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Mathematical modeling of the stress-strain relations of the foot elements in the conditions of lateral malleolus hypoplasia

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One of the most common complications of long-term talocrural joint (TCJ) injury is the development of chronic instability. Among the risk factors for its occurrence - congenital or acquired shortening (hypoplasia) of the lateral malleolus of varying degrees. Objective. Determine the effect of lateral malleolus hypoplasia on the distribution of stresses in the bone and ligament elements of the foot. Methods. Mathematical modeling of the distal end of the lower extremity was performed. There are two variants of the position of the heel bone — varus and valgus with an angle of deviation from the vertical axis in both cases 15°. A vertical distributed load of 700 N was applied to the tibial plateau. On the supporting surface of the feet model's were rigidly fixed. Measurements of mechanical stresses were performed at control points. According to the criteria for estimating the stress-strain relations (SSR), the Mises stress was used. Results. It was determined that lateral malleolus hypoplasia increases the values of stresses on the lateral side of the distal tibial bone from 6.3 MPa to 6.4 MPa, from the medial — on the heel bone from 5.8 MPa to 6.0 MPa, talus from 2.1 MPa to 2.3 MPa. SSR on TCJ are also varies. In the case of a neutral position of the heel bone, lateral malleolus hypoplasia causes a decrease in the values of the ligaments on the lateral side of the TCJ, which can be explained by their elongation and, consequently, the projection increase in length In the case of varus or valgus position of the heel bone under conditions of lateral ankle hypoplasia, it was found that the varus position of the heel bone overstrains the ligaments on the lateral side, valgus - from the medial. Conclusions. Decreased stress in the ligaments of the TCJ in cases of valgus or varus position of the heel bone is one of the factors reducing the functional stability of the joint and may be the cause of its chronic instability. Key words. Injury of the talocrural joint joint, ligaments, instability, finite element method, lateral malleolus hypoplasia, stress-strain condition.

Одним із частих ускладнень лікування травм надп'ятково-гомілкового суглоба (НГС) у віддаленому періоді є розвинення його хронічної нестабільності. Серед чинників ризику її виникнення — уроджене або набуте укорочення (гіпоплазія) латеральної кісточки різного ступеня. Мета. Визначити вплив гіпоплазії латеральної кісточки на розподіл напружень у кісткових і зв'язкових елементах стопи. Методи. Проведене математичне моделювання дистального кінця нижньої кінцівки. Відтворено два варіанти положення п'яткової кістки — варусне та вальгусне з кутом відхилення від вертикальної осі в обох випадках 15°. Вертикальне розподілене навантаження величиною 700 Н прикладали до плато великогомілкової кістки. По опорній поверхні стопи моделі мали жорстке закріплення. Заміри величин механічних напружень проводили в контрольних точках. За критерії оцінки напружено-деформованого стану (НДС) використано напруження за Мізесом. Результати. Визначено, що за гіпоплазії латеральної кісточки збільшуються величини напружень із латерального боку на піднадп'ятковій кістці від 6,3 МПа до 6,4 МПа, із медіального — на п'ятковій від 5,8 МПа до 6,0 МПа, надп'ятковій від 2,1 МПа до 2,3 МПа. Також змінюється НДС у зв'язках НГС. У випадку нейтрального положення п'яткової кістки гіпоплазія латеральної кісточки спричинює зниження величин напружень у зв'язках із латерального боку НГС, що можна пояснити їхнім подовженням та, відповідно, проєкційним збільшенням довжини. У випадку варусного або вальгусного положення п'яткової кістки за умов гіпоплазії латеральної кісточки виявлено, що за варусного положення п'яткової кістки перенапружуються зв'язки з латерального боку, вальгусного — із медіального. Висновки. Зменшення величин напружень у зв'язках НГС у випадках вальгусного або варусного положення п'яткової кістки є одним із чинників зниження функціональної стійкості суглоба та може бути причиною розвитку його хронічної нестабільності. Ключові слова. Ушкодження надп'ятково-гомілкового суглоба, зв'язки, нестабільність, метод скінченних елементів, гіпоплазія латеральної кісточки, напружено-деформований стан.

Key words. Injury of the talocrural joint joint, ligaments, instability, finite element method, lateral malleolus hypoplasia, stress-strain condition

Introduction

Injuries of the talocrural joint (TCJ) occupy one of the first places in the structure of injuries of the lower extremities and account for 10 to 20 % of all injuries of the musculoskeletal system, and injuries of the TCJ ligaments occur in 35–50 % of such cases [1, 2]. One of the frequent complications in the treatment of such TCJ lesions in the long term is the development of its chronic instability (CI). The clinical picture of TCJ CI is quite characteristic and consists of excessive mobility (hypermobility) of the foot, the presence of symptoms of a «drawer», episodes of pain and edema and, as a consequence, the development of early degenerative changes in TCJ [3, 4]. The many factors influencing the development of TCJ CI include congenital or acquired shortening (hypoplasia) of the lateral bone of varying severity, which can lead to these changes [5].

