Translated by E.V. Trushina

Review

https://doi.org/10.23934/2223-9022-2024-13-1-108-115

Surgical Treatment of Post-Amputation Foot Deformations in Diabetic Neuropathy

P.S. Bardyugov[1] ✉, M.V. Parshikov[2], N.V. Yarygin[2]

Diabetic Foot Department
[1] National Medical Research Center for Endocrinology
11, Dmitry Ulyanov Str., Moscow 117292, Russian Federation
[2] Russian University of Medicine
4, Dolgorukovskaya Str., Moscow 127006, Russian Federation

✉ **Contacts:** Petr S. Bardiugov, Traumatologist-Orthopedist, Diabetic Foot Department, National Medical Research Center for Endocrinology. Email: petrbardiugov@gmail.com

RELEVANCE The number of amputations performed on patients with diabetic foot syndrome is increasing all over the world. Almost half of these operations are the so-called "minor amputations" carried out within the foot. The high recurrence rate of neuropathic ulcers, impaired biomechanics, and a decrease in the quality of life of patients after these surgeries encourage the study of this problem and the search for possible treatment options due to the capabilities of surgical treatment for post-amputation foot deformities.

AIM OF STUDY To evaluate the nature of surgical interventions for post-amputation foot deformities in patients with diabetic neuropathy.

MATERIAL AND METHODS The literature search was carried out in the databases of medical publications PubMed, CyberLeninka, Google Scholar, Scopus, Medline, eLIBRARY among articles in English and Russian. The search was performed using the following terms: transmetatarsal resection, diabetic foot syndrome, transmetatarsal amputation, minor amputation.

RESULTS Surgical treatment methods for deformities after amputation of part of the forefoot are widely presented in the world literature and are more studied. The possibilities of correcting foot deformities that occurred after amputation of the entire anterior section (from transmetatarsal amputation to the level of the Chopart`s joint) are less covered, this direction and methods have been studied to a lesser extent.

CONCLUSIONS Surgical methods for the correction of post-amputation foot deformities have firmly entered the wide international practice. Their effectiveness is confirmed by studies with a high level of evidence. Nevertheless, a wider, academic research of the problem of orthopedic status in patients with this pathology and the corresponding methods of surgical treatment is required.

Keywords: minor amputations, diabetic foot syndrome, post-amputation deformities, biomechanical dysfunction

For citation Bardyugov PS, Parshikov MV, Yarygin NV. Surgical Treatment of Post-Amputation Foot Deformations in Diabetic Neuropathy. *Russian Sklifosovsky Journal of Emergency Medical Care.* 2024;13(1):108–115. https://doi.org/10.23934/2223-9022-2024-13-1-108-115 (in Russ.)

Conflict of interest Authors declare lack of the conflicts of interests

Acknowledgments, sponsorship The study had no sponsorship

Affiliations

Petr S. Bardyugov	Traumatologist-Orthopedist of the Diabetic Foot Department, National Medical Research Center for Endocrinology; https://orcid.org/0000-0002-5771-0973, petrbardiugov@gmail.com; 55%, collection and processing of material, analysis of data obtained, text writing and editing
Mikhail V. Parshikov	Doctor of Medical Sciences, Professor of the Department of Traumatology, Orthopedics and Disaster Medicine, Russian University of Medicine; https://orcid.org/0000-0003-4201-4577, parshikovmikhail@gmail.com; 25%, research concept and design, text editing
Nikolay V. Yarygin	Doctor of Medical Sciences, Professor, Corresponding Member of RAS, Head of the Department of Traumatology, Orthopedics and Disaster Medicine, Russian University of Medicine; https://orcid.org/0000-0003-4322-6985, dom1971@yandex.ru; 20%, research concept and design, text editing

MA – "minor" amputations
DFS – diabetic foot syndrome
DM – diabetes mellitus
FRDM – Federal Register of Patients with Diabetes Mellitus
PAD – post-amputation deformities
RCT – randomized controlled trial

INTRODUCTION

According to the latest data from the Federal Register of Patients with Diabetes Mellitus (FRDM), in 2016, the prevalence of diabetic foot syndrome (DFS) in the Russian Federation among patients with diabetes mellitus (DM) was: type 1 DM - 4.7%, type 2 DM - 1.9%. The ratio of various forms of DFS in type 1 diabetes: neuropathic with trophic ulcer - 41.6%, neuropathic (Charcot foot) - 17.9%, neuroischemic - 28.3%, ischemic - 12.2%; type 2 diabetes: 41.6%, 7.4%, 32.4%, 18.5%, respectively.

From 2013 to 2016, in the Russian Federation there was an increase in new cases of amputations/year: in type 1 diabetes - from 10.5 to 12.4/10 thousand adult patients, in type 2 diabetes - from 9.6 to 10 .9/10 thousand adult patients, respectively (Fig. 1). At the same time, there was significant interregional variability in their frequency - from 2.9 to 0.13% in type 1 diabetes; from 6.0 to 0.04% in type 2 diabetes.

