Review article
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Evolution of tactical approaches to eliminating limb length discrepancy

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Abstract

Introduction Limb length discrepancy (LLD) can be debilitating and may cause other medical and social problems. LLD is a serious physical condition and have a significant impact on the patient's quality of life changing the gait, forming pathological adaptive mechanisms and causing long-term musculoskeletal disturbances in children.

The objective was to analyze the evolution of tactical approaches to the rehabilitation of patients with lower limb length inequality.

Material and methods The original literature search was conducted on key resources including Scientific Electronic Library (www.elibrary.ru) and the National Library of Medicine (www.pubmed.org). Literature searches included both Russian and English studies. The search strategy was comprised of keywords: lower limbs, limb length inequality, approaches and means of limb length correction, osteosynthesis. Clinical guidelines, clinical recommendations, systematic reviews, randomized controlled trials and multicenter cohort studies were selected for analysis.

Results and discussion Normal individuals can often experience a difference in the length of the lower limbs from several mm to 1.5 cm and have no effect on the gait, condition of adjacent joints and joints of the opposite limb. Some authors report inequality of 5 mm leading to orthopaedic pathology. A variety of conservative and surgical treatments are offered for limb length equalization. Elimination of LLD is a common and unresolved medical problem. Conservative treatment of LLD can be considered as one of the stages of rehabilitation. Some patients can benefit from conservative treatments. Alternatively, surgical equalization is a treatment option for patients with LLD.

Conclusion Surgical methods offered earlier to address LLD had disadvantages, which ultimately minimized their use, and orthopaedic surgeons abandoned some of them due to the high risk of severe complications. The device and the technique developed by Dr. Ilizarov in the 50s of the last century was an epoch-making event in the elimination of LLD and are constantly being improved.

Keywords: lower limbs, length inequality, methods and means of length correction, osteosynthesis

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INTRODUCTION

Limb length discrepancy (LLD) can be debilitating and may cause other medical and social problems. LLD is a serious physical condition and have a significant impact on the patient's quality of life changing the gait, forming pathological adaptive mechanisms and causing long-term musculoskeletal disturbances in children. The pathology is often progressive and causes secondary deformities of the spine, pelvis, adjacent joints and joints of the opposite limb, which is accompanied by impaired biomechanical conditions for their functioning and overload. LLD causes persistent scoliotic deformities, pelvic and lumbodynia, disc herniations, cervicalgia, chronic fatigue and discomfort which are caused by constant mechanical overload of the musculoskeletal system as a result of suboptimal body statics [1, 2]. LLD worsens the quality of life of patients: it limits motor activity, reduces communication capabilities, complicates the educational process, the choice of profession, and often becomes a problem for starting a family [3]. Progression of LLD can lead to disability in patients with post-traumatic conditions and hemihypertrophy [4–8]. The presence of an orthopaedic defect in LLD patients (consequences of injury and hemihypertrophy) leads to negative self-esteem and personality isolation. This provokes the development of depressive disorders and can aggravate orthopaedic problems over time with the appearance of social maladjustment and social phobia. The combination of the above components of LLD leads to a pronounced regression in the quality of life of the patient and his/her immediate environment. In recent years, there has been an increase in the number of patients with LLD requiring its elimination. This circumstance can be associated with improved orthopaedic diagnosis and increased availability of highly specialized medical care [9–21].

The objective was to analyze the evolution of tactical approaches to the rehabilitation of patients with lower limb length inequality.

MATERIAL AND METHODS

The original literature search was conducted on key resources including Scientific Electronic Library (www.elibrary.ru) and the National Library of Medicine (www.pubmed.org). Literature searches included both Russian and English studies. The search strategy was comprised of keywords: lower limbs, limb length inequality, approaches and means of limb length correction, osteosynthesis. Clinical guidelines, clinical recommendations, systematic reviews, randomized controlled trials and multicenter cohort studies were selected for analysis. Exclusion criteria invluded experimental and case studies, observations, reports, clinical cases, uncontrolled cohort studies. 195 articles that met the inclusion criteria were reviewed, 64 publications were explored with 9 between 2016 and 2021, 15 articles were published within 10 years, 40 articles were published more than 10 years ago, one of them was published about a hundred years ago and was the starting point of the research.

