The First International Conference "Innovations in Medical Science and Education"

Influence of forefoot deformities on the gait cycle

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Abstract. Modern treatment of foot deformities made it possible to increase the positivity of the outcomes of their surgical treatment. Surgical correction of anatomical distortions significantly improves the supporting and motor functions of the foot. To achieve this goal are widely used in various corrective interventions on the anterior section of the foot. The abundance of methods for these operations indicates that there are no optimal standards to date. The influence of bone and articular changes to locomotion and dynamics of movements of the lower extremities remains largely unexplored. Expanding the diagnosis of dynamic changes in the gait cycle as a result of deformity of the forefoot can help optimize the choice of correction method. This will give the potential to determine the indications for a particular method of restoring the correctness of anatomical relationships. Therefore, diagnostics of the transformation of the gait cycle with deformations of the forefoot is of undoubted interest. The purpose of the study is to evaluate the biomechanical features of movement of a person with anterior foot deformity, pain syndrome caused by deformity, and to explain the influence of the deformed foot shape on the change of individual phases of the gait cycle. To find out the changes in the walking function, we used a three-dimensional video analysis method. The main group was represented by 29 patients with anterior deformity of feet. The research was organized in 2018-2020. The average age was 51.3±16.5 years (from 20 to 80 years female patients were 29 (96.7%)). The control group consisted of 22 healthy women without foot deformities, with an average age of 45.4±15.5 years. The tool base of the research was the Vicon motion capture system (digital infrared cameras Vicon T40-10 PCs., video cameras Vicon bonita 720-2 PCs., dynamometer platform AMTI – 2 PCs., software Vicon Nexus, Vicon Polygon). The study used a full Body Plugin Gate (URM-FRM) skeletal model consisting of 39 reflective markers arranged in a certain order on the human body. The analysis of kinematic data revealed that all 29 studied patients had violations of biomechanics of movements in the joints of the lower extremities. There was an increase in the time of double support by 22.2% from 0.21±0.057 s for the control group to 0.27±0.064 s for the main group. Video analysis allowed us to combine the data obtained using computer graphical visualization of movements with the indicators of the support reaction force and the speed of movement of the lower extremities in patients with foot deformities, as well as to reveal the internal architecture of the gait cycle.

Keywords: human gait, kinematic parameters, foot deformity, metatarsalgia, gait cycle, motion capture system, Vicon.

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1. INTRODUCTION

Deformities of the anterior part of the foot are a complex and multicomponent pathology. The only method that can permanently change the shape of the foot is surgical. The decision on the choice of a surgical intervention method is based on a comprehensive and maximally complete study of each specific situation. It is not enough to focus only on the static picture of the deformity of the foot, given that the foot is a highly mobile segment of the lower limb.

The gait cycle (GC) consists of the stance phase and swing phase. The cycle is limited to the period of time from the beginning of contact of the foot with the support surface until the beginning of the next contact of the same foot with the support surface. The study of human gait for clinical purposes is undergoing an indisputable and justified development. The attention of researchers is attracted by the information that can be obtained by interpreting the biomechanical parameters of the GC. It is important for practical doctors to find a short way to informative parameters of gait assessment, which will eliminate the abundance of low-value secondary information. In clinical practice, more often the evaluation of the function by a doctor is carried out only during a clinical examination and has a large share of subjectivity. It is established that the characteristics of the foot in static and stationary positions are not necessarily reflected in the characteristics of the moving foot [1]. An important step in understanding the pathology of the foot is an objective analysis of not only the static position of the foot, but also the kinematics of the foot in the state of its movement [2]. Altered gait patterns are often associated with valgus deformity of the first toe. [3, 4, 5, 6].

As a result of long-term research in the orthopedic scientific community, a lot of data on the kinematics of the GC has been accumulated, modern manuals have been issued and specialized periodicals in the field of considering human movements are published. Many studies have been devoted to the study of normal and pathological gait [7, 8, 9, 10], but after analyzing them, it can be found out that scientific works devoted to the study of the structure of the GC under conditions of foot deformities, while relying on the analysis of objective indicators, are not enough to cover this topic. Therefore, the identification of changes in the GC with deformities of the anterior part of the foot does not cause doubts about the relevance. The purpose of the study is to evaluate the biomechanical features of the movement of a person with a deformity of the forefoot, pain syndrome caused by deformation, as well as to explain the influence of the shape of the deformed foot on the change of individual phases of the GC.

2. METHODS

This study was done in the Centre of Biomechanics Research of Human Movement at the Astrakhan State University and the Department of Traumatology and Orthopedics of the Astrakhan State Medical University. Data acquisition and analysis of movements was done with help of Vicon equipment (Vicon, UK), including ten infrared digital cameras Vicon T40, a video camera Bonita 720, a Vicon Giganet Lab digital multiplex switch, Vicon Nexus and Polygon software, as well as a stabilometric force platform AMTI (AccuGaitACG, USA).

The main group was represented by 29 patients who applied to the clinical department of the chair. The criterion for selecting patients for this study, in addition to the presence of hallux valgus of moderate or severe degree, was the mandatory presence of pain in the foot.

Medical reports of three-dimensional video analysis of this group of patients with anterior deformity were analyzed. The research was organized in 2018-2020 years. The average age was 51.3±16.5 years (from 20 to 80 years); 29 female patients were studied.