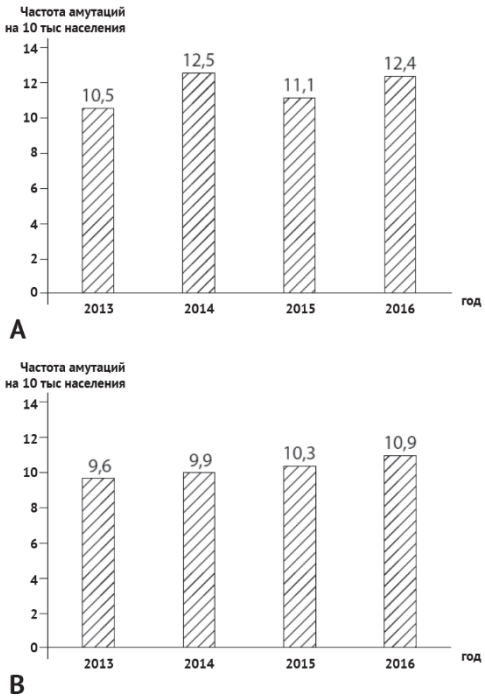

Fig. 1. Frequency of new observations of amputations per year per 10 thousand adult patients with type 1 (A) and type 2 (B) diabetes mellitus

The proportion of amputations performed at the hip level in both types of diabetes decreased slightly: in type 1 diabetes - from 43.6% in 2013 to 37.0% in 2016; in type 2 diabetes - from 52 .2% in 2013 to 45.5% in 2016. However, the number of amputations performed at the lower leg level has increased. The number of so-called "minor" amputations (MA) within the foot has especially increased [1] (Fig. 2).

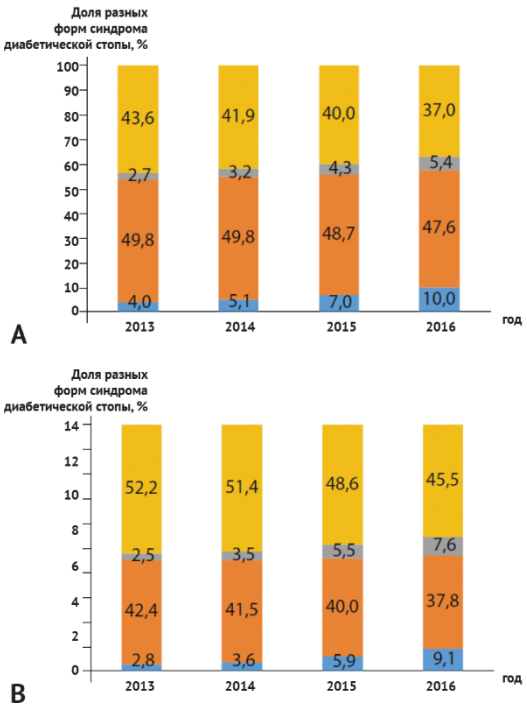

Fig. 2. Distribution by level of amputations in patients with type 1 (A) and type 2 (B) diabetes mellitus

In 2016, data were published for the first time on the dynamics of lower limb amputations in patients with diabetes in 26 countries of the Organization for Economic Cooperation and Development (OECD) for the period from 2000 to 2011. According to this analysis, the number of amputations decreased from 13.2 per 100 thousand population in 2000 (range 5.1–28.1) to 7.8 in 2011 (1.0–18.4), respectively. This frequency of amputations, although somewhat lower, is comparable with Russian statistics [2].

At the same time, the distribution of the proportion of MA performed within the foot according to foreign authors correlates with domestic ones. Thus, data from the Finnish national register demonstrate the following relationship between MA and high amputations in the period from 1997 to 2007: an increase from 0.86 (0.8–0.92) to 1.35 (1.26–1.46) ($p<0.001$) [3].

Therefore, we can note a trend toward an increase in the number of patients who have undergone MA internationally.

MA involves removing non-viable tissue within a segment of the foot during the development of a purulent-necrotic process and aims to protect the patient from amputation at a higher level (lower leg or thigh), and sometimes to save his life.

Aim of the study: to evaluate the nature of surgical interventions for post-amputation foot deformities in patients with diabetic neuropathy.

MATERIAL AND METHODS

The literature search was carried out using the databases of medical publications PubMed, CyberLeninka, Google Scholar, Scopus, Medline, eLIBRARY among articles in English and Russian. The search was performed using the following terms: minor amputations, transmetatarsal resection, diabetic foot syndrome, transmetatarsal amputation, minor amputation.

Literary sources devoted to methods of orthopedic correction of foot deformities in isolation from DFS and manifestations of DFS without mentioning orthopedic treatment methods (surgery for purulent complications, vascular surgery, hypoglycemic therapy, etc.) were excluded from the study.