RESULTS AND DISCUSSION

Upright walking can suggest the presence of a slight difference in the length of the lower limbs with a longer leg having greater functional loading, leads to the development of the following process: a leg that has a greater length has a greater functional load, being engaged in greater performance, receiving more nutrition due to increased blood flow and growing faster. A leg with a shorter functional length experiences less loading, less performance, receiving less nutrition due to less intense blood supply than the opposite limb and, as a result, it grows more slower. The process occurring in opposite directions would result in relative LLD with age [22].

One more orthopaedic feature of the human population requires no use of any orthopaedic products or surgical treatment, and the authors treat this condition as normal: normal individuals may have a difference in the length of the lower limbs from several mm to 1.5 cm, which does not affect the gait and condition of adjacent joints and joints of the opposite limb [2]. Rush and Steiner reported the length of the lower limbs measured from radiographs of 1,000 military personnel discharged from the army. Identical leg length was established in 23 % of cases; asymmetrical length of the lower limbs was observed in 77 % of those examined [20].

Similar data were reported by Kovaleva et al. who noted different leg length in 40–90 % of the population [1]. Some authors reported gait disturbances even with a difference in leg length of about 1.5 cm. However, most orthopaedic surgeons agree with the opinion of Marx, who established gait disturbance with the difference in leg length of greater than 2 cm, and shortening of 1 to 2 cm causing no lameness being compensated by adaptive mechanisms [4, 23–34]. The use of orthopaedic shoes cannot compensate for shortening completely and satisfy patients. Impaired biomechanics of the limb, the patient's dependence on prosthetic manufacturing, psychophysical discomfort associated with wearing orthoses and orthopaedic shoes, and cosmetic defects force patients to seek surgical help [35].

Only 10 % of the population have the same length of the lower extremities, and 90 % of the population has a LLD of up to 1.0 cm. Moreover, pathology of the large joints of the lower extremities is noted in many patients with LLD of greater than 5 mm. Modern authors agree with the opinion of Marks that LLD greater than 2.0 cm are often a problem, but there is evidence that LLD of 5 mm can lead to orthopaedic pathology [36]. Khamis and Carmeli came to similar conclusions [37]. They examined the clinical role of LLD and found a significant association between anatomical LLD and gait disturbance. The data obtained indicated that deviations in the gait can occur even with a length inequality of more than 1 cm, and the severity correlated with an increase in leg length inequality. Different techniques have been offered by orthopaedic surgeons to eliminate LLD and depended on the general level of development of medicine and orthopaedics, in particular and on the doctor's own preferences.

For example, in the pre-surgical era, doctors tried to conservatively stimulate limb growth "tapping" the heel of the short limb. At the beginning of the last century, it was a tourniquet that was applied at the level of the proximal metaphysis of the leg to create venous stasis lasting 30 minutes. With the tourniquet removed active hyperemia of the limb occurred stimulating physeal function. The procedure had to be repeated daily for a long time until the end of the patient's natural growth. Autologous blood to be introduced into the knee cavity was used to stimulate the growth of a short leg in an attempt to stimulate the growth zones by exposing them to ultraviolet and ultrashort rays. Iodine growth stimulation technique of a short lower limb suggested the use of iodine tincture to the skin of the knee joint to ensure increased blood flow in the underlying tissues and improve physeal function [23, 39].

Conservative treatments using insoles, prosthesis, orthosis are still applied to address LLD. However, their long-term use may fail to compensate for biomechanical disorders [40]. Campbell et al. reported low-quality evidence that shoe lifts reduce pain and improve function in patients with LLD and common painful musculoskeletal conditions [41]. Iv. Cahanin et al. reported conflicting evidence on the relevance of LLI and conservative treatment options, the associated material costs and concluded that they may be unnecessary and potentially harmful in short-term [42].

In addition to conservative methods, attempts were made to surgically stimulate the growth zones of the short segment. For example, some surgeons offered a longitudinal osteotomy of the tibia or cortical bone perforation near the epiphysis. In other cases, the so-called "biogenic stimulation" was used in some cases by placing a bouillon bone pin into the distal femoral metaphysis, proximal tibial metaphysis or greater trochanter. These methods caused aseptic inflammation and increased local circulation near the physis enhancing the function [39, 43, 44]. All of the above measures did not produce the results expected and could only be used in children. This circumstance stimulated orthopaedic surgeons to look for more effective ways to solve the problem.

