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Study of deformations of bone regenerate under different options of osteosynthesis of lower leg bones in the case of their congenital pseudoarthrosis

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Congenital pseudarthrosis of the leg bones is accompanied by its shortening and deformation. It's still unclear what is an optimal method of surgical treatment. Objective. Using a mathematical model, to study the relative deformations of the regenerate (RDR) in the zone of pseudarthrosis bones of the lower leg under different options of osteosynthesis. Methods. The zone of nonunion was modeled of the bones of the lower leg third of tibia and 4 variants of osteosynthesis on were analysed: intramedullary rod and needle (1); rod, spoke and bone graft in the form of a block on the tibia (2) or on both (3) bones; rod, spoke and bone with a graft on both bones of the leg with wrapping titanium mesh (4). A rotationally stable and unstable rod was used. Under the influence of the load on compression and torsion determined the values of RDR in the zone of pseudarthrosis. Results. In the case of osteosynthesis of option 1, intramedullary rods of both types (due to axial mobility of their elements) do not provide minimal deformation regenerates of both bones, so there is a possibility of their growth during the growth of the patient. Bone blocks grafts (options 2 and 3) take over part of the compressive load and the level of the RDR of the bones decreases up to 20 times. Rotationally stable rod is better under conditions of torsional loads, since RDR of the tibia is reduced by 20 times. However, bone graft blocks negate this advantage, providing rotational stability of bone fragments lower legs. The use of titanium mesh provides an additional strength of fixation of fragments of both tibia bones and level RDR of bones is reduced by 10 % compared to models of osteosynthesis with a block of grafts for both loading options. Conclusions. The use of only intramedullary rods that «grow» leads to the greatest deformations of regenerates. A rod with rotational stability is better under torsional loading conditions. Blocks from bone grafts reduce the level of RDR of bones tibia to a level of less than 0.1 % for both loading options, and the titanium mesh to an additional 10 %.

Уроджений псевдоартроз кісток гомілки супроводжується її вкороченням і деформацією. Питання щодо вибору оптимальної методики хірургічного лікування залишається відкритим. Мета. На математичній моделі вивчити відносні деформації регенерату (ВДР) у зоні псевдоартрозу кісток гомілки за різних варіантів остеосинтезу. Методи. Моделювали зону незрощення кісток гомілки в нижній третині та 4 варіанти остеосинтезу: інтрамедулярним стрижнем і спицею (1); стрижнем, спицею та кістковим трансплантатом у вигляді блока на великогомілкову (2) або на обидві (3) кістки; стрижнем, спицею та кістковим трансплантатом на обидві кістки гомілки з обгорненням титановою сіткою (4). Використано ротаційно стабільний і нестабільний стрижні. Під дією навантаження на стискання та кручення визначали величини ВДР у зоні псевдоартрозу. Результати. У разі остеосинтезу варіанта 1 інтрамедулярні стрижні обох типів (через осьову рухомість їхніх елементів) не забезпечують мінімальну деформацію регенератів обох кісток, тому виникає можливість їхнього зростання в процесі росту пацієнта. Блоки кісткових трансплантатів (варіант 2 і 3) приймають на себе частину стискального навантаження та рівень ВДР кісток знижується до 20 разів. Ротаційно стабільний стрижень є кращим за умов навантажень на кручення, оскільки ВДР великогомілкової кістки знижується в 20 разів. Проте блоки з кісткових трансплантатів нівелюють цю перевагу, забезпечуючи ротаційну стабільність фрагментів кісток гомілки. Використання титанової сітки надає додаткову міцність фіксації фрагментів обох кісток гомілки та рівень ВДР кісток знижується на 10 % відносно моделей остеосинтезу з блоком трансплантатів за обох варіантів навантаження. Висновки. Застосування лише інтрамедулярних стрижнів, які «зростають» призводить до найбільших деформацій регенератів. Стрижень із ротаційною стабільністю є кращим за умов навантаження на кручення. Блоки з кісткових трансплантатів знижують рівень ВДР кісток гомілки до рівня менш ніж 0,1 % за обох варіантів навантаження, а титанова сітка — додатково на 10 %. Ключові слова. Уроджений псевдоартроз, великогомілкова кістка, малогомілкова кістка, остеосинтез, навантаження, деформація, математичні моделі.

