injury that occurs occasionally and can be isolated or combined with tears of the posterior or anterior cruciate ligaments. The key link of damage to the posterior lateral corner is the rupture of the tendon of the hamstring muscle, mained stabilizer of excess external rotation lower legs. Objective. Determine the optimal fixation position tendon graft on the posterior surface of the tibia subject to recovery of the hamstring muscle which ensuring the greatest stability of the lower leg during external rotation. Methods. Models of the knee joint were built with different attachment points of the popliteal graft muscle in the ANSYS software environment. The criteria for evaluating the effectiveness of selecting the fixation point of the transplant were chosen as the degree of movement of the finite parts elements of the model. Results. The smallest movements in all directions received in the case when the transplant fixed as far as possible outwards and upwards, near the joint surface. Maximum — in the direction of the coordinate axes, as well as full movement were recorded for the control model, in the absence of the hamstring tendon The nature of the distribution of displacement fields in all models p graft and control were identical. Biggest there were additional displacements in the direction of the x axis (outward). on the front border of the platform, and the largest negative (so far redins) on the back. The largest additional shifts to the sides the y (front) axes are fixed at the leftmost limit and the largest negative (back) — to the rightю Conclusions. In view of the stability of the lower leg during rotational loading, the most effective is fixation of the hamstring graft on the back surface of the fibula is as late as possible and closer to its cardiac surface, finished in this case, the dimensions are found to be the smallest in all directions. The greatest displacement in all directions obtained in the control model for less tendon hamstring muscle.

Ушкодження задньолатерального кута колінного суглоба — травма, яка трапляється зрідка, може бути ізольованою чи поєднаною з розривами задньої або передньої схрещених зв'язок. Ключовою ланкою ушкодження задньолатерального кута є розрив сухожилка підколінного м'яза, основного стабілізатора надлишкової зовнішньої ротації гомілки. Мета. Визначити оптимальне положення фіксації сухожилкового трансплантата на задній поверхні великогомілкової кістки за умов відновлення підколінного м'яза, що забезпечує найбільшу стабільність гомілки під час зовнішньої ротації. Методи. Побудовано моделі колінного суглоба з різними точками кріплення трансплантата підколінного м'яза в програмному середовищі ANSYS. Критеріями оцінювання ефективності вибору точки фіксації трансплантата обрано ступень переміщення частин скінченних елементів моделі. Результати. Найменші переміщення у всіх напрямках отримані у випадку, коли трансплантат фіксували максимально назовні та догори, біля суглобової поверхні. Максимальні — у напрямку координатних осей, а також повного переміщення зафіксовані для контрольної моделі, за відсутності сухожилка підколінного м'яза. Характер розподілу полів переміщень у всіх моделей із трансплантатом і контрольній був ідентичним. Найбільші додатні переміщення у напрямку осі x (назовні) виникали на передній межі платформи, а найбільші від'ємні (досередини) — на задній. Найбільші додатні переміщення у бік осі y (вперед) зафіксовані на крайній лівій межі, а найбільші від'ємні (назад) — на правій. Висновки. З огляду на стабільність гомілки під час ротаційного навантаження найефективнішою є фіксація трансплантата підколінного м'яза на задній поверхні великогомілкової кістки максимально латерально та ближче до її суглобової поверхні, оскільки в цьому випадку величини переміщень виявились найменшими у всіх напрямках. Найбільші переміщення у всіх напрямках отримані в контрольній моделі за відсутності сухожилка підколінного м'яза. Ключові слова. Колінний суглоб, трансплантат, сухожилок.

Key words. Knee joint, transplant, tendon

Introduction

An injury to the posterolateral angle of the knee joint occurs occasionally and may be isolated or combined with tears of the posterior or anterior cruciate ligaments [1, 2]. The key link of damage to the posterolateral corner is the rupture of the tendon of the popliteal muscle — the main stabilizer of excess external rotation of the shin (Fig. 1). Such injuries can be isolated or occur in complex traumas, in combination with ruptures of the posterior and anterior cruciate ligaments, dislocations of the lower leg, etc.