RESULTS

In distal diabetic neuropathy, a muscle-tendon imbalance occurs due to degenerative fibrous and fatty restructuring of the distal muscles – interosseous and lumbrical ones. This leads to "overtightening" of the long flexor and extensor tendons and the formation or strengthening of existing hammertoe and claw toe deformities, incomplete and even complete dislocations of the toes [4, 5]. Neuropathy reduces the elasticity of the gastrocnemius and soleus muscles. As a consequence, limited dorsiflexion in the ankle joint and equinus of the foot occurs [6]. The described biomechanical disorders and static deformations of the feet lead to the formation of zones of increased mechanical impact, in the area of which, against the background of distal neuropathy and specific histo-biochemical changes, "neuropathic" ulcerative defects are formed [7–9].

The probability of recurrence of ulcers after MA is 40–65% in the first 3 years after amputation. These patients are considered to be in the highest (third) risk group [10–12].

Attempts to classify the severity of biomechanical dysfunction in patients with DFS were carried out by domestic researchers [13]. However, no unified taxonomy or other orthopedic classification reflecting the cause-and-effect relationship between the level of amputation and the severity of neuropathy was found.

Among post-amputation deformities (PADs) of the foot, it is advisable to distinguish two main groups, based on the level of previous amputation:

– PAD of the forefoot (loss of part of the toes, heads of metatarsal bones), when the forefoot is partially preserved;

– PAD of the stump of the foot (loss of the entire forefoot, up to the Chopart joint).

SURGICAL TREATMENT OF ANTERIOR PAD

Post-amputation deformity of the anterior segment in patients with DFS requires the same approach that is necessary for static deformities of the feet (without previous MA) [14]. Surgical methods for orthopedic correction of static deformities in patients with DFS are quite widely presented in the scientific literature. The recommendations of the International Working Group of the Diabetic Foot (IWGDF) [15, 16] can serve as a generally accepted guideline. According to them, it is advisable to resort to surgical treatment in the absence of effectiveness of all methods of conservative offloading of areas of ulcerative defect, such as non-removable knee-high offloading devices, removable knee-high or ankle-high offloading devices, felted foam. If there is no ulcer, then as a preventative measure it is recommended to use removable ankle-high offloading devices, footwear modification, and toe spacers or orthoses (Fig. 3).