The aim of the study: To determine the effect of lateral bone hypoplasia on the distribution of stresses in the bone and ligament elements of the foot.

Material and methods

In the laboratory of biomechanics of the State Institution «Professor M. I. Sytenko Institute of Abnormalities of the Spine and Joints of the National Academy of Medical Sciences of Ukraine» we performed mathematical modeling to determine the effect of lateral bone hypoplasia on the stress-strain state (SSS) of the foot elements.

To solve this problem, a mathematical finite element model (MFEM) of the distal end of the lower extremity with additions was previously developed [6, 7], which contained the bone elements of the foot and leg (Fig. 1).

MFEM contained the main connections between the TCJ and the posterior area of the foot: *lig. caneofibulare* (calcaneofibular), *lig. talofibulare anterius* (anterior talofibular), *lig. talofibulare posterius* (posterior talofibular), *lig. tibiofibulare anterius* (anterior tibiofibular), *lig. tibiofibulare posterius* (posterior tibiofibular), *membrana* (interosseous membrane), *lig. tibiocalcaneo medial* (medial tibiocalcaneal), *lig. tibiotalar anterius* (anterior tibiotalar), *lig. tibiotalar posterius* (posterior tibiotalar), *aponeurosis plantaris* (plantar aponeurosis).

The position of the lateral bone was chosen when its apex is located at the level of the medial bone (normally 1–1.5 cm below the level). Since the ligaments work only in tension, two variants of the heel bone position were simulated during the study: varus and valgus. The angle of deviation from the initial position of the heel bone in both cases was 15° (Fig. 2).

The material was considered homogeneous and isotropic. A 10-node tetrahedron with a quadratic approximation was chosen as the finite element. The mechanical properties of biological tissues were taken from those in the literature [8, 9]. The following characteristics were used for the analysis: modulus of elasticity (E, Young's modulus), Poisson's ratio (ν) (Table 1).

The models were tested under the influence of a vertical distributed load of 700 N, which corresponds to the average weight of an adult [10].

Table 1

Mechanical characteristics of materials used in the modeling process

Material	Young's modulus (E), MPa	Poisson's ratio, ν
Cortical bone	18350	0.29
Spongy bone	330	0.30
Cartilaginous tissue	10.5	0.49
Ligaments	110 000	0.20

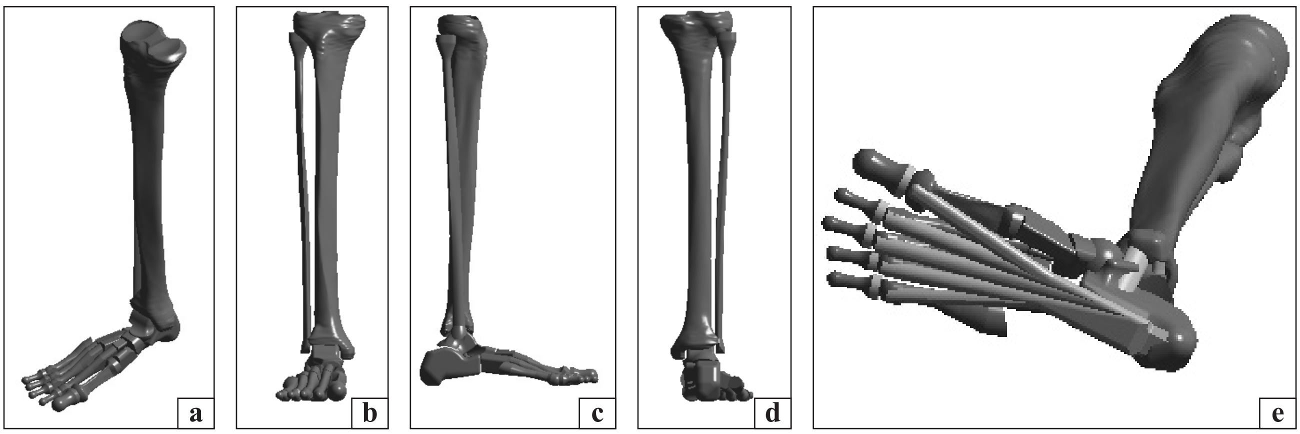

Fig. 1. MFEM of the right tibia and foot in lateral bone hypoplasia: general view (a), front (b), in the sagittal plane (c), back (d), bottom (e)

The load was applied to the plateau of the tibia. The models were rigidly fixed on the supporting surface of the feet. The scheme of loading of models is given in fig. 3, a.

To compare the changes in the SSS models, control points were selected at which measurements of mechanical stresses were performed (Table 2). The layout of the control points is shown in Fig. 3, b, c.

The calculation of SSS of the models was performed using the finite element method. Mises stress was used as a criterion for estimating the stress state of the models [8].

The simulation was performed using the SolidWorks computer-aided design system. Calculations of SSS of the models were performed using the CosmosM software package [11].

Results and discussion

In the first stage of our study, we evaluated the stress-strain state of the tibia model with lateral bone hypoplasia under single-support standing conditions and during the normal position of the heel bone.

