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Work of muscles responsible for the functioning of the foot in conditions of knee joint contracture

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Prolonged walking with knee joint contracture causes changes in the functioning of the muscles of the lower leg and foot. Objective. To study the functioning of the foot and leg muscles in the conditions of knee joint contracture using a human walking model. Methods. The gait analysis was performed in the OpenSim 4.0 program. The modeling was based on the gait2394 model. The following muscles were studied: m. peroneus brevis, m. peroneus longus, m. peroneus tertius, m. tibialis posterior, m. tibialis anterium, m. flexor digitorum longus, m. flexor hallucis longus, m. extensor digitorum longus, m. extensor hallucis longus. Results. Restriction of joint mobility leads to a redistribution of muscle strength. In conditions of 15° knee joint flexion contracture, support on the toes causes significant overstrain of the muscles responsible for the functioning of the lower leg, foot and toes. In particular, the m. peroneus brevis and m. peroneus longus are quite long, their function is impaired, but the required increase in strength is from 10 to 400 %, while the m. peroneus tertius (short), for foot flexion in some phases of the step, its strength increased threefold. Among the muscles of the lower leg, the greatest increase in isometric strength was required for the m. tibialis anterior compared to the m. tibialis posterior, which works mainly for foot extension. For the muscles responsible for flexion/extension of the toes in conditions of knee joint contracture, a significant, sometimes 3–5 times, increase in strength was necessary to perform the required function. Conclusions. Knee joint contracture leads to a change in the biomechanics of the entire lower extremity, namely, to an increase in changes in the functioning of the muscles responsible for the functioning of the foot, which work under such conditions with a constant increase in tension. Given the impact of knee joint contracture on the functioning of the muscles of the lower extremity, it is possible to predict the course of the pathological process, determine which muscle groups are most affected and which muscle group needs to be corrected before and after surgery.

Тривала ходьба в умовах контрактури колінного суглоба спричинює зміни в роботі м'язів гомілки та стопи. Мета. На моделі ходьби людини вивчити роботу м'язів стопи та гомілки за умов контрактури колінного суглоба. Методи. Аналіз ходьби проводили в програмі OpenSim 4.0. За основу моделювання взято модель gait2394. Вивчали роботу м'язів: m. peroneus brevis, m. peroneus longus, m. peroneus tertius, m. tibialis posterior, m. tibialis anterium, m. flexor digitorum longus, m. flexor hallucis longus, m. extensor digitorum longus, m. extensor hallucis longus. Результати. Обмеження рухомості в суглобах приводить до перерозподілу сили м'язів. За умов згинальної контрактури колінного суглоба 15° опора на пальці стопи спричинює значне перенапруження м'язів, відповідальних за функціонування гомілки, стопи та пальців. Зокрема, m. peroneus brevis, m. peroneus longus доволі довгі, їхня функція порушується, але визначене необхідне збільшення сили становить від 10 до 400 %, водночас m. peroneus tertius (короткий), для згинання стопи у деяких фазах кроку його сила підвищилася втричі. Серед м'язів гомілки найбільше підвищення ізометричної виявилося необхідним для m. tibialis anterior порівняно з m. tibialis posterior, який працює здебільшого на розгинання стопи. Для відповідальних за згинання/розгинання пальців стопи м'язів в умовах контрактури колінного суглоба необхідним виявилося значне, іноді в 3–5 разів, збільшення сили для виконання необхідної функції. Висновки. Контрактура колінного суглоба призводить до зміни біомеханіки всієї нижньої кінцівки, а саме: до наростання змін у роботі м'язів, відповідальних за функціонування стопи, які працюють за таких умов з постійним збільшенням напруження. Ураховуючи вплив контрактури колінного суглоба на роботу м'язів нижньої кінцівки, можна прогнозувати перебіг патологічного процесу, визначити, які групи м'язів страждають найбільше та якій групі м'язів необхідно проводити корекцію до та після хірургічного втручання. Ключові слова. Колінний суглоб, контрактура, моделювання, сила м'язів.

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

Introduction

Deviation from the normal anatomical structure and functioning of the musculoskeletal system of a person is one of the serious diseases of the population. The registered prevalence of orthopedic diseases ranges from 7.2 to 36.2 %. Knee joint injuries account for 12.7 % of women and 4.8 % of men [1].

One of the most common complications of knee joint abnormalities is contracture, which can occur both as a result of injuries and the development of a degenerative process (gonarthrosis). It is known that even a contracture of 5° causes lameness, an increase in the amount of limitation of mobility, especially under the conditions of a long course, leads to changes in the work of the joints of the lower extremities and the spine.