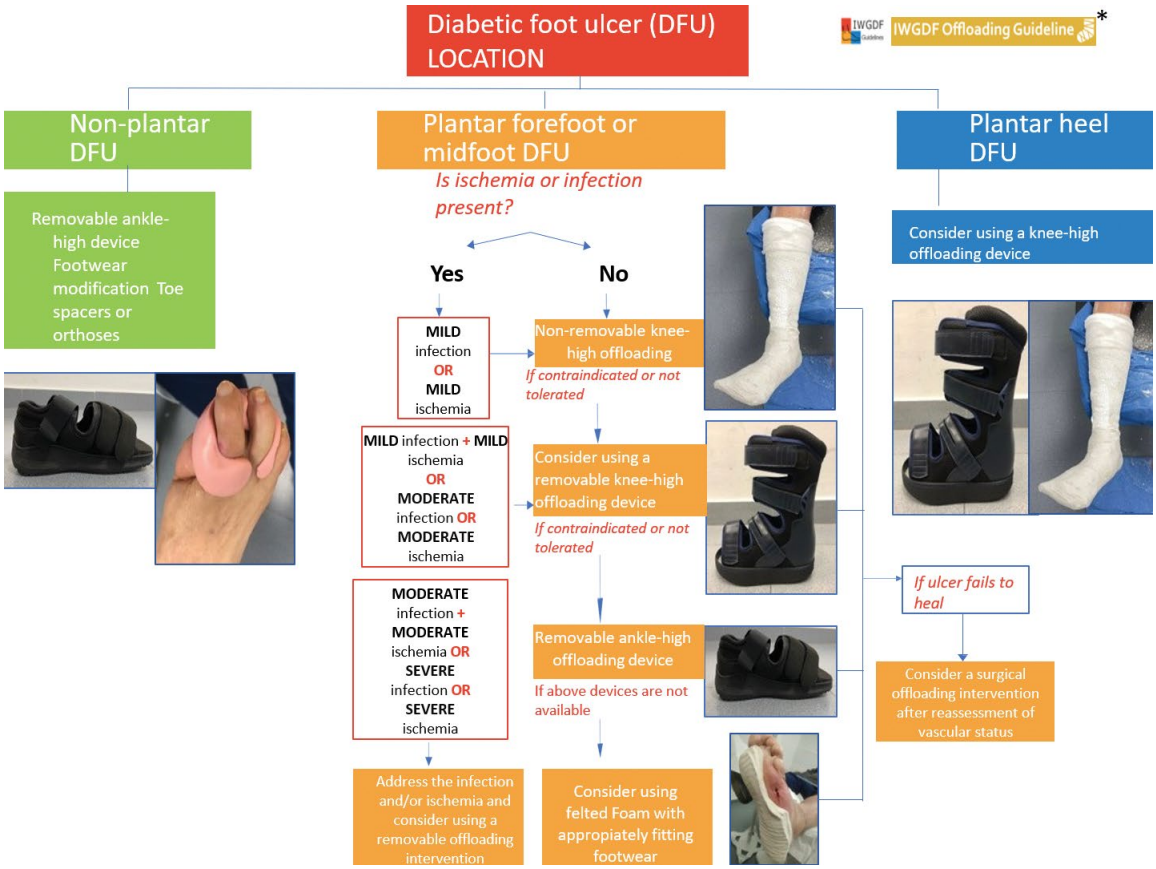

Fig. 3. Algorithm for orthopedic treatment (offloading) of diabetic ulcers [15, 16]

These recommendations are primarily based on studies with the highest level of evidence—randomized controlled trials (RCTs). Such research was conducted in relation to the following surgical treatment methods:

Resection of the heads of the metatarsal bones [17] is performed in the presence of ulcers of the plantar surface in the projection of the heads of the metatarsal bones.

Lengthening the triceps surae muscle is the most studied method to reduce plantar pressure on the entire anterior compartment and promote the healing of ulcers in this area, covered in the largest number of RCTs [18–20] and a literature review [21] (Fig. 4).

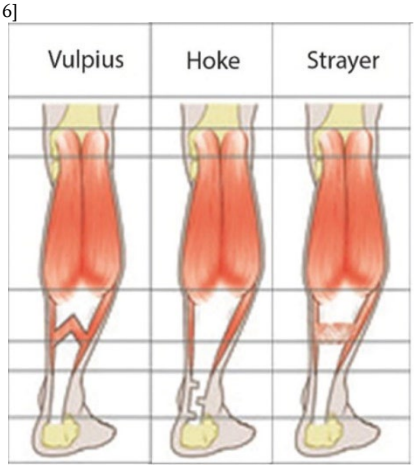

Fig. 4. Scheme of methods for lengthening of the triceps surae muscle

Tenotomy of the flexor and extensor tendons of the toes [22, 23], allows surgeons, by eliminating the hammertoe deformity, to remove the area of the ulcerative defect from stress.

Other techniques have also demonstrated their effectiveness, but, based on retrospective controlled studies, they are presented in recommendations of a "lesser strength".

Among them is **Keller resection arthroplasty of the metatarsophalangeal joints** [24–26], which makes it possible to increase mobility in the corresponding joint and reduce pressure on the plantar surface of the toe.

And uncontrolled studies of "lower level of evidence", such as observation of a series of cases devoted to **metatarsal osteotomy** [27–32], due to which the area of the ulcerative defect is offloaded in the projection of the head of the corresponding metatarsal bone, and conditions are created for the healing of the ulcer.

A combination of correction methods appears to be more promising in relation to PAD of the feet. Hamilton G. A. et al. [33] described a successful experience of tendon-muscular plastic surgery (simultaneous lengthening of the triceps muscle, transposition of the peroneus longus tendon onto the peroneus brevis tendon) and resection of the lesser metatarsal heads in relation to patients with ulcers under the heads of the remaining lesser metatarsals.

The positive effect of the technology of transposition of the peroneal muscles is explained by the fact that resection of the heads of only the lesser metatarsals is performed; while to avoid overloading of the plantar surface in the projection of the head of the first metatarsal bone, pronation (for which the peroneus longus muscle is "responsible") is "weakened"; in contrast to the previously described variants of post-amputation deformities, when, on the contrary, a decrease in supination of the foot stump is required.

SURGICAL TREATMENT OF PAD OF THE FOOT STUMP

The nature of the deformities that occur after amputation of the forefoot and require correction are mentioned in the work of D.I. Lavrova and B.V. Shishkin in 2017 [34]. **In relation to the diabetic foot, this is equinus, varus, or equinovarus deformation of its stump.** In advanced forms of deformation, the stump takes on the character of a vicious one, that is, non-supporting, with neuropathic ulcers in areas of increased mechanical impact (distal part of the stump, external plantar surface of the stump).

Surgical treatment of PAD of the foot stump

The nature of the deformities that occur after amputation of the forefoot and require correction are mentioned in the work of D.I. Lavrova and B.V. Shishkin in 2017 [34]. In relation to the diabetic foot, this is equinus, varus, or equinovarus deformation of its stump. In advanced forms of deformation, the stump takes on the character of a vicious one, that is, non-supporting, with neuropathic ulcers in areas of increased mechanical impact (distal part of the stump, external plantar surface of the stump).

Thus, taking into account the previously described influence of distal neuropathy on the formation of deformities of the distal segment of the lower extremity in combination with the loss of the entire forefoot, we can assume how severe the degree of impairment of the biomechanics of the lower limb is in patients who have undergone this type of surgical treatment for purulent-necrotic complications in DFS.