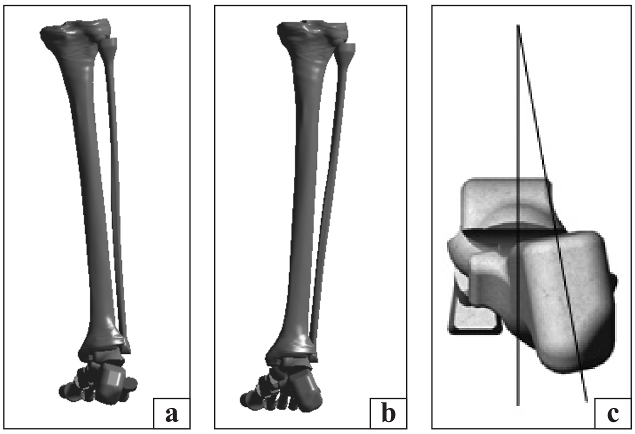

Fig. 2. Models of abnormal setting of the foot: varus (a) and valgus (b) position of the heel bone, angle 15°; calcaneotibial angle (c)

The picture of stress distribution in the bone elements of the model is shown in Fig. 4.

Under conditions of hypoplasia of the lateral bone during single-support standing and in normal position of the heel bone there are maximum stresses in the bone elements: on the lateral side the most intense was the subtalar bone (6.4 MPa) compared to the heel bone (2.6 MPa). On the medial side, on the other hand, the heel bone was tighter (6.0 MPa versus 2.3 MPa in the subtalar area). The maximum stress was determined on the support surfaces of the heel and subtalar bones — 37.4 MPa and 21.0 MPa, respectively.

The SSS relationship between the model and the foot with lateral bone hypoplasia under normal heel bone position is shown in Fig. 5.

The maximum tension in the ligaments was recorded on the lateral side, namely, *lig. talofibulare*

Table 2

MFEM control points of the right tibia and foot

Side	Control point	Anatomic structure
Lateral	1	*lig. calcaneofibulare*
	2	*lig. talofibulare anterius*
	3	*lig. talofibulare posterius*
	4	*lig. tibiofibulare anterius*
	5	*lig. tibiofibulare posterius*
	6	membrana (мембрана)
	13	heel bone
	14	subtalar bone
Medial	7	*lig. tibiocalcaneo medial*
	8	*lig. tibiotalar anterius*
	9	*lig. tibiotalar posterius*
	10	*aponeurosis plantaris*
	15	heel bone
	16	subtalar bone
	11	heel bone
	12	subtalar bone

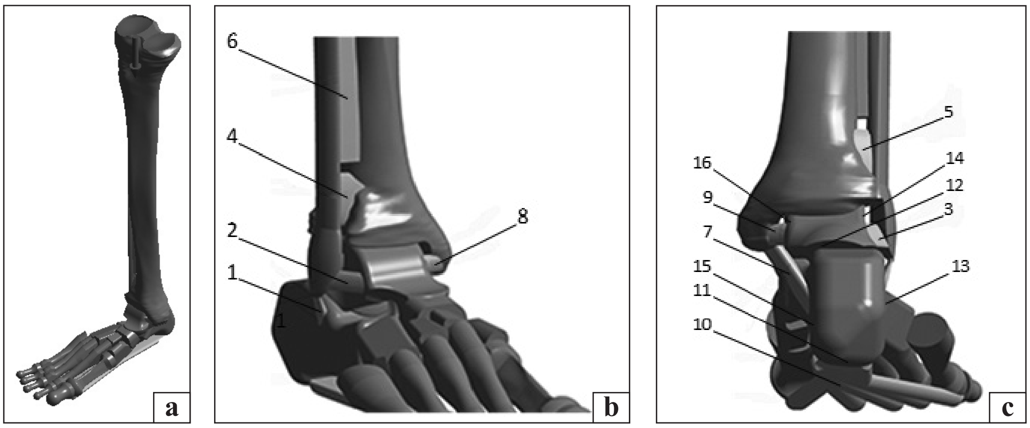

Fig. 3. Schemes: a) load MFEM of the right tibia and foot; b, c) location of control points on it