To date, there are known studies on the work of the muscles around the knee joint in conditions of limitation of its mobility [2], as well as those examining the changes in the work of the muscles of the hip joint during knee contracture [3]. But in the case of formation of a contracture of the knee joint, in order to preserve the symmetry of the length of the limbs and reduce lameness, a person is subconsciously forced to overextend the foot. And the greater the angle of the flexion contracture, the greater the angle it is necessary to extend the supracalcaneal joint. This way of moving leads to overstraining of the muscles of the foot and lower leg.

Purpose: to study the work of the muscles of the foot and lower leg under conditions of contracture of the knee joint on a human walking model.

Material and methods

The analysis of walking was carried out in the OpenSim 4.0 software [4]. The model gait2394 [3, 5] is used as the basis of modeling, which allows studying 76 muscles of the lower limbs and trunk. The non-scale model is an object with a height of 1.8 m and a mass of 75.16 kg. We investigated muscle dysfunction under conditions of knee joint contracture, which was modeled by limiting its extension to 15°. The analysis was performed for the muscles of the right lower limb, comparing with the parameters of the base model (the same limb without limitation of extension).

The study involved assessment of the work of the following muscles: *m. peroneus brevis, m. peroneus longus, m. peroneus tertius, m. tibialis posterior, m. tibialis anterium, m. flexor digitorum longus, m. flexor hallucis longus, m. extensor digitorum longus, m. extensor hallucis longus*. The analysis of the change in the strength of the muscles of the lower limb was carried out in relation to the time parameters of the step (Fig. 1).

It is based on the 8-phase model of walking [6]:

1. Front thrust (0.65 s) — the first period of the support phase of the step, when the heel touches the support surface. The hips are in a position of slight flexion, the lower leg is fully extended at the knee joint (phase of two-legged stance).

2. The phase of rolling from the heel to the foot (0.65–0.83 s) — the heel is successively included in the load, then the whole foot. The thigh is gradually extended, the lower leg is bent from 0° to 15° in the knee joint.

3. The period of rolling from the foot to the front part (0.83–0.87 s) — the center of gravity of the body is under the foot, the contralateral limb does not touch the supporting surface (period of single-support standing). The hip is gradually extended, the lower leg — from 15° of flexion to 0° (to a neutral position) in the knee joint.

4. Back thrust (0.87–1.15 s) — the heel breaks away from the surface, the load is redistributed to the heads of the metatarsal bones. The hips are fully extended, the shin is in a position from neutral (0°) to full extension (3°–5° overextension in the knee joint).

5. The phase of separation of the supporting limb from the plane of support (1.15–1.27 s) — hip extension decreases, the lower leg gradually bends to 30°–35° in the knee joint, the toes come off the surface.

6. The beginning of the transfer period (1.27–1.48 s) — the hip gradually bends, the lower leg progressively bends in the knee joint up to 60°.

7. The middle transfer phase (1.48–1.63 s) — the thigh is flexed due to the contraction of the muscles of the front surface of the thigh, the lower leg is progressively extended from a flexion position of 60° to a neutral position (0°) in the knee joint. During this period, the weight of the body is completely distributed on the contralateral limb.

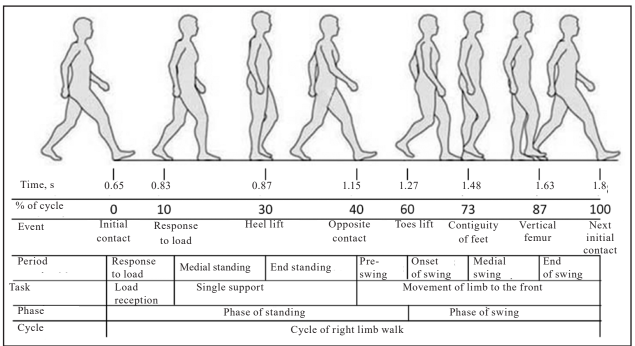

Fig. 1. Right leg step cycle diagram (percentage of phase duration, phase time for the model)

8. The final phase of transfer (1.63–1.8 s) — maximum hip flexion up to 30°, full extension of the lower leg (up to 3°–5° overextension in the knee joint), the foot takes a neutral position.

Results and their discussion

The peroneus (*fibularis*) muscles (fibula muscles) perform actions of plantar flexion of the foot and its outward rotation. Their work in conditions of contracture of the knee joint is shown in Fig. 2.