New methods of surgical compensation for LLD have been proposed to include acute bone lengthening or shortening to be followed by immobilization of the limb, compression-distraction osteosynthesis (external, combined and internal osteosynthesis) and operations on growth zones (temporary or permanent epiphysiodesis) [23, 25, 39, 43]. Shortening osteotomies have used by orthopaedic surgeons for a long time, and some surgeons, although much less frequently, still use them. It is generally accepted that the maximum acute surgical shortening of the femur can be 5–6 cm, while that of the tibia can be not greater than 3 cm. This type of osteotomy allows for acute elimination of LLD and can be traumatic in terms of surgical technique and controversial in terms of justification for its use. The main disadvantage of limb shortening techniques in eliminating LLD is that the procedure is performed for a healthy segment and has been shown to be a rare surgical intervention used by orthopaedic surgeons [6, 23, 45].

An acute lengthening osteotomy was first used for an orthopaedic case by the Russian surgeon Dmitriev in 1891. He performed a Z-shaped lengthening osteotomy of the femur followed by immobilization. However, the method has not found wide application due to the limited elongation capabilities [37, 38]. Abbott and Malakhov reported many cases of lower limb lengthening at the beginning of the twentieth century [23, 43]. In 1923, Bier reported his experience of limb lengthening in seven patients. In 1929, Jones and Lovett reported femur lengthening of 6 to 10 cm. In 1937, Bogoraz first reported his attempt in Russia to rapidly increase growth that was associated with to a high level of complexity of the treatment process and high rate of postoperative complications [23, 43]. It is generally accepted that the type of osteotomy can affect osteoregeneration, creating different conditions for the callus. Oblique or Z-shaped bone osteotomies can provide optimal conditions for regeneration with the length of the osteotomy exceeding the expected length gain by 2 to 5 cm. Complicated bone osteotomies (polygonal and differently shaped) which were difficult to perform and highly traumatic were initiated to improve the spatial orientation of bone fragments, which would affect the strength of the callus. More than 40 different techniques of osteotomy were offered, including a number of stepped and "tongue-shaped" ones, and were mainly used by the authors [4, 32, 39, 46]. We encountered conflicting data on the determining influence of osteotomies on the formation of a distraction regenerate. Researchers justify the merits of the osteotomy they use based on personal preferences, established national traditions and orthopaedic schools. Nahm, Boyce Nichols, reported percutaneous osteotomy for pediatric cases as low-energy and circulation-preserving showing benefits and indications for various types of osteotomies, including multihole drill hole osteotomy, corticotomy, and Gigli saw osteotomy. However, the authors believe that some types of osteotomies are technically difficult and should be performed only by experienced surgeons [47]. The authors suggest that some types of osteotomies are technically demanding and should be performed by experienced surgeons [47].

The rate of acute lengthening and its relationship with the complication rate deserves special attention. Burnei et al. reported the analysis of their 25-year clinic's experience with the amount of lengthening per segment varying between 3 and 17 cm, the longest staged lengthening measuring 20 cm, in two stages, and the greatest overall lengthening being 25 cm for an entire lower limb. The authors concluded that limb lengthening procedures up to 5 cm le d to rapid consolidation of the distraction regenerate and minimal complications. Lengthenings exceeding 5 cm required a good psychological preparation and careful monitoring. In lengthenings more than 10 cm, a faster rate of consolidation requires a double corticotomy, the use of intramedullary fixation and the immobilization of adjacent joints. The authors suggested that good results in restoring LLD could be achieved using an Ilizarov external fixator, and temporary epiphysiodesis at the age of 10–12 years was the least aggressive and quite effective method of treatment. Limb shortening by segmental resection should become 'obsolete' [48].

Poor outcomes of one-stage correction of lower limb length inequality forced orthopaedic surgeons to look for more advanced ways to achieve results, which are based on a gradual tensile effect on osteotomized bone fragments. The earliest surgical methods of limb lengthening suggested "stretching" the limb through the bone osteotomy and subsequent skeletal traction on its distal fragment by using a load of 15–20 kg in adult patients.