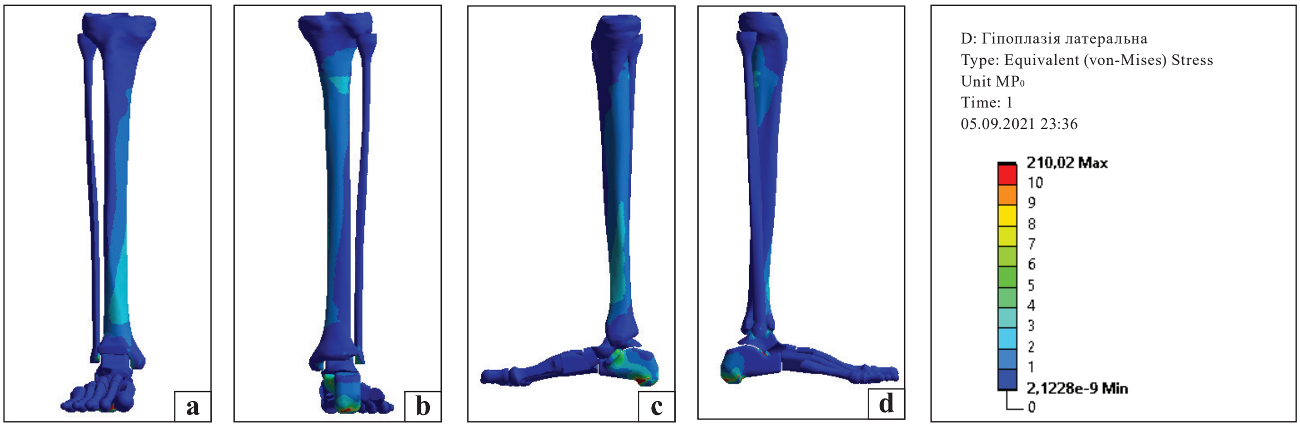

Fig. 4. Picture of stress distribution in the bone elements of the tibia and foot model with lateral bone hypoplasia in the normal position of the heel bone: front (a), back (b), medial (c), lateral (d) sides

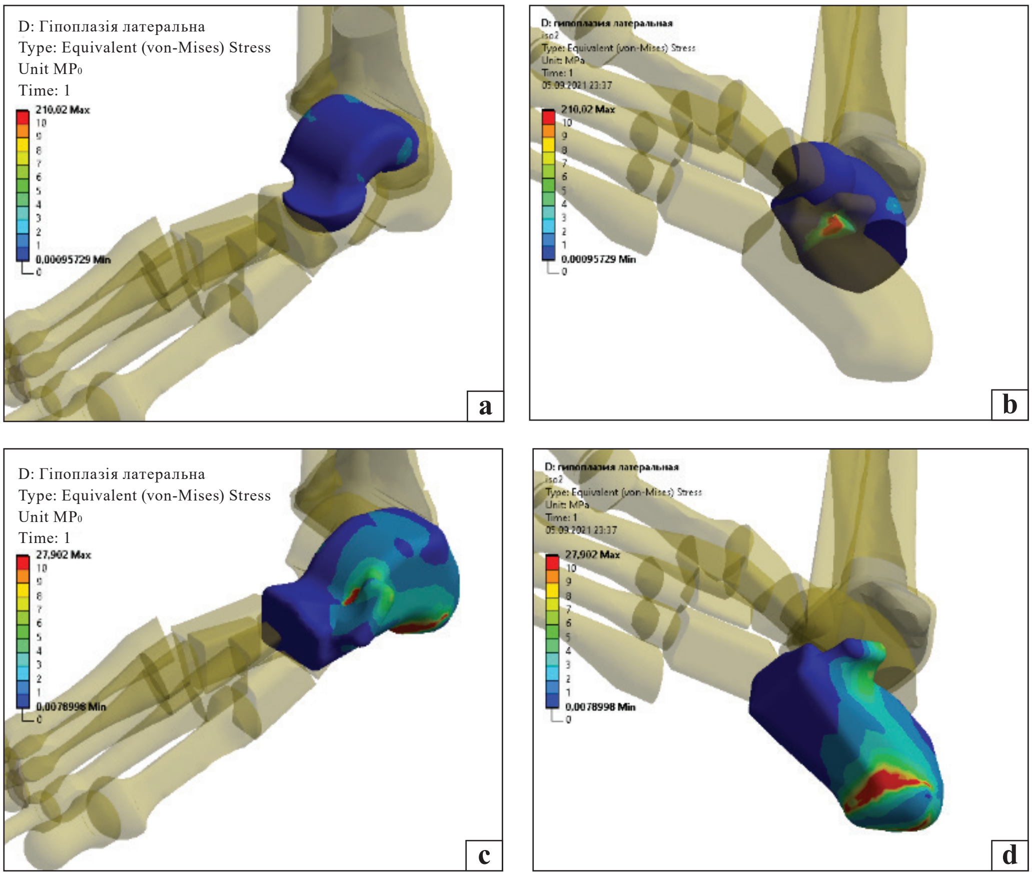

Fig. 5. Picture of the distribution of stresses in the relationship of the tibia and foot model in hypoplasia of the lateral bone in the normal position of the heel bone: SSS on the subtalar bone — top (a) and bottom (b); on the heel bone — top (c) and bottom (d)

posterius and *lig. talofibulare anterius*, where they became 4.4 MPa and 2.6 MPa, respectively. The intermediate value of 3.4 MPa was defined in *lig. calcaneofibulare*. In other lateral ligaments, the stresses did not exceed 0.5 MPa.

On the medial side, the tension in the ligaments was slightly lower. The most intense were *lig. tibiotalar anterius* and *lig. tibiotalar posterius* — 3.5 MPa and 3.3 MPa. In *lig.tibiocalcaneo medial* the maximum stress was 2.7 MPa, and *aponeurosis plantaris* was almost not stressed — 0.2 MPa.