M. peroneus longus is the longest muscle of the lateral region of the leg. The main functions are inversion of the ankle and foot, assistance in plantar flexion of the supracalcaneal joint and support of the transverse arch of the foot [7]. Under the conditions of single-support standing, it keeps the lower limb from medial bending, which is especially important in the case of knee joint diseases complicated by valgus.

Simulation results showed that in the case of contracture of the knee joint, the necessary force of *m. peroneus longus* (Fig. 2, b) decreased, which is probably due to forced plantar flexion of the foot. But in the 4th phase of the step, during the separation of the heel from the support, a «failure» in the contraction of the muscle was observed, which is due to the almost complete absence of support on the heel under conditions of contracture. In the phases of the transfer of the foot (7th) and lowering to the support (8th), an increase in the necessary force of muscle contraction was found from 10 to 40 %.

M. peroneus brevis (short fibula muscle) is responsible for 63 % of the force required to evert the foot and also helps in plantar flexion along with *m. peroneus longus*. According to modeling data (Fig. 2, c), its work was similar to that of m. peroneus longus, but at the time of foot transfer (the 7th phase) the necessary increase in contraction force to 70 % was established.

M. peroneus tertius (third fibula muscle) due to its location on the back surface of the 5th metatarsal bone helps during dorsiflexion and eversion of the foot [8], during walking in the phase of foot transfer it works as a long extensor of the toes [9]. Therefore, the primary function of the dorsiflexor muscle is to increase the force required to support the foot when it is off the support. Especially the violation of the balance of the isometric force m. peroneus tertius was observed in phases 7–8, that is, before lowering to the support, when it is necessary to dorsiflex the foot to support the heel.

The group of tibial muscles m. tibialis anterior and m. tibialis posterior (Fig. 3)

The main function of *M. tibialis anterior (anterior tibial muscle)* is to dorsiflex the foot [10]. The muscle plays an important role during walking by stabilizing the calcaneus joint when the foot contacts the support, during lift off and adduction of the foot. The muscle supports the medial part of the longitudinal arch of the foot during any movement. So, the simulation results (Fig. 3, a) revealed that in the presence of knee joint contracture, the necessary isometric force of the muscle to ensure its function increased in almost all phases of the step by the amount from 10 to 30 %.

The function of *M. tibialis posterior (posterior tibial muscle)* is plantar flexion of the foot in the supracalcaneal-tibial joint and eversion of the foot in the subcalcaneal joint. This muscle plays a supporting role by elevating, tensioning and strengthening the medial longitudinal arch of the foot. This helps distribute the weight of the body when the foot is on the ground. According to the simulation results (Fig. 3, b), as a result of the contracture of the knee joint, an increase in the necessary muscle contraction force was noted at all stages, especially during the separation of the heel from the support (5th step phase).

Let us proceed with considering the muscles responsible for the function of the toes. *M. flexor digitorum longus (long toe flexor)* bends the second to fifth toes first at the distal interphalangeal joint, then at the proximal joint, and finally at the metatarsophalangeal joint. It helps during plantar flexion of the foot in the calcaneus joint. While walking, running or jumping *m. flexor digitorum longus* pulls the toes down toward the ground to provide maximum grip and push off. During standing, the muscle helps maintain balance [11]. Modeling (Fig. 4, a) showed that the largest necessary isometric force of *m. flexor digitorum longus* with contractures of the knee joint occurred during the step period from the moment of separation of the toes to the lowering of the foot on the support (5, 6, 7 phases of the step). Its increase has been established almost twice. A significant increase in muscle contraction force was observed throughout the whole step.

M. flexor hallucis longus (flexor of the big toe longus) flexes all joints of the big toe when the foot comes off the ground. In addition, it stabilizes the first metatarsal head and keeps the distal pad of the big toe in contact with the ground during toe-off and toe-off.

As shown (Fig. 4, b), due to knee joint contracture, this muscle was also in excessive contraction at all phases of the step, i.e., to perform its main function, it was necessary to significantly increase the isometric force, especially at the stages of foot transfer (phases from the 5th to the 7th).