Key words. Congenital pseudarthrosis, tibia, fibula, osteosynthesis, load, deformation, mathematical models

Introduction

Congenital pseudarthrosis of the tibial bones (CPTB) is a pathological condition that belongs to orphan diseases and is accompanied by shortening and deformation of the lower limb, namely tibia [1]. Currently, the etiology of the disease is still being studied, but a clear connection with neurofibromatosis type I [2], osteofibrous dysplasia (Campanacci's disease) and fibrous dysplasia is already known [3]. CPTB can be diagnosed both at birth and in the first years of a child's life [4]. Usually, the main manifestations are deformation of the tibia (anterior bending), shortening, or pathological mobility in its middle or lower third [5].

The treatment of this disorder mostly involves various options for surgical interventions: intramedullary fixation of the tibia using bone grafts alone [6] or with stimulation of osteogenesis through the introduction of bisphosphonates and bone morphogenetic proteins [7], installation of external fixation devices (including the Ilizarov technique) [8], replacement of the tibial bone with a vascularized autograft [9], the «induced membrane» method according to Masqulet [10], or combined methods of intraosseous, periosseous, and external fixation, etc. [11]. All of them are aimed at achieving the same goal — consolidation in the area of pseudoarthrosis of the bones of the tibia, restoration of the correct axis of the lower limb and its length [12].

Considering the number of methods of surgical treatment, the question of choosing the optimal one remains open today. That is why the search and development of new promising directions for solving the complex problem of pediatric orthopedics — the treatment of CPTB — continues. Modernization of fixators and types of bone plastic and, accordingly, biomechanical research in this field is currently being carried out [13].

Purpose: using a mathematical model to study the deformations of the bone regenerate in the area of pseudoarthrosis of the lower leg bones in different options for osteosynthesis.

Material and methods

In the biomechanics laboratory of the State Institution «Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Sciences of Ukraine» mathematical modeling of several variants of osteosynthesis of the bones of the lower leg under the conditions of congenital pseudarthrosis of the tibial bone was performed. To solve this task, an experimental model of the distal end of the lower limb was built, which contained tibia and fibula bones, as well as bone elements of the foot [14]. The zone of non-union of the lower third of the tibia and four variants of osteosynthesis were modeled: intramedullary rod and needle (variant 1); rod, needle and bone graft in the form of a block on the tibia (2) or on both (3) bones; with a rod, a needle and a bone graft on both bones of the leg wrapped with a titanium mesh (4) (Fig. 1). Rotationally stable and unstable «growing» rods were used.

Tibial osteosynthesis involved modeling of an intramedullary two-segment rod with longitudinal mobility and rotational stability, designed and patented at the State Institution «Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Sciences of Ukraine» [15].

The material was considered homogeneous and isotropic. A 10-node tetrahedron with quadratic approximation was chosen as the finite element. When choosing the mechanical properties of biological tissues, it was taken into account that in congenital pseudarthrosis, bone tissue has low mechanical strength [16–18]. For the bone autograft in the form of a block, the properties of healthy bone were chosen [19]. Considering the fact that the bone tissue grows into the titanium mesh, the latter was modeled as a 1 mm thick layer around the graft block with mixed mechanical properties of titanium and cortical bone [20]. The characteristics of artificial materials were chosen from the technical literature [21]. The mechanical characteristics of the materials used in the calculations are given in Table 1.

The study involved modeling of two types of loads — for vertical axial compression and torsion. The model loading schemes are shown in Fig. 2.

The magnitudes of the relative deformations of the bone regenerate in the zone of pseudoarthrosis — the element that undergoes the greatest deformations as a result of the lowest value of the modulus of elasticity — were determined. The study of the stress-strain state of the models was performed using the finite element method. The von Mises stress [22] was used as a criterion for assessing the stress state of models.

The modeling was carried out in the SolidWorks automated design system; the stress-strain state of the models was calculated using the CosmosM software complex [23].

Results and their discussion

The analysis of models of the tibia with pseudarthrosis of both bones in the lower third according to various options for their osteosynthesis using an intramedullary rod of the Fassier-Duval type without

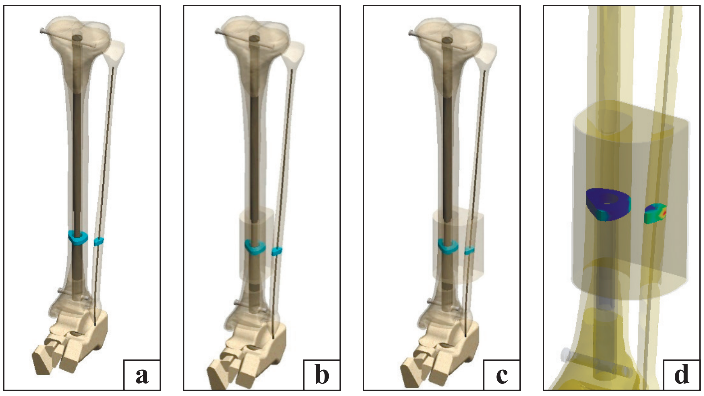

Fig. 1. Models of the lower leg with a bone fracture in the lower third. Osteosynthesis: a) rod and spoke; b) rod and spoke + bone graft in the form of a block on the tibia; c) rod and spoke + bone graft on both bones; d) rod and spoke + bone graft on both bones, covered with titanium mesh