The second stage of the study assessed the stress-strain state of the tibia and foot model with lateral bone hypoplasia under the varus position of the heel bone. The picture of stress distribution in the bone elements of the model is given in Fig. 6.

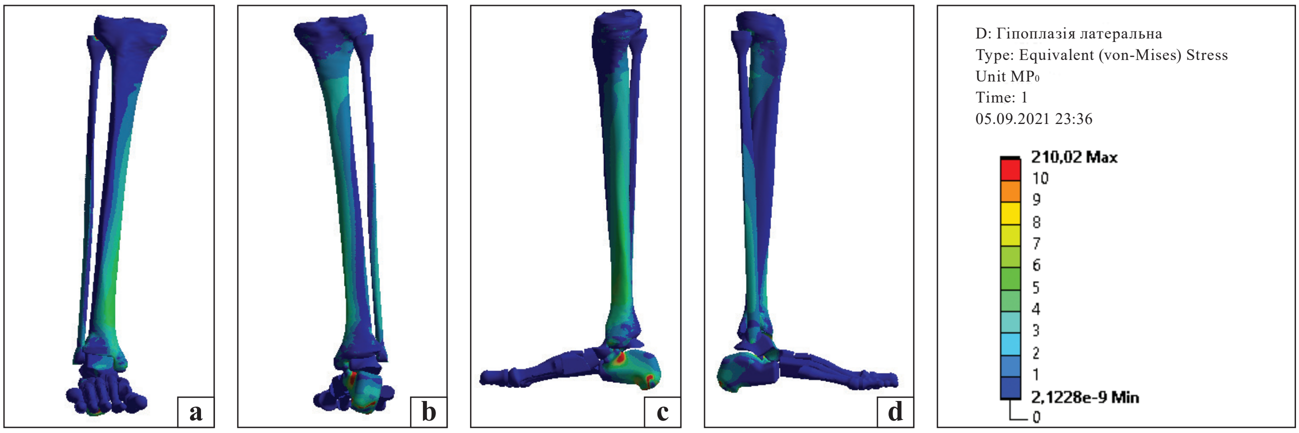

Fig. 6. Picture of stress distribution in the bone elements of the tibia and foot model with lateral bone hypoplasia in varus position of the heel bone: front (a), back (b), medial (c) and lateral (d) sides

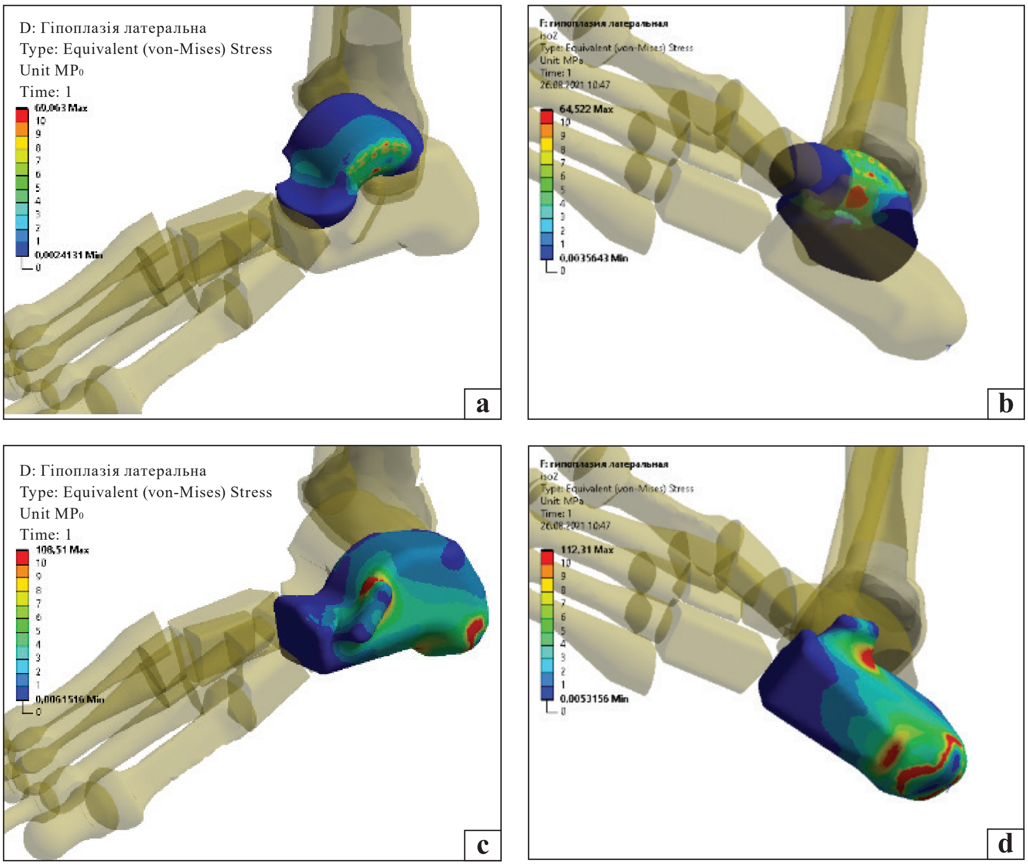

Fig. 7. Picture of stress distribution in the relationship of the tibia and foot model in lateral bone hypoplasia in varus position of the heel bone. SSS on the subtalar bone — top (a), bottom (b); on the heel bone — top (c) and bottom (d)