Scientific evidence for surgical methods of "offloading" in these deformities is much more sparse. Of the methods mentioned in the recommendations of the International Working Group on the Diabetic Foot (IWGDF), only **triceps lengthening** can be distinguished; the remaining surgical techniques are designed to operate on remaining structures of the forefoot. However, in the literature one can find a sufficient number of publications devoted to various methods of treating PAD of the foot stump with a lower level of evidence (series of clinical cases).

Peroneus brevis tendon transposition. This surgical intervention consists of cutting off the peroneus brevis tendon from the site of attachment and fixation to the peroneus longus tendon in combination with percutaneous lengthening of the Achilles tendon: as a result, correction of excessive equinovarus (supination) deformity of the foot stump occurs [35].

Intramedullary fixation of the first metatarsal bone is performed after manual removal of excess supination simultaneously with the formation of the foot stump. A long screw is inserted intramedullarily through the first metatarsal bone into the talus, followed by closing

the screw slot by the adductor pollicis muscle or allograft [36]. The authors focus their attention on the lower level of suppuration of the surgical wound and the consistency of the sutures in comparison with tendon repairs performed for the same purpose (correction of equinovarus deformity of the stump).

Transposition of the flexor digitorum longus and extensor digitorum longus tendons. When forming the stump, the specified tendons are fixed with anchor screws to the stump of the first metatarsal bone (tendon of the long flexor of the first digit) and the stump of the IV metatarsal bone (tendon of the extensor digitorum longus); in this way, the supination-pronation tendon-muscle balance is maintained, which prevents the development of deformities [37].

The last three methods are described by one team of authors. In their opinion, they are applicable both in the form of preventive measures (at the stage of stump formation) and in later stages - to correct the developed deformity.

Transposition of the tibialis anterior, extensor pollicis longus, and extensor digitorum longus tendons onto the talus. This technique is described in the work of Green C. J. et al. [38], and carried out in relation to 41 patients. The technology consisted of simultaneous disarticulation at the level of the Chopart joint, isolation of the tendons of these muscles, and fixation of the latter transosseally to the neck of the talus together with the release of the gastrocnemius muscle (Strayer or Vulpius technique) with a combination of minimally invasive Achilles tendon lengthening. The results were assessed over 4 years. The formation of equinus contracture of the ankle joint and ulcer development was observed in only one patient. The authors note that the patients are able to move independently without the need to use bulky orthopedic products in the vast majority of cases.

Arthrodesis of the ankle and subtalar joints in the corrective position has demonstrated success as a method of prevention and treatment of typical deformities characteristic of the short stump of the foot. But, unfortunately, a small series of cases were analyzed. De Gere et al. [39] noted that in 6 out of 7 patients, the tactics used made it possible to avoid the formation of ulcers while maintaining the ability to actively move during 4 years of observation. One of the 7 developed severe purulent complications, leading to amputation of the limb at the level of the lower leg. It is indicated that the surgical treatment included two stages: removal of purulent-necrotic tissue, and subsequently stump formation, Achilles tendon lengthening, and arthrodesis of the joints in the physiological position of the stump using an intramedullary pin.

DISCUSSION

The loss of any functional anatomical formation, that is, amputation of even one toe, cannot but entail biomechanical impairment of the distal lower limb. In the presence of distal neuropathy, which aggravates the already impaired biomechanics, overload of the remaining supporting structures of the foot stump inevitably occurs. However, the category of patients with PAD of the feet is not singled out as a separate group of specific orthopedic pathology against the general background of DFS, and is not considered specifically taking into account the presence of obvious features. The specific cause-and-effect relationships between the level of MA and the nature of the biomechanical problems have not yet been adequately studied or classified.

Probably the main source of information on treatment methods for DFS that one can rely on (clinical recommendations of the International Working Group of the Diabetic Foot - IWGDF), describes methods that are applicable almost only for the PAD, in which part of the forefoot is preserved. For cases where the entire forefoot is lost, there is virtually no information on surgical treatment options (except for universal triceps surae lengthening).

Moreover, this guideline does not specify when it is possible to judge the lack of effectiveness of the ongoing conservative treatment and proceed to surgical methods, that is, there are no specific indications. Clinical criteria other than ulcer healing – the patient's functional activity, biomechanical parameters and quality of life – are not considered.

These recommendations lack clearly defined tactics: the techniques are taken out of context, there are no recommendations in which cases is it advisable to use a single technique, and in which – their combination, despite the obvious difference between the orthopedic status and the degree of biomechanical impairment in patients with primary deformities (without previous amputations), with PAD of the foot, and PAD of the stump.