Popliteal tendon repair is often referred to as the «key» to successful treatment of posterior knee instability. At the same time, the problem is that the restoration of the function of the popliteal muscle is performed not quite anatomically, accurately reproducing only its attachment to the femoral condyle. Surgical intervention for plastic surgery of the popliteal tendon involves drilling a channel in the external condyle of the tibia from front to back, the exit point of which on the back surface of the tibia is the geometric place of attachment of the graft — in the projection of the popliteal tendon (Fig. 2, tendon graft is shown in green color). In addition, repair involves replacement of the muscle that contracts and pulls the tibia in relation to the thigh with a tendon graft of constant length. Such restoration will never be either anatomical or physiological. However, there is no other option to restore the function of the popliteal muscle, and choosing the lesser of two evils, we stabilize the external rotation of the tibia with a tendon graft of constant length. Graft attachment point on the back surface of the tibia is the subject of our interest in the present study. Exact recommendations for its selection are not given in the literature.

Purpose: to determine the optimal position of fixation of the tendon graft on the back surface of the tibia under conditions of recovery of the popliteal muscle, which provides the greatest stability of the tibia during its external rotation.

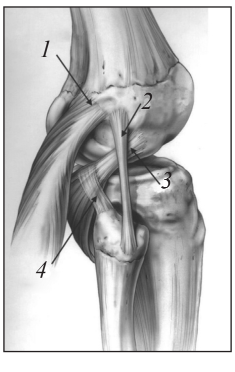

Fig. 1. Anatomical structures of the posterolateral corner of the knee joint: *1* — external head of the gastrocnemius muscle; *2* — lateral bypass ligament; *3* — popliteal tendon [3]

Material and methods

The research was carried out using the software package, based on the finite element method in the ANSYS software environment. The object of the study was the knee joint and its ligaments. In order to simplify calculations, the geometric model comprised only the articular ends of the tibia, fibula, and femur, which form the knee joint (Fig. 3).

Considering the complex geometry of the bone surface, the articular ends were constructed from computed tomography (CT) data of an adult knee joint using specialized CT-images processing software (3D Slicer).

The received model in stl format was used for further calculations. Therefore, the shape and dimensions of the model corresponded to the real human knee joint. At the same time, the overall (maximum) dimensions of the model in the horizontal plane were 100 × 70 mm. To reduce the total number of finite elements, the model was limited in height to 15 cm. The calculated model of the knee joint corresponded to the position of extension in its vertical orientation.

It stands to mention that when modeling the stability of the knee joint, it is quite difficult to fully reflect its structure and the behavior of individual ligaments, both in terms of the geometry and physics of this anatomical structure. Each ligament consists of fibers that form bundles; the latter are attached to the articular ends of the bones at several points, occupying a certain area on the surface of the bone. At the same time, the ligament can vary in thickness, expanding to the places of attachment, and also, due to the different direction of the fibers, it can have a rotation of the cross section around its longitudinal axis. In addition, ligaments possess not only elastic physico-mechanical properties, but also such as contractility and relaxation, which are a time-consuming task to define and take into account.

It is obvious that the reproduction of the peculiarities of the structure and properties of connections would significantly increase the time for building the model (geometrical side of the problem) and performing the calculation (physical side of the problem). In addition, sometimes it is impossible to take into account some features of ligaments.

With this in mind, we have considered the ligament as a tension-only element, that is, we have assumed that only longitudinal forces can occur in the ligament that stretch it. Therefore, we considered it possible to replace the actual forms of connections with cylindrical elements with low bending stiffness (by reducing the dimensions of the cylinder diameter). The bases of the cylinders were fixed at the starting points of the ligaments, which were defined as the center of the ligament contact zone with the bone surface. The diameters of all cylinders were equal to 2 mm, and the lengths were determined by the places of attachment of ligaments (Fig. 4).

Table 1 shows the actual cross-sectional dimensions and ligament lengths of the knee joint.