The operations were also not widely used due to high morbidity, unstable bone fixation and high complication rate that prevented from achieving a length gain. The long-term hypomobility of the patient was an important factor with this lengthening technique since the individual was bedridden in a forced position for a long time [5, 23, 39, 43, 44].

Skeletal traction for lengthening lower limb segments was replaced by distraction devices that amounted to more than 1000. The devices can be divided into seven types: mono- and bilateral devices, arched (sectoral) and semicircular, circular and combined (hybrid) devices, intramedullary distractors. Of the many devices offered, the external fixation device developed by the Soviet doctor G.A. Ilizarov in the 50s of the last century has become the most widely-used fixators in the world. G.A. Ilizarov developed a fundamentally new method of treating orthopaedic and trauma patients. The Ilizarov method is based on the natural physiological factors arising in the tissues of the operated limb in response to directionally created distraction or compression stress. Maintaining forces in the device for the required period of time provides the possibility of dosed correction of the segment, including restoration of the length and biomechanical axis [7, 38, 45, 49]. Osteosynthesis with the Ilizarov apparatus allows you to control the distraction process, lengthen and correct multiplanar deformities at the same time. Many modern authors suggest that the Ilizarov method provides comprehensive solution of the problems associated with shortening and deformities of the lower extremities, despite the difficulties of its application [20, 25, 26, 39, 45, 50–56]. The Ilizarov bone lengthening suggests stable fixation of the "segment-apparatus" system; preservation of osteogenic tissues and blood supply in the segment being lengthened; adherence to LL protocol; control of correction efforts and functional load of the operated limb; maintaining a harmonious general somatic balance in the "patient-device" system throughout the entire period of osteosynthesis [4, 5, 25, 46, 57–61].

The problem of limb length correction, according to the available literature, has almost a century-long history and has undergone many evolutionary improvements. Each of the methods offered involved either certain modifications of existing approaches, or the use of new methodological and technological techniques and devices, and both had certain advantages and disadvantages. However, all the technologies proposed in the "pre-Ilizarov" era did not have universality to be widely used in clinical practice for solving specific clinical problems. Ilizarov's methodology, which is based on natural biological processes and regularities facilitated optimal conditions for tissue regeneration during elongation, and construction design and modifications of the apparatus ensure stability throughout the entire time required for the organotypic restructuring of newly formed tissues. Therefore, we can conclude that the Ilizarov method of transosseous osteosynthesis has shown to be the most effective technique for limb length equalization among global orthopaedic technology.

CONCLUSION

The evolution of limb lengthening is associated with a long history of research, struggle for the new techniques, improvements and continuous training, and the elimination of LLD remains a challenging issue in orthopaedic surgery when coupled with multiplanar deformity correction. Conservative treatment of LLD can be considered as a stage of rehabilitation and a variety of conservative modalities for LLD may fail to result in a good outcome, and surgical treatment is the priority in solving the problem. The Ilizarov apparatus and method developed in the 50s of the last century were an epoch-making event in the elimination of LLD and are being constantly improved.