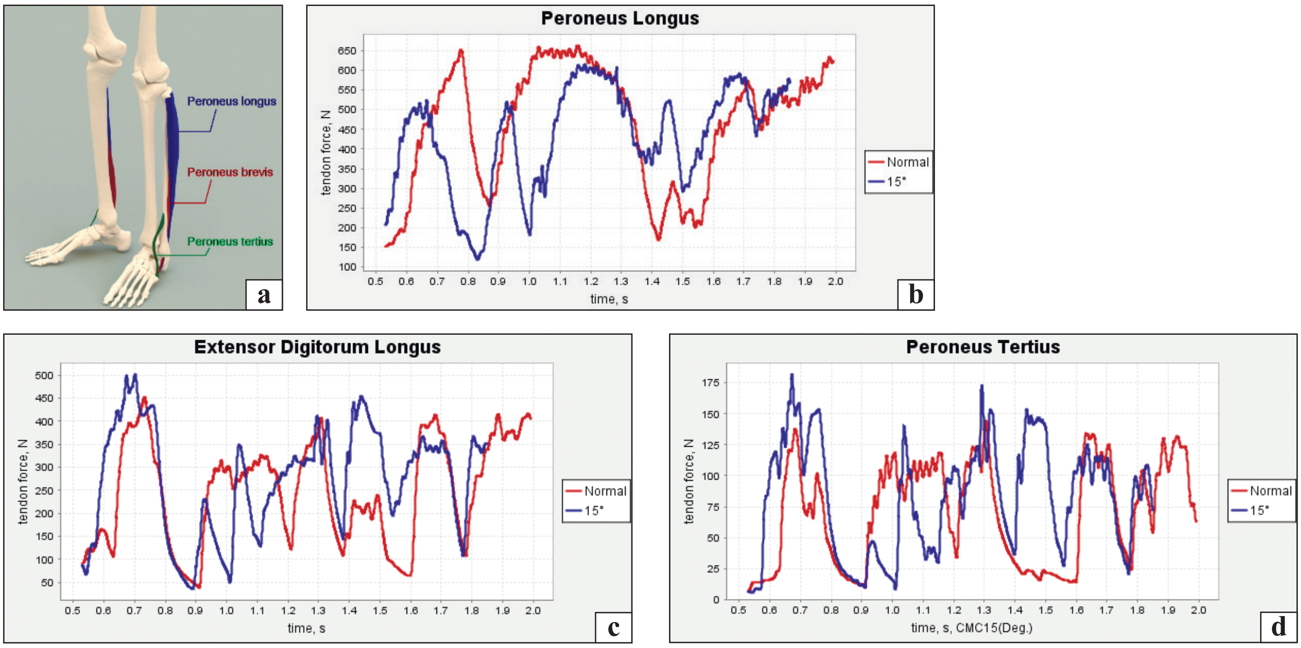

Fig. 2. Fibular muscles: a) anatomical location on the model; b) *m. peroneus longus*; c) *m. peroneus brevis*; d) *m. peroneus tertius*

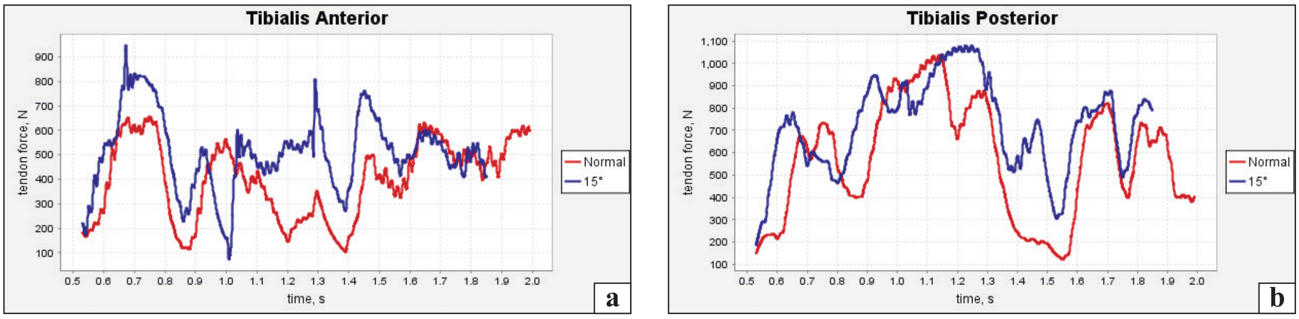

Fig. 3. Force of tibial muscles: a) *m. tibialis anterior*; b) *m. tibialis posterior*