The material of the elements (bone and ligament of the knee joint) was considered elastic, homogeneous and isotropic. Since the subject of research is, first of all, the stressed-deformed state of the ligamentous apparatus of the knee joint, and also taking into account the significant difference in the elastic properties of bone tissue and ligaments, the articular ends of the bones were given the properties of compact bone tissue (spongy bone was not selected): module Young's ratio is 2 × 104 MPa, Poisson's ratio is 0.25 [10]. Mechanical values of the ligament apparatus used in the calculations corresponded to the average values of the properties of the ligaments of the knee joint of an adult (Table 2).

It should be noted that replacing the anatomical shape of the ligaments with their simplified models in the form of cylinders results in a change in some characteristics of the models, namely: stiffness of the cross section of the rod (ligaments) during stretching (EA), Young's modulus (E), cross-sectional plane (A). Therefore, it was necessary to determine such modulus of elasticity, the value of which would give the models of connections stiffness indicators similar to the real ones. For this purpose, the given elastic modulus of the ligaments was calculated based on the equality of the tensile stiffness values of the ligament and the cylinder simulating it:

$$ElAl = EcAc, \quad (1)$$

where ElAl is the tensile stiffness of the ligament, EcAc is the tensile stiffness of the cylinder.

Hence, the modulus of elasticity of the ligament is:

$$Ec = ElAl / Ac. \quad (2)$$

The results of the calculations are given in Table 2.

The calculation model was loaded as follows. From the side of the shin, the knee joint is known to be formed by the articular ends of two bones: tibia and fibula, which are shown in the calculation model. These bones can be movable relative to each other, and in the case of applying a load to the lower leg, the impact on both bones must be transmitted simultaneously. In order to exclude mutual displacement of the fibula and tibia bones, the joint ends in the lower part of the model were rigidly connected to each other by a cylindrical element (platform) with a height of 10 mm and a diameter of 120 mm (Fig. 5, a, b, d). Mechanical properties of the platform corresponded to the properties of compact bone.

The basis of this study is the evaluation of one of the functions of the popliteal muscle — ensuring the stability of the lower leg during external rotation. Therefore, the load of the model was carried out by a torque, which was applied to the lower base of the cylindrical platform in the outward direction (Fig. 5, d). That is, external rotation of the tibia was performed. The magnitude of the moment was chosen arbitrarily, and after preliminary calculations it was determined at the level of 15 N × m.

The following boundary conditions were applied to the model: movement of the femur fragment in all directions was prohibited, vertical movements were allowed for the lower leg model, and free movements were allowed in other directions.

For ease of orientation, a rectangular coordinate system was introduced (Fig. 5, a). In relation to the model, *x*-axis was directed from the inside-out; *y* — perpendicular to *x*-axis, back to front; *z* was perpendicular to the *x0y* plane, from bottom to top. That is, *z*-axis coincided with the vertical axis of the lower limb model, and the *x0y* plane was perpendicular to this axis.

In order to carry out a study on determining the most optimal fixation position of the popliteal

Table 1

Dimensions of the ligaments of the knee joint [3–8]

Ligament	Length, mm	Cross-sectional plane, mm^2
Anterior cruciate	32.00	37.40
Posterior cruciate	35.00	64.05
Lateral collateral	48.15	8.76
Medial collateral	68.99	24.54
Popliteal tendon	34.30	21.90

Table 2

Mechanical properties of ligaments of the knee joint [7–9]

Ligament	Young's modulus, MPa	Poisson's ratio	Reduced Young's modulus, MPa
Anterior cruciate	123	0.4	1464
Posterior cruciate	168	0.4	3425
Lateral collateral	280	0.4	781
Medial collateral	224	0.4	1750
Popliteal tendon	130.9	0.4	913

muscle graft on the back surface of the tibia, 9 calculation schemes were built, which differed in the place of its attachment. A control 10th model was also built, where there was no popliteal tendon. The transplant was modeled in the form of a cylinder with a diameter of 2 mm; its elastic properties are shown in Table 2. The upper edge of the graft was attached to the anatomical starting point of the popliteal tendon on the external condyle of the femur, and the position of its fixation on the back surface of the tibia was changed vertically and horizontally in the frontal plane. For the convenience of attaching the lower part of the graft to the tibia, it was carried out through cylindrical elements created on the back surface of its external condyle (Fig. 6, a, b).