The support of the foot in the varus position of the heel bone led to a significant redistribution of stresses on the bone elements of the model, namely their growth from the medial side of the heel bone to 13.8 MPa, subtalar — up to 13.3 MPa. On the lateral side, stresses increased slightly in the heel bone — 4.6 MPa, but they decreased in the heel bone — 1.8 MPa. On the supporting surface of both bones, an increase in stress values was found, which reached 74.0 MPa and 108.0 MPa on the heel and subtalar bones, respectively.

The distribution of stresses in the ligaments of the tibia and foot in the case of lateral bone hypoplasia at the varus position of the heel bone is shown in Fig. 7.

The varus position of the heel bone under the foot rests has led to an increase in the tension in the ligaments located on the lateral side. The maximum

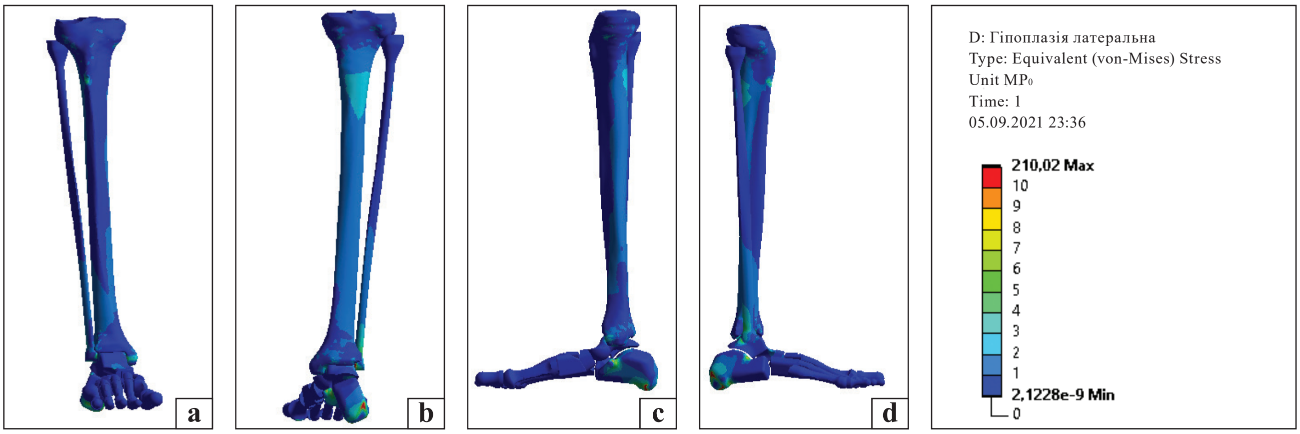

Fig. 8. Picture of stress distribution in the bony elements of the tibia and foot model in hypoplasia of the lateral bone in valgus position of the heel bone: front (a), back (b), medial (c) and lateral (d) sides