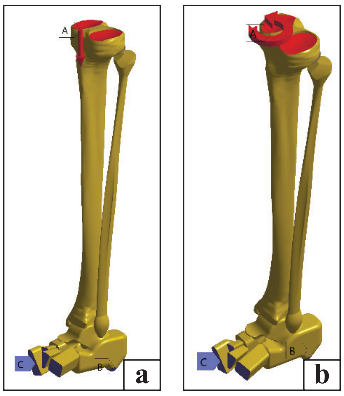

Fig. 2. Models load schemes: a) vertical axial compression; b) torsion

Table 1

Mechanical characteristics of the materials used

Material	Young's modulus (E), MPa	Poisson's ratio, ν
Cortical bone	12240	0.30
Spongy bone	330	0.30
Cartilaginous tissue	5.58	0.45
Bone regenerate	1.0	0.45
Bone autograft	18350	0.29
Alloy steel	210000	0.30

rotational stability under the action of compressive load made it possible to obtain the values of the relative deformation of regenerated bones, shown in Fig. 3 and in Table 2. It was determined that in this case the vertical axial load causes the greatest relative deformations of the regenerate and the tibia (1.96 %) and fibula (1.6 %) bones. This is the result of the longitudinal mobility of the rod, which ensures its increase during the growth of the patient. Adding a bone graft to the model in the form of a block on the tibia sharply reduced the relative deformations of the regenerates: to 0.120 % of the tibia, to 0.064 % of the fibula. When a block of bone grafts was used on both bones, the relative deformations of their regenerates decreased to 0.1 and 0.016 %, respectively.

Administration of a rod with rotational stability for osteosynthesis showed that the pattern of distribution of relative deformations in the bone regenerate under the influence of axial compressive loads almost did not change (Fig. 4, Table 2).

The presence of axial mobility, a factor common to both types of rods, determined their similar reaction to axial compressive loads and, accordingly, the same deformations of the regenerates of both tibia bones. It should be noted that the use of titanium mesh made it possible to reduce the deformations of the regenerate by another 10 % compared to the «rod and spoke + bone graft on both bones» osteosynthesis option.

The next stage of the study was assessment of the relative deformations of the bone regenerate in all models of the lower leg with different options of osteosynthesis under the influence of torsional loading.

The authors determined that the largest relative deformations of the bone regenerate occurred in the model of osteosynthesis of the lower leg bones using only a rotationally unstable rod of the Fassier-Duval type: in the pseudoarthrosis zone of the tibia — 1.92 %, fibula — 0.13 %. The amount of relative deformations of the regenerated tibia was reduced in the case of using bone grafts in the form of a block on this bone itself to 0.035 %, on both bones of the tibia to 0.024 %. On the fibula, the relative deformations of the regenerate when using a block of transplants only on the tibia did not exceed 0.06 %, on both tibia bones it was 0.056 % (Fig. 5, Table 3).

Under the influence of the torsional load, the advantages of the rod with rotational stability were revealed (Fig. 6, Table 3). The study showed that the replacement of the Fassier-Duval rod with a rotationally stable one in the case of torsional loads made it possible to reduce the relative deformation of the regenerated tibia to 0.251 %, fibula to 0.086 %. At the same time, the use of additional blocks of bone grafts (both in the two bones of the lower leg and in the tibia alone) provided the same level of regeneration