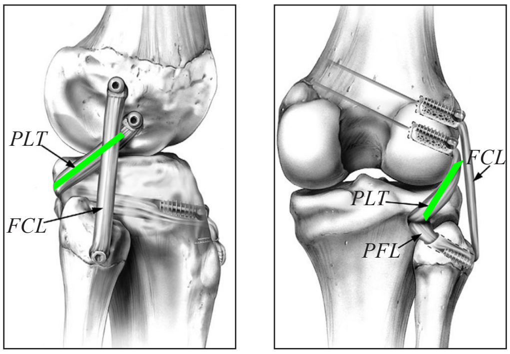

Fig. 2. Reconstruction of the posterolateral angle according to LaPrade. Lateral and posterior view. FCL — bundle that restores the peroneal bypass ligament, PLT — tendon of the popliteal muscle, PFL —popliteal fibular ligament [3]

Results and their discussion

Based on the results of the calculations, the patterns of the distribution of stresses, deformations and movements in the elements of the knee joint model (articular ends of bones and ligaments) were obtained. It should be reminded that the study was conducted to determine the optimal position of the graft for restoration of the popliteal muscle on the back surface of the external condyle of the tibia. Since

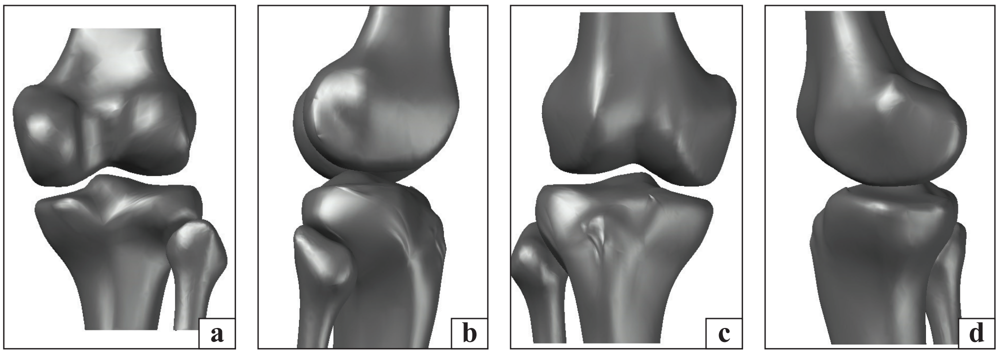

Fig. 3. Three-dimensional model of the knee joint: view from the back (a), from the outside (b), from the front (c), and from the inside (d)

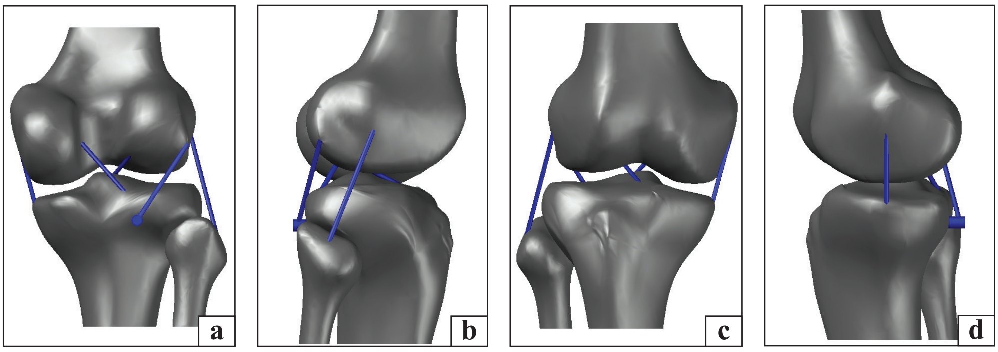

Fig. 4. Diagram of the location of the ligaments of the knee joint: view from the back (a), from the outside (b), from the front (c) and from the inside (d)