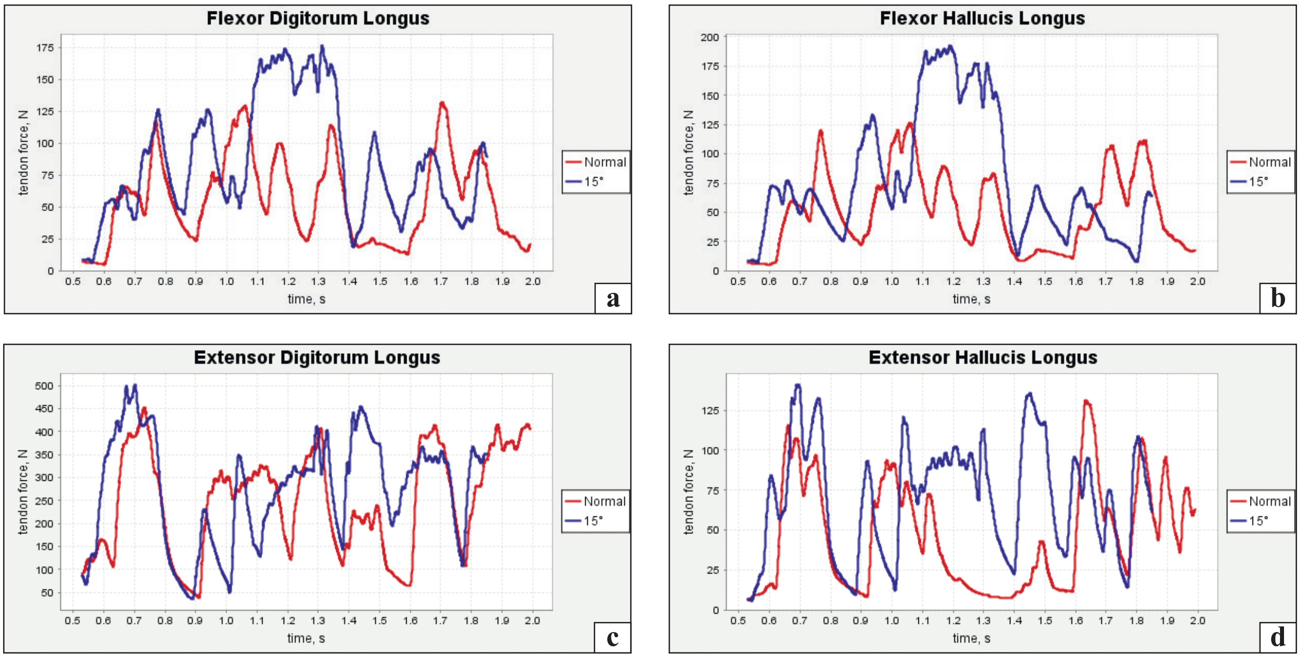

Fig. 4. Muscle work: a) *m. flexor digitorum longus*; b) *m. flexor hallucis longus*; c) *m. extensor digitorum longus*; d) *m. extensor hallucis longus*

M. extensor digitorum longus (long extensor of the toes) extends the lateral four toes and flexes the metacalcaneal joint. According to the simulation results, it was determined that the main force on the muscle occurs when the foot is on the support — the phase of support on the heel, rolling of the foot and separation of the toes from the support. The diagram (Fig. 4, c) shows that the muscle was under tension and its smoothed normal work changed to intermittent work due to contractures.

M. extensor hallucis longus (long extensor of the big toe) extends the metatarsophalangeal and interphalangeal joints of the big toe, helps during inversion of the foot and dorsiflexion of the metacalcaneal joint. In the case of contracture of the knee joint, the strength of *m. extensor hallucis longus* increased during the period of foot transfer, and at some stages — 3–5 times the norm (Fig. 4, d).

Discussion

The modeling of the work of the muscles of the lower leg and foot in the case of contracture of the knee joint confirmed that the limitation of mobility in it leads to a redistribution of the force of the studied muscles. Moreover, over time, the condition of the muscles worsened, which can cause the development of degenerative joint diseases [12].

Limitation of the extension of the knee joint significantly distorts a person's gait. There is a bent knee position at the beginning of the stance phase and throughout the walking cycle. There is no heel strike; the foot is placed on the floor exactly for contractures of less than 15°, and for more than 15° the support falls on the toes. The popliteal angle is reduced.

Modeling of human walking in 15° flexion contracture of the knee joint showed that the support on the toe triggered a significant overstraining of the muscles responsible for the functioning of the lower leg, foot and toes. The foot and metatarsal joint have the main function of maintaining the balance of the body during standing and walking. Therefore, excessive muscle overload leads to a violation of this function. That is, the function of plantar flexion/extension of the foot changes, and for normal functioning these muscles need to increase the force of contraction. The shorter the muscle, the more isometric force must be returned to achieve normal function.