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REFERENCES

1. Kovaleva MA, Golovkova EV, Yakhontov VI. Laser chromophoresis gel "Relikt-05" in the treatment of absolute shortening of the bones of the lower extremities in children and adolescents. *XX Interregional Scientific and Practical Conference of Rehabilitologists of the Far East "Development of Medical Rehabilitation in the Far East", April 04, 2019*. Khabarovsk; 2019:72-76. (In Russ.)
2. Pawik Ł, Pawik M, Wrzosek Z, et al. Assessment of the quality of life in patients with varying degrees of equalization of lower limb length discrepancy treated with Ilizarov method. *J Orthop Surg Res*. 2021;16(1):62. doi: 10.1186/s13018-021-02202-1
3. Chhina H, Klassen AF, Kopec JA, et al, Aggarwal A, Nunn T, Cooper AP. What matters to children with lower limb deformities: an international qualitative study guiding the development of a new patient-reported outcome measure. *J Patient Rep Outcomes*. 2021;5(1):30. doi: 10.1186/s41687-021-00299-w
4. *Congenital shortening of the lower extremities in children*. Ed. AV Popkov. Chelyabinsk: 2011:510. (In Russ.)
5. Kaplunov OA, Kaplunov AG, Shevtsov VI. *Cosmetic correction of the shape and length of the legs*. Moscow: GEOTAR-Media Publ., 2010:160. (In Russ.)
6. Artemiev AA, Arkhipov DM, Baranovsky YuG, et al. *Aesthetic and reconstructive surgery of the lower limb*. Moscow: GEOTAR-Media Publ.; 2008:248. (In Russ.)
7. Csernátony Z, Kiss L, Manó S, et al. Multilevel callus distraction: a novel idea to shorten the lengthening time. *Med Hypotheses*. 2003;60(4):494-497. doi: 10.1016/s0306-9877(02)00432-2
8. Paley D., Herzenberg J.E. *Principles of Deformity Correction*. Berlin: Springer-Verlag, 2002:307-346.
9. Parmaksizoglu F, Koprulu AS, Unal MB, Cansu E. Early or delayed limb lengthening after acute shortening in the treatment of traumatic below-knee amputations and Gustilo and Anderson type IIIC open tibial fractures: The results of a case series. *J Bone Joint Surg Br*. 2010;92(11):1563-1567. doi: 10.1302/0301-620X.92B11.23500
10. Perttunen JR, Anttila E, Södergård J, et al. Effect of intramedullary gradual elongation of the shorter limb on gait patterns. *Pediatr Int*. 2003;45(3):324-332. doi: 10.1046/j.1442-200x.2003.01712.x
11. Krieg AH, Lenze U, Speth BM, Hasler CC. Intramedullary leg lengthening with a motorized nail. *Acta Orthop*. 2011;82(3):344-350. doi: 10.3109/17453674.2011.584209
12. Bidwell JP, Bennet GC, Bell MJ, Witherow PJ. Leg lengthening for short stature in Turner's syndrome. *J Bone Joint Surg Br*. 2000;82(8):1174-1176. doi: 10.1302/0301-620x.82b8.9688
13. Jasiewicz B, Kacki W, Koniarski A, et al. Leg lengthening in patients with congenital fibular hemimelia. *Ortop Traumatol Rehabil*. 2002;4(4):413-420.
14. Takata M, Watanabe K, Matsubara H, et al. Lengthening of the normal tibia in a patient with hemihypertrophy caused by Klippel- Trenaunay-Weber syndrome: a case report. *J Orthop Surg* (Hong Kong). 2011;19(3):359-363. doi: 10.1177/230949901101900320
15. Märtson A, Haviko T, Kirjanen K. Extensive limb lengthening in Ollier's disease: 25-year follow-up. *Medicina* (Kaunas). 2005;41(10):861-866.
16. Jabłonski M, Posturzyńska A, Gorzelak M, et al. Problem and tolerance of leg lengthening after total hip replacement. *Chir Narzadow Ruchu Ortop Pol*. 2008;73(6):351-354.
17. Schiedel F, Rödl R. Lower limb lengthening in patients with disproportionate short stature with achondroplasia: a systematic review of the last 20 years. *Disabil Rehabil*. 2012;34(12):982-987. doi: 10.3109/09638288.2011.631677
18. Sułko J, Radło W. Limb lengthening in children with osteogenesis imperfecta. *Chir Narzadow Ruchu Ortop Pol*. 2005;70(4):243-247. (in Polish)
19. Chen D, Chen J, Jiang Y, Liu F. Tibial lengthening over humeral and tibial intramedullary nails in patients with sequelae of poliomyelitis: a comparative study. *Int Orthop*. 2011;35(6):935-940. doi: 10.1007/s00264-010-1032-6
20. Watanabe K, Tsuchiya H, Sakurakichi K, et al. Treatment of lower limb deformities and limb-length discrepancies with the external fixator in Ollier's disease. *J Orthop Sci*. 2007;12(5):471-475. doi: 10.1007/s00776-007-1163-9
21. Wu CC, Chen WJ. Tibial lengthening: technique for speedy lengthening by external fixation and secondary internal fixation. *J Trauma*. 2003 Jun;54(6):1159-1165; discussion 1165. doi: 10.1097/01.TA.0000046254.92637.19
22. Protsenko VN. Scoliosis, or are the legs of a modern human being equal in length? *Manual therapy*. 2012;(1):69-80. (In Russ.)
23. Malakhov OA, Kozhevnikov OV. *Inequality in the length of the lower limbs in children (clinical picture, diagnosis, treatment)*. Moscow: Medicine Publ.; 2008:365. (In Russ.)