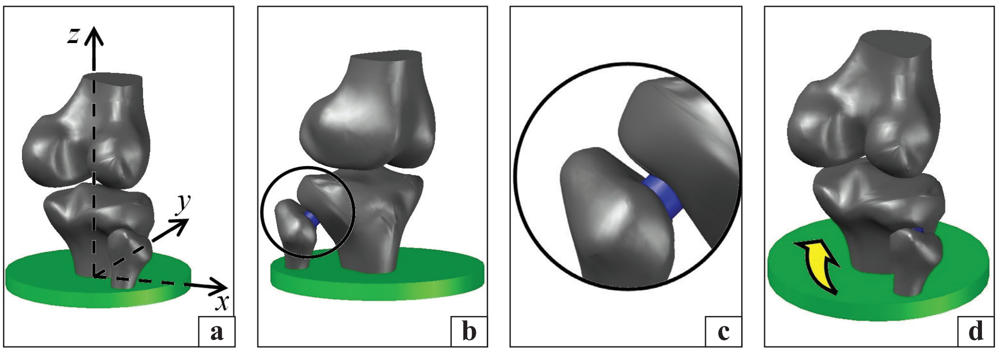

Fig. 5. Model of the knee joint: a) used coordinate system; b, c) connection of the tibia and fibula bones in the proximal epiphysis; d) direction of the rotational load action

the main goal of the operation is to ensure the stability of the lower leg during rotational loading, we chose the degree of movement of parts of the finite elements of the model as criteria for evaluating the effectiveness of selecting the graft fixation point. The main values were the maximum displacements of the points of the cylindrical platform in the directions of the x, y coordinate axes, as well as the total displacement of the platform.

Table 3 shows the largest and smallest, taking into account the sign, displacement of the points of the model along the coordinate axes, as well as the magnitude of total displacement. We can see that the outward displacement of the tibia in the frontal plane (positive direction along the x-axis) was greater than in the sagittal (along the y-axis) for all variants of graft fixation. At the same time, the values of outward movements were greater than inward movements, and forward movements were greater than backward movements. This indicates that under conditions of rotational load on the knee joint, the predominant displacement of the lower leg model occurs outward and forward.

Evaluation of movements along the x-axis (in the frontal plane) showed the following: regardless of the height of the graft fixation (levels 1, 2, 3), if the attachment point is shifted from the outside to the inside (from points C to points A, Fig. 6, b), the values of x_{max} increase. At the same time, x_{min} displacements during fixation of the graft below the articular surface (points 2ABS and 3ABS) decrease when moving from the lateral fixation point (point C) to the middle (point B), and then increase again when moving from the middle point B to the medial point A. However, at the upper level (1ABC), under the conditions of displacement of the fixation point from the outside to the inside (from C to A), the displacement of the x_{min} (in the direction of the x-axis to the inside) and x_{max} platform points gradually increases.

The nature of the distribution of y_{max} and y_{min} displacements in the direction of the y coordinate axis was similar to those along the x-axis (Table 3).

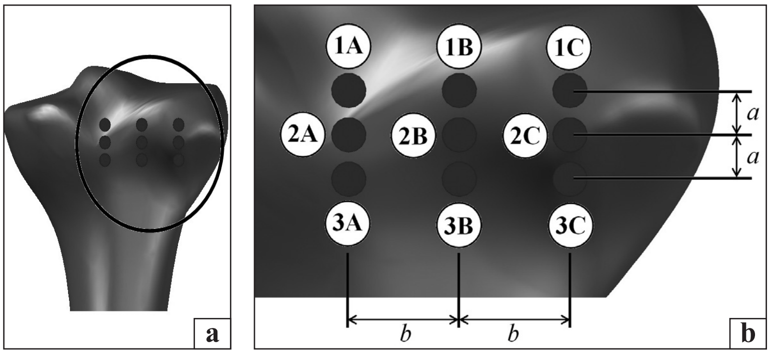

Fig. 6. Diagram of the location of fixation points of the graft for the reconstruction of popliteal tendon