Since *m. peroneus longus* and *m. peroneus brevis* are quite long, as a result of contracture their function is disturbed, but the necessary increase in strength is from 10 to 400 %. *M. peroneus tertius* (short) has to triple the force in some phases of the step to bend the foot. Among the muscles of the lower leg, the greatest isometric increase was necessary for *m. tibialis anterior* compared to *m. tibialis posterior*, which works mostly to extend the foot.

As for the muscles responsible for bending/extending the toes, in conditions of contracture of the knee joint, a significant, sometimes 3–5 times, increase in strength was necessary to perform the required function.

Thus, it can be argued that the contracture of theknee joint leads to a change in the work of not only the muscles around it, but also significantly affects the work of the muscles of the foot, which must be taken into account during the treatment of such patients.

Conclusions

Contracture of the knee joint causes changes in the biomechanics of the entire lower limb, namely: increasing changes in the work of the muscles responsible for the functioning of the foot, which under these conditions work in a mode of constant increase in tension.

Taking into account the impact of the contracture of the knee joint on the work of the muscles of the lower limb, it is possible to predict the course of the pathological process, determine which of the muscles suffer the most and which group of muscles needs to be corrected before and after surgery.

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

References

1. Rico Licona C. Incidencia de padecimientos ortopédicos en pacientes adultos atendidos en un Hospital de asistencia privada [Prevalence of orthopedic conditions in adult patients seen at a private hospital] / C. Rico Licona // Acta ortopedica mexicana. — 2007. — Vol. 21 (4). — P. 177–181. (in Spanish)
2. Fishchenko V. O. Biomechanical justification of rehabilitation measures after total knee replacement [Biomekhanichne obgruntuvannia reabilitatsiinykh zakhodiv pislia totalnoho endoprotezuvannia kolinnoho suhloba] / V. O. Fishchenko, Obeidat Khaled Jamal Saleh, O. D. Karpinska // Trauma (Ukraine). — 2022. — Vol. 23 (1). — P. 66–68. — DOI: 10.22141/1608-1706.1.23.2022.883. (in Ukrainian)
3. Anderson F. C. Dynamic optimization of human walking / F. C. Anderson, M. G. Pandy // Journal of Biomechanical Engineering. — 2001. — Vol. 123 (5). — P. 381–390. — DOI: 10.1115/1.1392310.
4. OpenSim: Open-source software to create and analyze dynamic simulations of movement / S. L. Delp, F. C. Anderson, A. S. Arnold [et al.] // IEEE Transactions on Biomedical Engineering. — 2007. — Vol. 54 (11). — P. 1940–1950. — DOI: 10.1109/TBME.2007.901024.
5. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures / S. L. Delp, J. P. Loan, M. G. Hoy [et al.] // IEEE Transactions on Biomedical Engineering. — 1990. — Vol. 37. — P. 757–767.
6. Loudon J. The clinical orthopedic assessment guide / J. Loudon, S. Bell, J. M. Johnston. — Kansas : Human Kinetics, 2008. — P. 395–408.
7. Moore K. L. Clinial oriented anatomy / K. L. Moore, A. F. Dalley, A. M. R. Agur. — Philadelphia : Wolters Kluwer, 2010.

8. Yammine K. The fibularis (peroneus) tertius muscle in humans: a meta-analysis of anatomical studies with clinical and evolutionary implications / K. Yammine, M. Erić // BioMed research international. — 2017. — Vol. 2017. — Article ID: 6021707. — DOI: 10.1155/2017/6021707.
9. Olewnik Ł. Fibularis tertius: anatomical study and review of the literature / Ł. Olewnik // Clinical anatomy (New York, N.Y.). — 2019. — Vol. 32 (8). — P. 1082–1093. — DOI: 10.1002/ca.23449.
10. Palastanga N. Anatomy and human movement: structure and function / N. Palastanga, R. Soames. — 6th ed. — London, United Kingdom : Churchill Livingstone; 2012.
11. A gait analysis of simulated knee flexion contracture to elucidate knee-spine syndrome / K. Harato, T. Nagura, H. Matsumoto [et al.] // Gait & Posture. — 2008. — Vol. 28 (4). — P. 687–692. — DOI: 10.1016/j.gaitpost.2008.05.008.

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WORK OF MUSCLES RESPONSIBLE FOR THE FUNCTIONING OF THE FOOT IN CONDITIONS OF KNEE JOINT CONTRACTURE

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