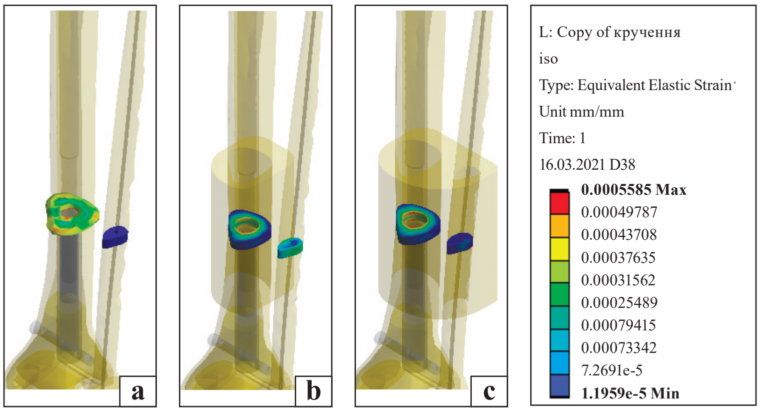

Fig. 3. Relative deformations of the bone regenerate in the model of the lower leg with pseudarthrosis of both bones in the lower third under the influence of compressive load. Fassier-Duval rod. Osteosynthesis: a) rod and spoke; b) rod and spoke + bone graft in the form of a block on the tibia; c) rod and spoke + bone graft on both bones

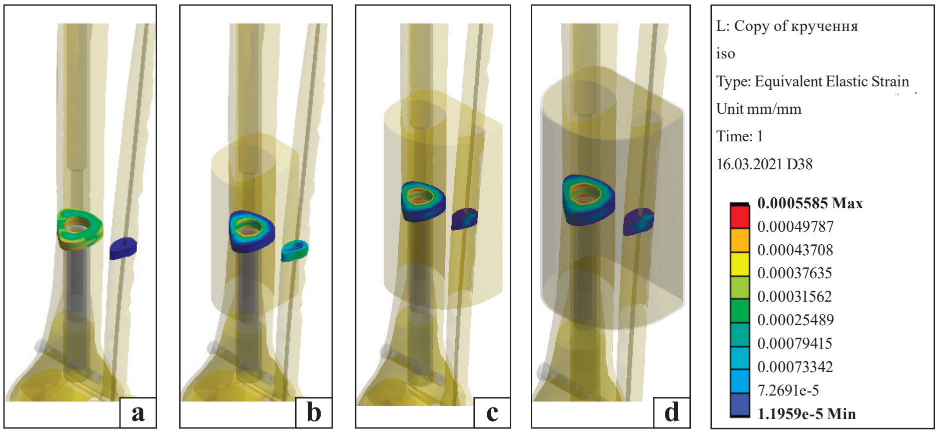

Fig. 4. Relative deformations of the bone regenerate in the model of the lower leg with pseudoarthrosis of both bones in the lower third, compressive load. Rotationally stable rod. Osteosynthesis: a) rod and spoke; b) rod and spoke + bone graft in the form of a block on the tibia; c) rod and spoke + bone graft on both bones; d) rod and spoke + bone graft on both bones, covered with a titanium mesh

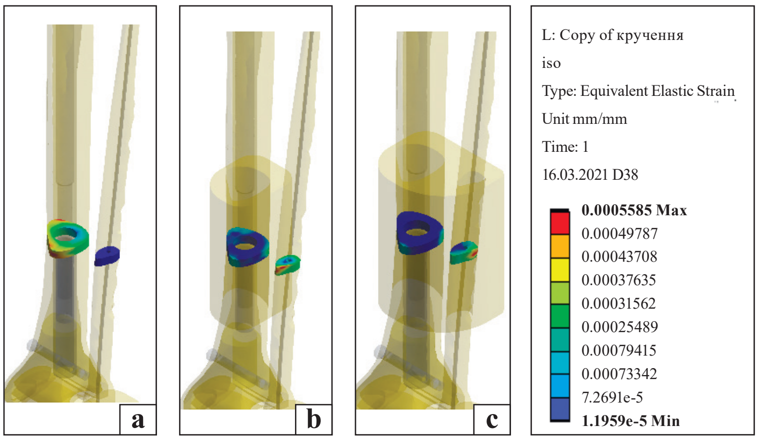

Fig. 5. Relative deformations of the bone regenerate in the model of the lower leg with pseudarthrosis of both bones in the lower third under the influence of torsional load. Fassier-Duval rod. Osteosynthesis: a) rod and spoke; b) rod and spoke + bone graft in the form of a block on the tibia; c) rod and spoke + bone graft on both bones