Table 3

Displacement of platform points

Point location	Displacement, mm				
	along x-axis		along y-axis		maximum total displacement (d)
	x_{max}	x_{min}	y_{max}	y_{min}	
1A	9.999	–4.324	8.369	–5.955	10.245
1B	9.703	–4.125	8.136	–5.691	9.959
1C	9.147	–4.015	7.710	–5.452	9.385
2A	9.954	–4.422	8.335	–6.042	10.183
2B	9.487	–4.149	7.963	–5.673	9.722
2C	9.431	–4.292	7.949	–5.773	9.651
3A	9.947	–4.471	8.336	–6.082	10.170
3B	9.672	–4.365	8.127	–5.909	9.894
3C	9.644	–4.529	8.127	–6.047	9.848
Without tendon	10.696	–5.491	8.994	–7.192	10.848

Notes: x_{max}, x_{min} — displacement along x-axis in positive and negative directions (x_{max} — outward, x_{min} — inward), y_{max}, y_{min} — displacement along y-axis (y_{max} — forward, y_{min} — backward), d — maximum total displacement.

The change in the values of total movements (*d*) depending on the position of the fixation point of the hamstring muscle graft on the tibia was fully correlated with the change in movements in the frontal plane x_{max}, x_{min} (along the *x*-axis).

Thus, it was established that under the conditions of displacement of the place of fixation of the graft from points C to points A (from the periphery of the tibial plateau to the center), the displacements increase in all directions, that is, the resistance of the knee joint to external rotation deteriorates. At the same time, there is either a gradual increase or a decrease in values under the conditions of the transition from point C to point B and then an increase again due to displacement of the fixation from point B to point A. However, in all calculated cases, the magnitudes of displacements in the case of graft fixation at point A were higher than such at point C. The only exception was the movement of *xmin* (to the inside, in the frontal plane) for models of graft fixation at the 3ABS level. In this case, the *xmin* movements at point A turned out to be slightly smaller than at point C.

The specified increase in displacements in the event of displacement of the fixation point of the graft from the outside to the inside is explained by the increase in the length of the graft in this case and its state of axial stretching. And according to the formula for determining the absolute elongation obtained according to Hooke's law [11]:

$$\Delta l = Nl / EA \qquad (3)$$

it follows that, all other conditions being equal, the elongation will be greater in the element whose length is greater.

The described nature of changes in the movement of model points indicates that the lower and more central we fix the graft on the tibia during popliteal plastic surgery, the less rotationally stable the knee joint will be.

Discussion

Among all the calculation schemes, where the presence of the restored popliteal muscle was modeled, the smallest movements in all directions were obtained in the case when the graft was fixed at point 1C — maximally outward and upward, near the articular surface. And the largest x_{max} and y_{max} are obtained in the model with fixation of the graft at the upper level in the center of the tibia (point 1A). The maximum movement of x_{min} was recorded when the graft was attached at the lower level from the outside (point 3C), and y_{min} was also fixed at the lower level, but in the center of the tibia (point 3A).

It should be noted that among all calculated values, as expected, the maximum values of displacements in the direction of the coordinate axes, as well as the total displacement, were obtained for the control model, where the influence of the popliteal tendon was not taken into account, i. e. it was absent. The considered values of displacements (x_{max}, x_{min}, y_{max}, y_{min}, *d*) obtained in the control model exceeded similar values in the model with minimum displacements by 17, 37, 17, 32, 16%, respectively. At the same time, the largest movements among the models with the installation of a popliteal muscle graft exceeded the similar minimum values by 9, 13, 8, 11, 9%. In addition, the displacement values of the platform points of the control model exceeded the largest similar values obtained in calculations with the installation of a popliteal muscle graft by 7, 21, 7, 18, 6%.