Indeed, few studies of surgical methods for treating PAD of the feet with a high level of evidence have been published in the world literature: of the 5 mentioned, three are dedicated to triceps muscle lengthening. However, this is probably logical given how difficult it is to conduct a study of this level in comorbid patients. For example, the presence of neuropathic ulcers in DFS is due to too many factors besides the presence of deformations and areas of increased mechanical impact. This includes the patient's weight, level of physical activity, nature and quality of conservative orthopedic support (shoes, insoles, etc.), severity of neuropathy, adherence to treatment, etc. The lack of statistical analysis of publications representing observations of a number of clinical cases can be explained by the small sample size.

The only thing that is the same for all the works devoted to the correction of post-amputation deformities is the statement of the positive dynamics of correction of orthopedic status, functional capabilities; only in some cases confirmed photographically, illustratively. In assessing the surgical treatment of foot deformities, various scales have been developed that are widely used in patients without DFS, for example, AOFAS [40], Grulier [41]. However, such scales, unfortunately, are not used in assessing the effectiveness of surgical treatment of PAD. All the while, this would be logical, given the specifics of the pathogenesis of DFS.

CONCLUSION

Surgical methods for correcting foot deformities, including post-amputation deformities, in the treatment of diabetic foot syndrome have no longer been exotic, rare, experimental, and become firmly established in wide international practice. Their effectiveness was confirmed by a number of studies with a high level of evidence. Nevertheless, a broader, academic study of the problem of orthopedic status in patients with post-amputation deformity and the corresponding methods of surgical treatment are required.

REFERENCES

1. Galstyan GR, Vikulova OK, Isakov MA, Zheleznyakova AV, Serkov AA, Egorova DN, et al. Trends in the epidemiology of diabetic foot and lower limb amputations in Russian Federation according to the Federal Diabetes Register (2013–2016). *Diabetes mellitus*. 2018;21(3):170–177.
2. Carinci F, Massi Benedetti M, Klazinga NS, Uccioli L. Lower extremity amputation rates in people with diabetes as an indicator of health systems performance. A critical appraisal of the data collection 2000–2011 by the Organization for Economic Cooperation and Development (OECD). *Acta Diabetol*. 2016;53(5):825–832. PMID: 27443839 https://doi.org/10.1007/s00592-016-0879-4
3. Winell K, Venermo M, Ikonen T, Sund R. Indicators for comparing the incidence of diabetic amputations: a nationwide population-based register study. *Eur J Vasc Endovasc Surg.* 2013;46(5):569–574. PMID: 24007756 https://doi.org/10.1016/j.ejvs.2013.07.010
4. Fernando M, Crowther R, Lazzarini P, Sangla K, Cunningham M, Buttner P, et al. Biomechanical characteristics of peripheral diabetic neuropathy: a systematic review and meta-analysis of findings fromthe gait cycle, muscle activity and dynamic barefoot plantar pressure. *Clin Biomech (Bristol, Avon)*. 2013;28(8):831–845. PMID: 24035444 https://doi.org/10.1016/j.clinbiomech.2013.08.004
5. Andersen H. *Motor neuropathy. Handbook of Clinical Neurology*. Elsevier; 2014. p. 81–95. https://doi.org/10.1016/b978-0-444-53480-4.00007-2
6. Frykberg RG, Bowen J, Hall J, Tallis A, Tierney E, Freeman D. Prevalence of equinus in diabetic versus nondiabetic patients. *J Am Podiatr Med Assoc*. 2012;10(2):84–88. PMID: 22461264 https://doi.org/10.7547/1020084
7. Sudnitsyn AS, Shchurova EN, Varsegova TN, Stupina TA, Migalkin NS. Some Morphological and Functional Aspects of Chronic Osteomyelitis in Patients with Neurogenic Foot Deformities. *Traumatology and Orthopedics of Russia.* 2019;25(2):102–110. https://doi.org/10.21823/2311-2905-2019-25-2-102-110
8. Artemova EV, Gorbacheva AM, Galstyan GR, Tokmakova AYu, Gavrilova SA, Dedov II. Neurohumoral mechanisms of keratinocytes regulation in diabetes mellitus. *Diabetes mellitus*. 2016;19(5):366–374. (In Russ.) https://doi.org/10.14341/DM8131
9. Lazzarini PA, Crews RT, Van Netten JJ, Bus SA, Fernando ME, Chadwick PJ, et al. Measuring plantar tissue stress in people with diabetic peripheral neuropathy: a critical concept in diabetic foot management. *J Diabetes Sci Technol*. 2019;13(5):869–880. PMID: 31030546 https://doi.org/10.1177/1932296819849092
10. Jupiter DC, Thorud JC, Buckley CJ, Shibuya N. The impact of foot ulceration and amputation on mortality in diabetic patients. I: from ulceration to death, a systematic review. *Int Wound J*. 2016;13(5):892–903. PMID: 25601358 https://doi.org/10.1111/iwj.12404
11. Armstrong DG, Boulton AJ, Bus SA. Diabetic foot ulcers and their recurrence. *N Engl J Med*. 2017;376(24):2367–2375. PMID: 28614678 https://doi.org/10.1056/NEJMra1615439
12. Crawford F, Cezard G, Chappell FM, Murray GD, Price JF, Sheikh A, et al. A systematic review andindividual patient data meta-analysis of prognostic factors for foot ulceration in people with diabetes: the international research collaboration for the prediction of diabetic foot ulcerations (PODUS). *Health Technol Assess*. 2015;19(57):1–210. PMID: 26211920 https://doi.org/10.3310/hta19570
13. Parshikov M, Bardiugov P, Yarygin N. Orthopaedic aspects of diabetic foot syndrome classifications. *Genij Ortopedii.* 2020;26(2):173–178. https://doi.org/10.18019/1028-4427-2020-26-2-173-178
14. Bardyugov P, Parshikov M. Foot deformities in patients with diabetic foot disease (literature review). *Genij Ortopedii*. 2022;28(3):452–458. https://doi.org/10.18019/1028-4427-2022-28-3-452-458
15. Bus SA, Lavery LA, Monteiro-Soares M., Rasmussen A, Raspovic A, Sacco ICN, et al. Guidelines on the prevention of foot ulcers in persons with diabetes (IWGDF 2019 update). *Diabetes Metab Res Rev.* 2020;36(Suppl 1):e3269. PMID: 32176451 https://doi.org/10.1002/dmrr.3269