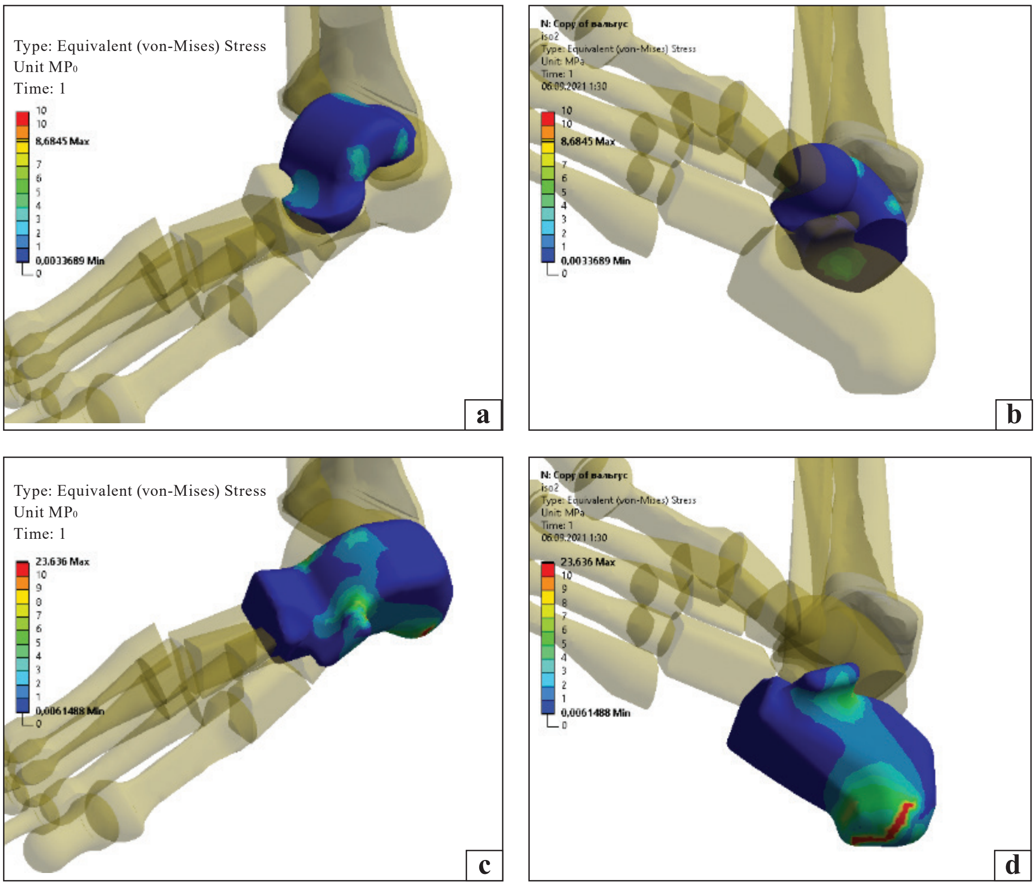

Fig. 9. Picture of the distribution of stresses in the ligaments of the tibia and foot in hypoplasia of the lateral bone in valgus position of the heel bone: on the subtalar bone — top (a) and bottom (b); on the heel bone — top (c) and bottom (d)

stress values (7.6 MPa) were defined in *lig. calcaneofibulare*. The exception was *lig. talofibulare posterius* and *lig. talofibulare anterius*, where stresses decreased to 2.1 MPa and 1.2 MPa, respectively.

On the medial side the tension in the *lig. tibiotalar anterius* and *lig. tibiotalar posterius* increased to 3.8 MPa and 4.2 MPa, respectively. Also, an increase in the amount of stress to 0.5 MPa was found in *aponeurosis plantaris*, and in *lig. tibiocalcaneo medial* — a decrease of up to 1.0 MPa compared to the support at the normal position of the heel bone.

The last stage of the study assessed the distribution of stresses in the bone elements of the tibia and foot model in lateral bone hypoplasia under the valgus position of the heel bone (Fig. 8).

Table 3

Stress values at control points of models in lateral bone hypoplasia depending on the position of the heel bone

Side	Control point	Anatomic structure	Stress, MPa			
			Norm	Hypoplasia		
				norm	varus	valgus
Lateral	1	*lig. calcaneofibulare*	8.4	3.4	7.6	0.2
	2	*lig. talofibulare anterius*	2.6	2.6	1.2	1.5
	3	*lig.talofibulare posterius*	8.2	4.4	2.1	3.3
	4	*lig.tibiofibulare anterius*	0.6	0.5	3.0	0.5
	5	*lig.tibiofibulare posterius*	1.2	1.0	2.3	0.4
	6	membrana	0.2	0.2	1.4	0.3
	15	heel bone	2.6	2.6	4.6	9.8
	14	subtalar bone	6.3	6.4	1.8	10.1
Medial	7	*lig.tibiocalcaneo medial*	3.2	2.7	1.0	9.7
	8	*lig.tibiotalar anterius*	3.4	3.5	3.8	14.3
	9	*lig.tibiotalar posterius*	4.6	3.3	4.2	8.8
	10	*aponeurosis plantaris*	0.,2	0.2	0.5	1.8
	15	heel bone	5.8	6.0	13.8	3.0
	16	subtalar bone	2.1	2,3	13.3	2.5
Support surface	11	heel bone	37.4	37.4	74.0	50.0
	12	subtalar bone	20.2	21.0	108.0	69.1

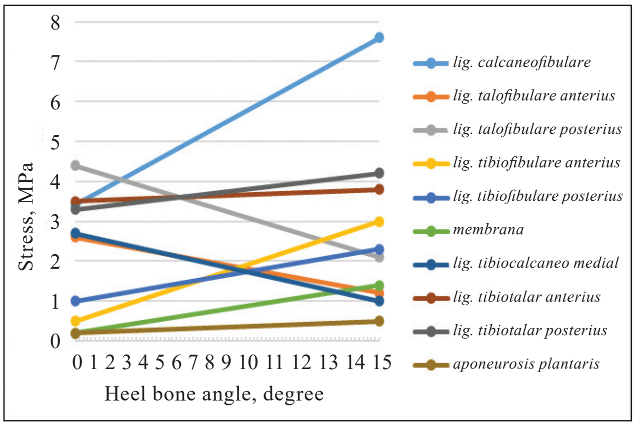

Fig. 10. Graph of the dependence of stress magnitude in the ligaments of the model in lateral bone hypoplasia depending on the magnitude of the angle of the varus position of the heel bone