24. Marks VO. *Orthopedic diagnostics*. Minsk, Science and technology Publ.; 1978:511. (In Russ.)
25. Solomin LN. *Fundamentals of transosseous osteosynthesis using G.A. Ilizarov*. St. Petersburg: MORSAR AV Publ.; 2005;544.
26. Birch JG, Samchukov ML. Use of the Ilizarov method to correct lower limb deformities in children and adolescents. *J Am Acad Orthop Surg*. 2004;12(3):144-54. doi: 10.5435/00124635-200405000-00002
27. Nakase T, Kitano M, Kawai H, et al. Distraction osteogenesis for correction of three-dimensional deformities with shortening of lower limbs by Taylor Spatial Frame. *Arch Orthop Trauma Surg*. 2009;129(9):1197-1201. doi: 10.1007/s00402-008-0702-y
28. Iobst C. Limb lengthening combined with deformity correction in children with the Taylor Spatial Frame. *J Pediatr Orthop B*. 2010;19(6):529-534. doi: 10.1097/BPB.0b013e32833dec43
29. Kenawey M, Krettek C, Liodakis E, et al. Leg lengthening using intramedullay skeletal kinetic distractor: results of 57 consecutive applications. *Injury*. 2011;42(2):150-5. doi: 10.1016/j.injury.2010.06.016
30. Lenze U, Hasler CC, Krieg AH. Intramedullary motorized nail for equalization of posttraumatic leg length discrepancies. *Unfallchirurg*. 2011 Jul;114(7):604-10. (In German) doi: 10.1007/s00113-010-1820-x
31. Schep NW, van Lieshout EM, Patka P, Vogels LM. Long-term functional and quality of live assessment following post-traumatic distraction osteogenesis of the lower limb. *Strategies Trauma Limb Reconstr*. 2009;4(3):107-112. doi: 10.1007/s11751-009-0070-3
32. Hahn SB, Park HW, Park HJ, et al. Lower limb lengthening in turner dwarfism. *Yonsei Med J*. 2003;44(3):502-507. doi: 10.3349/ymj.2003.44.3.502
33. Niedzielski K, Synder M, Borowski A. Distraction epiphysiolysis in the treatment of uneven limb length. *Ortop Traumatol Rehabil*. 2002;4(4):459-463.
34. Simpson AH, Shalaby H, Keenan G. Femoral lengthening with the Intramedullary Skeletal Kinetic Distractor. *J Bone Joint Surg Br*. 2009;91(7):955-961. doi: 10.1302/0301-620X.91B7.21466
35. Kolchev OV, Borzunov DYu. Elimination of congenital lower limb shortening (historical information). *Genij Ortopedii*. 2010;(1):140-146. (In Russ.)
36. Gordon JE, Davis LE. Leg Length Discrepancy: The Natural History (And What Do We Really Know). *J Pediatr Orthop*. 2019;39(Issue 6, Supplement 1 Suppl 1):S10-S13. doi: 10.1097/BPO.0000000000001396
37. Khamis S, Carmeli E. Relationship and significance of gait deviations associated with limb length discrepancy: A systematic review. *Gait Posture*. 2017;57:115-123. doi: 10.1016/j.gaitpost.2017.05.028
38. Devyatov AA. *Transosseous osteosynthesis*. Chisinau: Shtiintsa Publ.; 1990:315. (In Russ.)
39. Shevtsov VI, Popkov AV. *Surgical lengthening of the lower extremities*. Moscow: Medicine Publ.; 1998:192. (In Russ.)
40. Hasler CC, Krieg AH. Current concepts of leg lengthening. *J Child Orthop*. 2012;6(2):89-104. doi: 10.1007/s11832-012-0391-5
41. Campbell TM, Ghaedi BB, Tanjong Ghogomu E, Welch V. Shoe Lifts for Leg Length Discrepancy in Adults With Common Painful Musculoskeletal Conditions: A Systematic Review of the Literature. *Arch Phys Med Rehabil*. 2018;99(5):981-993.e2. doi: 10.1016/j.apmr.2017.10.027
42. Cahanin Iv RL, Jefferson JR, Flynn TW, Goyeneche N. Pain and physical performance among recreational runners who receive a correction for an iliac crest height difference: a case series. *Int J Sports Phys Ther*. 2019;14(5):794-803.
43. Abbott LC. The operative lengthening of the tibia and fibula. *J Bone Joint Surg Am*. 1927;9(1):128-152.
44. Sailhan F. Bone lengthening (distraction osteogenesis): a literature review. *Osteoporos Int*. 2011;22(6):2011-2015. doi: 10.1007/s00198-011-1613-2
45. Golyakhovskii V, Frenkel' V. *Rukovodstvo po chreskostnomu osteosintezu metodom Ilizarova*. Translated from English. Moscow: BINOM Publ.; 1999:272. (In Russ)
46. Li AD, Bashirov RS. *Guide to transosseous compression-distraction osteosynthesis*. Tomsk, 2002:310. (In Russ)
47. Nahm N, Boyce Nichols LR. Percutaneous Osteotomies in Pediatric Deformity Correction. *Orthop Clin North Am*. 2020;51(3):345-360. doi: 10.1016/j.ocl.2020.03.001
48. Burnei G, Vlad C, Gavriliu S, et al. Upper and lower limb length equalization: diagnosis, limb lengthening and curtailment, epiphysiodesis. *Rom J Intern Med*. 2012;50(1):43-59.
49. Ilizarov GA. *A method for splicing bones in fractures and an apparatus for implementing this method*. USSR no. 98471, 1954. Available at: https://www.fips.ru/registers-doc-view/fips_servlet. Accessed Aug 1, 2023. (In Russ)
50. Javid M, Shahcheraghi GH, Nooraie H. Ilizarov lengthening in centralized fibula. *J Pediatr Orthop*. 2000;20(2):160-162.
51. Kawoosa AA, Butt MF, Halwai MA. Deformity correction and massive lengthening on a centralized fibula with the Ilizarov technique. *Acta Orthop Belg*. 2008;74(5):704-708.