The values of x_{min} were smaller than x_{max} depending on the point of attachment of the graft by 53–57 %, and y_{min} compared to y_{max} — by 26–30 %. The displacements of y_{max} were smaller than x_{max} by 15–16 %, but y_{min} were higher than x_{min} by 33–38 %. In the model in which the popliteal muscle was ab-

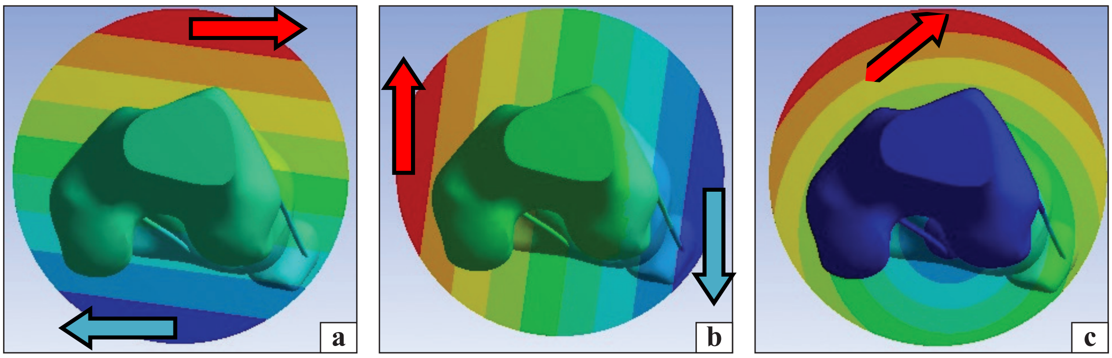

Fig. 7. Distribution of displacement fields in the calculation models (top view): along the *x*-axis (a), *y*-axis (b) and full displacement *d* (c). Arrows show the points of origin and directions of the specified maximum displacements

sent, the difference between the values of these movements was lower and they amounted to 48 % (x_{min} — x_{max}), 20 % (y_{min} — y_{max}), 31% (y_{min} — x_{min}), however, for the *ymax* pair — *xmax* the specified difference remained at the level of 16 %. For all fixation models, the displacement of the platform points mainly occurred in the outward and forward directions.

Maximum positive and negative displacements occurred at the points of the platform furthest from its center (Fig. 7). It was determined that the nature of the distribution of displacement fields in all models with a transplant and control was identical. The largest positive displacements in the direction of the *x*-axis (outward, red arrow) occurred at the front boundary of the platform, and the largest negative displacements (inward, blue arrow) occurred at the rear boundary (Fig. 7, a). At the same time, the largest positive movements in the direction of the *y*-axis (forward, red arrow) are recorded on the extreme left border, and the largest negative (back, blue arrow) on the right (Fig. 7, b). The maximum total displacements (*d*) were obtained at the points of the platform, which are located between the points where the largest displacements x_{max} and y_{max} occurred (Fig. 7, c). The direction of the full displacement *d* can be determined by the parallelogram rule, which is used to add vectors (the direction of the red arrow).

Assessment of the obtained data by the values of the maximum displacements, as well as the location of the points of their occurrence and the direction of displacements show that the optimal fixation point of the popliteal muscle graft on the back surface of the femur is point 1C.

Conclusions

In view of the stability of the lower leg during rotational loading, the most effective is the attachment of the graft under the conditions of plastic surgery of the popliteal muscle on the back surface of the tibia as laterally as possible and closer to its articular surface. This is confirmed by the displacements, which in this case turned out to be the smallest in all directions.

The largest displacements in all directions were obtained in the control model, where the popliteal tendon was absent.

Under the conditions of displacement of the fixation point of the popliteal muscle graft on the back surface of the tibia, displacements increase from the outside to the inside, indicating a decrease in the stability of the tibia during external rotation.

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

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STUDY OF THE INFLUENCE OF THE POSITION OF THE TENDON GRAFT HAMSTRING MUSCLE ON THE STABILITY OF THE KNEE JOINT UNDER THE CONDITIONS OF PLASTICITY OF THE STRUCTURES OF THE POSTEROLATERAL ANGLE

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