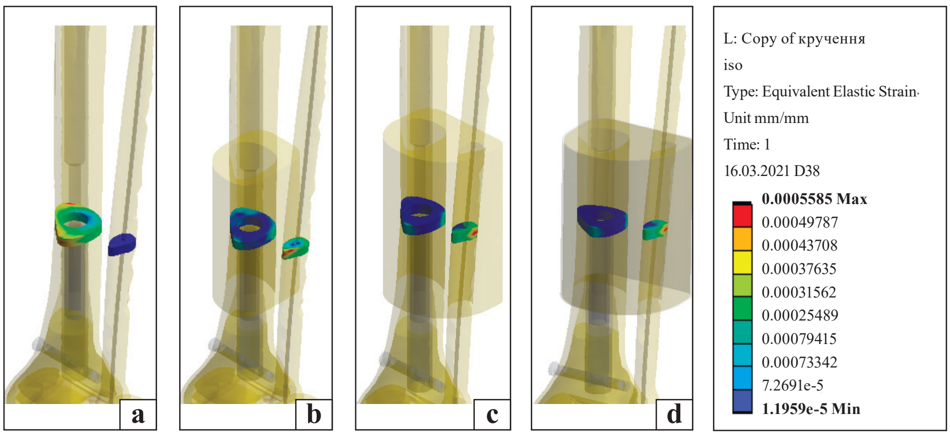

Fig. 6. Relative deformations of the bone regenerate in the model of the lower leg with pseudarthrosis of both bones in the lower third, torsional load. Rotationally stable rod. Osteosynthesis: a) rod and spoke; b) rod and spoke + bone graft in the form of a block on the tibia; c) rod and spoke + bone graft on both bones; d) rod and spoke + bone graft on both bones, covered with a titanium mesh

Table 2

Values of relative deformations (%) of bone regenerate under the influence of compressive load in the models with various types of osteosynthesis of the lower leg bones in congenital pseudarthrosis

Bone	Rod	Types of osteosynthesis			
		1	2	3	4
Tibia	unstable	1.96	0.120	0.100	—
	stable	1.94	0.120	0.100	0.090
Fibula	unstable	1.60	0.064	0.016	—
	stable	1.60	0.062	0.015	0.014

Table 3

Values of relative deformations (%) of bone regenerate under the influence of torsional load in models with different types of osteosynthesis of lower leg bones in congenital pseudarthrosis

Bone	Rod	Types of osteosynthesis			
		1	2	3	4
Tibia	unstable	1.920	0.035	0.024	—
	stable	0.251	0.034	0.023	0.021
Fibula	unstable	0.130	0.060	0.056	—
	stable	0.086	0.059	0.056	0.056

deformations as determined under the conditions of osteosynthesis modeling with a rotationally unstable rod. This indicates that in this case the function of rotational stabilization is taken over by bone graft blocks. The titanium mesh also provided additional stabilization, resulting in a decrease in the relative strain of the tibial regenerate to 0.021 %, but no change in the fibular regenerate.

Thus, mathematical modeling showed that in the case of congenital pseudarthrosis of the bones of the lower leg, osteosynthesis with only intramedullary rods of both types (rotationally stable or unstable) did not ensure minimum deformation of regenerate of both bones. This is explained by axial mobility of the elements of the rods, which makes it possible to increase their length during the growth of the patient. Blocks of bone grafts, placed around the tibia or both bones of the lower leg, eliminate this shortcoming by taking on part of the compressive load, which allows to significantly (up to 20 times) reduce the level of deformation of the regenerates.

The advantages of a rotationally stable rod were revealed under the influence of torsional loads, when 20 times smaller relative deformations of the regenerate at the level of pseudoarthrosis of the tibial bone were determined. Blocks of bone grafts in this case neutralize this advantage, as they provide rotational stability of bone fragments of the lower leg.

The use of a titanium mesh provides additional strength of fixation of fragments of both bones of the lower leg, which allows to reduce deformations of regenerated bones by 10 % compared to osteosynthesis models with a block of transplants on both bones of the lower leg in both loading options.

Conclusions

The use of osteosynthesis in bones of the lower leg during the treatment of congenital pseudarthrosis using only intramedullary «growing» rods does not provide a sufficient level of stability of fixation of bone fragments, which leads to the greatest deformations of bone regenerates.

The use of a rod with rotational stability is preferable in torsional loading, since the relative deformations of the regenerate at the level of tibial pseudoarthrosis are 20 times smaller than when modeling osteosynthesis with a rotationally unstable rod.

Installation of blocks from bone grafts makes it possible to diminish the level of relative deformation of the regenerates of both bones of the lower leg to the level of less than 0.1 % for both load variants. The use of a titanium mesh adds an additional 10 % to the reduction of deformations of bone regenerates.

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

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STUDY OF DEFORMATIONS OF BONE REGENERATE UNDER DIFFERENT OPTIONS OF OSTEOSYNTHESIS OF LOWER LEG BONES IN THE CASE OF THEIR CONGENITAL PSEUDARTHROSIS

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