52. Catagni MA, Radwan M, Lovisetti L, et al. Limb lengthening and deformity correction by the Ilizarov technique in type III fibular hemimelia: an alternative to amputation. *Clin Orthop Relat Res*. 2011;469(4):1175-1180. doi: 10.1007/s11999-010-1635-7
53. Oostenbroek HJ, Brand R, van Roermund PM. Growth rate after limb deformity correction by the Ilizarov method with or without knee joint distraction: lengthening in 30 children followed for at least 2 years. *Acta Orthop*. 2009;80(3):338-343. doi: 10.3109/17453670903025345
54. Rozbruch SR, Fragomen AT, Ilizarov S. Correction of tibial deformity with use of the Ilizarov-Taylor spatial frame. *J Bone Joint Surg Am*. 2006;88 Suppl 4:156-174. doi: 10.2106/JBJS.F.00745
55. Ariyawatkul T, Kaewpornsawan K, Chotigavanichaya C, Eamsobhana P. The Results of Lengthening in Congenital Posteromedial Angulation of Tibia. *J Med Assoc Thai*. 2016;99(10):1137-1141.
56. Merkulov VN, Tzykunov MB, Dorokhin AI, Duysenov NB. Treatment of post-traumatic deformations and limb shortenings in children and teenagers. *Bulletin of the RSMU*. 2009;(5):25-28. (In Russ)
57. Ilizarov GA, Deviatov AA. Operativnoe udlinenie goleni [Surgical elongation of the leg]. *Ortop Travmatol Protez*. 1971;32(8):20-25. (In Russ.)
58. Kolchev OV, Borzunov DYu. Growth and development of congenitally shortened leg after lengthening according to G.A. Ilizarov. *Genij Ortopedii*. 2009;(4):34-38. (In Russ.)
59. Popkov AV. Modern principles of treatment of patients with limb shortenings. *Genij Ortopedii*. 1998;(4):97-101. (In Russ.)
60. Smelyshev NN, Gerasimov DV. Manual of transosseous osteosynthesis. Kostanay: Kostanaypolygraphy Publ.; 2010:260. (In Russ.)
61. Stetsula VI, Veklich VV. *Fundamentals of controlled transosseous osteosynthesis*. Moscow: Medicine Publ.; 2003:224. (In Russ.)

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