16. Bus SA, Armstrong DG, Gooday C, Jarl G, Caravaggi C, Viswanathan V, et al. Guidelines on offloading foot ulcers in persons with diabetes (IWGDF 2019 update). *Diabetes Metab Res Rev*. 2020;36(Suppl 1):e3274. PMID: 32176441 https://doi.org/10.1002/dmrr.3274
17. Piaggesi A, Schipani E, Campi F, Romanelli M, Baccetti F, Arvia C, et al. Conservative surgical approach versus non-surgical management for diabetic neuropathic foot ulcers: a randomized trial. *Diabet Med*. 1998;15(5):412–417. PMID: 9609364 https://doi.org/10.1002/(sici)1096-9136(199805)15:5<412::aid-dia584>3.0.co;2-1
18. Mueller MJ, Sinacore DR, Hastings MK, Strube MJ, Johnson JE. Effect of Achilles tendon lengthening on neuropathic plantar ulcers. A randomized clinical trial. *J Bone Joint Surg Am*. 2003;85(8):1436–1445. PMID: 12925622 https://doi.org/10.2106/00004623-200308000-00003
19. Allam AM. Impact of Achilles tendon lengthening (ATL) on the diabetic plantar forefoot ulceration. *Egypt J Plast Reconstr Surg*. 2006;30(1):43–48.
20. Maluf KS, Mueller MJ, Strube MJ, Engsberg JR, Johnson JE. Tendon Achilles lengthening for the treatment of neuropathic ulcers causes a temporary reduction in forefoot pressure associated with changes in plantar flexor power rather than ankle motion during gait. *J Biomech*. 2004;37(6):897–906. PMID: 15111077 https://doi.org/10.1016/j.jbiomech.2003.10.009
21. Dallimore SM, Kaminski MR. Tendon lengthening and fascia release for healing and preventing diabetic foot ulcers: a systematic review and meta-analysis. *J Foot Ankle Res*. 2015;8(1):33. PMID: 26300980 https://doi.org/10.1186/s13047-015-0085-6 eCollection 2015.
22. Bonanno DR, Gillies EJ. Flexor Tenotomy Improves Healing and Prevention of Diabetes-Related Toe Ulcers: A Systematic Review. *J Foot Ankle Surg*. 2017;56(3):600–604. PMID: 28476394 https://doi.org/10.1053/j.jfas.2017.02.011
23. Askø Andersen J, Rasmussen A, Engberg S, Bencke J, Frimodt-Møller M, Kirketerp-Møller K, et al. Flexor Tendon Tenotomy Treatment of the Diabetic Foot: A Multicenter Randomized Controlled Trial. *Diabetes Care*. 2022;45(11):2492–2500. PMID: 36151947 https://doi.org/10.2337/dc22-0085
24. Armstrong DG, Lavery LA, Vazquez JR, Short B, Kimbriel HR, Nixon BP, et al. Clinical efficacy of the first metatarsophalangeal joint arthroplasty as a curative procedure for hallux interphalangeal joint wounds in patients with diabetes. *Diabetes Care*. 2003;26(12):3284–3287. PMID: 14633815 https://doi.org/10.2337/diacare.26.12.3284
25. Tamir E, Tamir J, Beer Y, Kosashvili Y, Finestone AS. Resection Arthroplasty for resistant ulcers underlying the hallux in insensate diabetics. *Foot Ankle Int*. 2015;36(8):969–975. PMID: 25810459 https://doi.org/10.1177/1071100715577952
26. Yammine K, Assi C. A Meta-Analysis of the Outcomes of Resection Arthroplasty for Resistant Hallucal Diabetic Ulcers. *J Foot Ankle Surg*. 2021;60(4):795–801. PMID: 33771433 https://doi.org/10.1053/j.jfas.2020.04.025
27. Biz C, Gastaldo S, Dalmau-Pastor M, Corradin M, Volpin A, Ruggieri P. Minimally invasive distal metatarsal diaphyseal osteotomy (DMDO) for chronic plantar diabetic foot ulcers. *Foot Ankle Int*. 2018;39(1):83–92. PMID: 29110516 https://doi.org/10.1177/1071100717735640