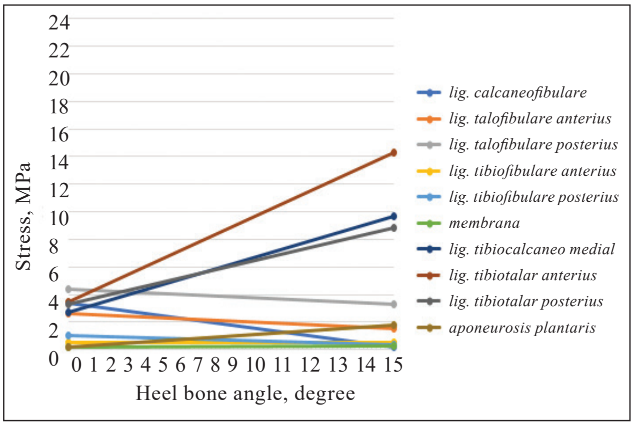

Fig. 11. Graph of the dependence of stress magnitude in the relationship of the model in lateral bone hypoplasia on the value of the angle of the valgus position of the heel bone

The valgus position of the heel bone in the case of foot support in lateral bone hypoplasia led to a significant increase in stresses on the lateral side of the subtalar bone — 10.1 MPa. On the lateral side of the heel bone stresses were determined at the level of 9.8 MPa. On the medial side, the stresses in the heel and subtalar bones were recorded at 3.0 MPa and 2.5 MPa, respectively. On the supporting surface of the heel bone, the stress values were 50.0 MPa, on the subtalar bone — 69.1 MPa.

The distribution of stresses in the ligaments of the tibia and foot in lateral bone hypoplasia under the valgus position of the heel bone is shown in Fig. 9.

In loading the limb in the valgus position of the heel bone, the tensest ligaments were on the medial side: *lig. tibiotalar posterius* — 14.3 MPa, *lig. tibiocalcaneo medial* — 9.7 MPa, *lig. tibiotalar anterius* — 8.8 MPa. On the lateral side, lower ligament stresses were recorded. The maximum value of stresses was defined in *lig. posterior talofibular* — 3.3 MPa.

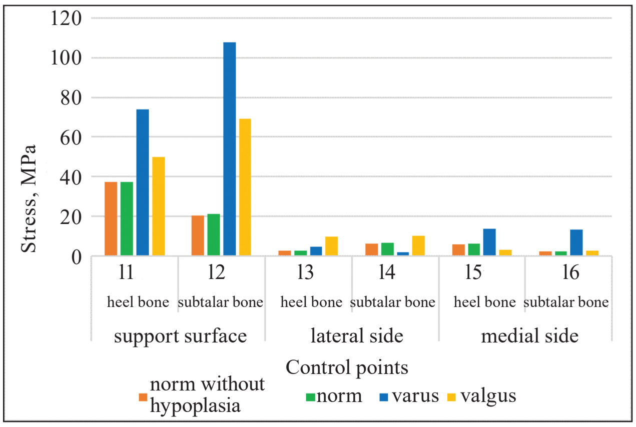

Fig. 12. Diagram of stress values in the heel and subtalar bones in the model in lateral bone hypoplasia depending on the position of the heel bone

Indicators of the magnitude of stresses in the control points of the models in lateral bone hypoplasia, depending on the options for the position of the heel bone are given in Table 3. As we can see, hypoplasia of the lateral bone in the normal position of the heel bone compared to the model of the normal structure of the foot has led to a decrease in SSS in the tensest ligaments on the lateral side: *lig. calcaneofibulare* and *lig. talofibulare posterius* — 3.4 MPa and 4.4 MPa, respectively. A slight increase was found in *lig.tibiotalar anterius* — from 3.4 MPa to 3.5 MPa.

Figure 10 shows the dependence of the magnitude of the stresses in the ligaments of the model in lateral bone hypoplasia depending on the magnitude of the angle of the varus position of the heel bone.

Figure 11 shows the dependence of SSS in the ligaments of the model in lateral bone hypoplasia on the value of the angle of the valgus position of the heel bone.

Figure 12 shows a diagram that allows a more detailed comparison of the values of stresses in the heel and subtalar bones of models in the case of lateral bone hypoplasia, depending on the options for the position of the heel bone.

In the bony elements of the TCJ model, hypoplasia of the lateral bone resulted in changes in the magnitude of lateral stresses on the subtalar bones from 6.3 MPa to 6.4 MPa, medial — on both bones: heel — from 5.8 MPa to 6.0 MPa, subtalar — from 2.1 MPa to 2.3 MPa.

Conclusions

The study showed that lateral bone hypoplasia leads to changes in SSS in both the bone elements of the TCJ and its ligaments. In particular, in the case of the neutral position of the heel bone, the values of stresses in the ligaments on the lateral side of the TCJ are reduced, which can be explained by their relative elongation and, accordingly, the projection increase in their length. In varus or valgus position of the heel bone in lateral bone hypoplasia, the models showed a very predictable result: in varus position of the heel bone, the ligaments on the lateral side were overstrained, in valgus — on the medial side.

Decreased stress in the ligaments of the TCJ in valgus or varus position of the heel bone is one of the factors reducing the functional stability of this joint and can lead to the development of its chronic instability.

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

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MATHEMATICAL MODELING OF THE STRESS-STRAIN RELATIONS OF THE FOOT ELEMENTS IN THE CONDITIONS OF LATERAL MALLEOLUS HYPOPLASIA

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