28. Botezatu I, Laptoiu D. Minimally invasive surgery of diabetic foot – review of current techniques. *J Med Life*. 2016;9(3):249–254. PMID: 27974928
29. Robinson D, Yassin M, Garti A, Ashkenazi U, Weisbrot M, Heller E. Percutaneous Correction of Forefoot Deformities in Diabetic Patients in Order to Prevent Pressure Sores. *Foot Ankle Surg*. 2016;22(2):80. https://doi.org/10.1016/j.fas.2016.05.200
30. Obolensky VN, Protsko VG, Osnach SA. Mini-Invasive Corrective Osteotomy in Patients with an Ulcerative Anterior Defect of the Diabetic Foot. *Khirurg*. 2018;(3–4):70–79. (in Russ.)
31. Fleischli JE, Anderson RB, Davis WH. Dorsiflexion Metatarsal Osteotomy for Treatment of Recalcitrant Diabetic Neuropathic Ulcers. *Foot Ankle Int*. 1999;20(2):80–85. PMID: 10063975 https://doi.org/10.1177/107110079902000203
32. Yammine K, Nahed M, Assi C. Metatarsal Osteotomies for Treating Neuropathic Diabetic Foot Ulcers: A Meta-analysis. *Foot Ankle Spec*. 2018;12(6):555–562. PMID: 30565498 https://doi.org/10.1177/1938640018819784
33. Hamilton GA, Ford LA, Perez H, Rush SM. Salvage of the neuropathic foot by using bone resection and tendon balancing: A retrospective review of 10 patients. *J Foot Ankle Surg*. 2005;44(1):37–43. PMID: 15704081 https://doi.org/10.1053/j.jfas.2004.11.001
34. Lavrova JI, Shishkin BV. Evaluation of the Gait Function Impairments and Standing in a Foot Amputation. *Medico-Sotsialnye Problemy Invalidnosty*. 2017;(1):44–47. (In Russ.)
35. Schweinberger MH, Roukis TS. Balancing of the Transmetatarsal Amputation with Peroneus Brevis to Peroneus Longus Tendon Transfer. *J Foot Ankle Surg*. 2007;46(6):510–514. PMID: 17980854 https://doi.org/10.1053/j.jfas.2007.05.012
36. Schweinberger MH, Roukis TS. Intramedullary Screw Fixation for Balancing of the Dysvascular Foot Following Transmetatarsal Amputation. *J Foot Ankle Surg*. 2008;47(6):594–597. PMID: 19239874 https://doi.org/10.1053/j.jfas.2007.12.002
37. Roukis TS. Flexor Hallucis Longus and Extensor Digitorum Longus Tendon Transfers for Balancing the Foot Following Transmetatarsal Amputation. *J Foot Ankle Surg*. 2009;48(3):398–401. PMID: 19423046 https://doi.org/10.1053/j.jfas.2008.12.013
38. Green CJ, Bibbo C, McArdle A, Knight C. A Functional Chopart's Amputation With Tendon Transfers. *J Foot Ankle Surg*. 2021;60(1):213–217. PMID: 32981826 https://doi.org/10.1053/j.jfas.2020.08.019
39. De Gere MW, Grady JF. A Modification of Chopart's Amputation with Ankle and Subtalar Arthrodesis by Using an Intramedullary Nail. *J Foot Ankle Surg*. 2005;44(4):281–286. PMID: 16012435 https://doi.org/10.1053/j.jfas.2005.04.014
40. Kitaoka HB, Alexander IJ, Adelaar RS, Nunley JA, Myerson MS, Sanders M. Clinical rating systems for the ankle-hindfoot, midfoot, hallux, and lesser toes. *Foot Ankle Int*. 1994;15(7):349–353. PMID: 7951968 https://doi.org/10.1177/107110079401500701
41. Groulier P, Curvale G, Prudent HP, Vedel F. Resultats du traitement de l`hallux valgus selon la technique de Mac Bride "modifee" avec ou sans osteotomie phalangienne ou metetarsienne complimentaire. *Rev Chir Orthop Reparatrice Appar Mot.* 1988;74(6):539–548. PMID: 3238084

Received on 12/01/2023
Review completed on 11/10/2023
Accepted on 13/10/2023