The control group consisted of 22 healthy subjects, without deformity of the feet, average age was 44.6±15.5 years.

All patients of the main group had indications for surgical treatment: severe deformity and chronic pain syndrome, and most often combined both indications. All the subjects of the main group had clinically diagnosed and instrumentally (radiography, plantoscopy) confirmed transverse spreading of the anterior part of the foot. 28 people in the main group had a valgus deviation of the first toe one or both feet, and signs of metatarsalgia - from mild to severe. One patient (3.4%) was diagnosed with arthrosis of the first metatarsophalangeal joint without deformity of the first toe. As part of the deformity, 10 patients (34.5%) had hammer-toes deformities of the small toes with areas of pronounced hyperkeratosis in the area of maximum physiological load falling on the gap between the heads of the second and third metatarsal bones.

The movement was carried out with a natural uniform speed for the patient. Before registering the indicators, the patient performed 7 passing cycles in order to adapt to the platform. To register the indicators, from 7 to 10 passing cycles were performed, depending on their quality (passing cycles with involuntary movements that were not part of the gait pattern were excluded). To create reports, was used the Vicon Polygon software. Due to the high informative value and diagnostic significance of the results of the study of gait function, the following parameters of the GC were analyzed:

1. Time characteristics (the time of the first and second periods of double support, the time of the support period, the beginning and time of the period of single support, the time of the GC);
2. Spatial characteristics (step length, step base, walking speed);
3. Kinematic characteristics (amplitudes and corresponding time intervals of movements of the ankle, knee and hip joints in three planes);
4. Kinetic characteristics(the vertical component of the support reaction).

The statistical analysis was carried out using Microsoft Office Excel and MathCad programs. For descriptive statistics, the data are presented in the form of M±SD, where M is the average value of the feature, SD is the standard deviation, minimum and maximum values are demonstrated for individual data. To assess the differences in the compared groups, the Student's T-criterion was used: the results of the main and control groups were compared. The degree of accuracy of the study is determined by the probability of an error-free forecast less than or equal to 0.95% of the significance level $p \leq 0.05$.

3. RESULTS

The GS was distinguished by the limitation of the time period from the beginning of the contact of the foot with the support surface to the beginning of the next contact of the same foot with the support. The obtained data of changes in the structure of the GC, the dependence of objective kinematic and kinetic indicators on the presence of deformities of the forefoot are reflected in Table.

Table 1. Averaged indicators of the spatio-temporal characteristics of the GC of the main and control groups

Indicator name	Main group	Control group
Cadence	107,32±6,3 steps/minute	114,00±6,9 steps/minute
Double support	0,27±0,064 c	0.21±0,057 c
Time of the support	62,09±2,1 %	59.8±2,3 %
Contact of the contralateral leg	50,25±1,84 %	50.3±1,93 %
Beginning period of single support	11,90±1,45%	9.67±1,53 %
Single support	0,42±0,046 sec.	0.42±0,049 sec.
Step Base	0,13±0,045 m	0.13±0,041 m
Step Length	1,11±0,055 m	1.27±0,062 m
Step cycle time	1,13sec.	1.06 sec.
Walking speed	1,02 MPS	1.21 MPS

As follows, from the obtained space-time characteristics of the GS (Table 1), in patients of the main group, an increase in the time of double support (the period of double support) was noted by 22.2% from 0.21±0.057 sec. for the control group to 0.27±0.064 sec. for the main group. A 15.7% decrease in walking speed was found in the main group. At the same time, the step length in the main group was reduced by 12.6%, and the time spent on one step increased by an average of 6.2%, which causes a decrease in walking speed in the vast majority of subjects in the main group. No significant differences were found between the spatio-temporal parameters for the left and right legs. This result can be explained by the fact that both feet were deformed to one degree or another. Only three patients had a problem on only one foot, however, no differences were found in these patients, except for one patient with an isolated valgus deformity of the first toe of the left foot of the third degree and an increase in the lameness index (rhythm coefficient) on the left.

A marked decrease in extension in the ankle joint in the support phase and an increase in flexion in both phases of the GC occurred in all 10 patients with a reverse transverse arch and rigid hammer-toes (Fig. 1).

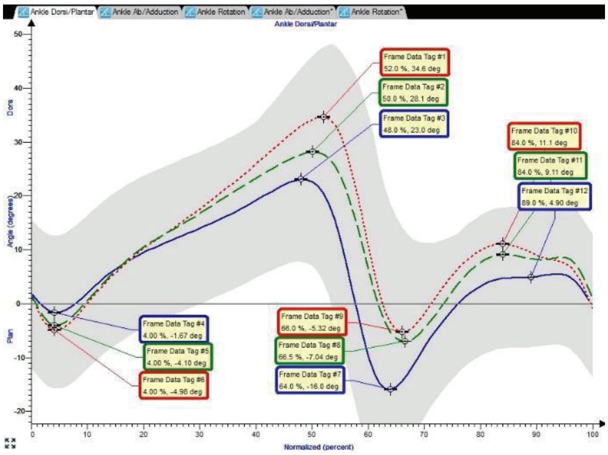

Figure 1. Dynamics of the angular displacements of the ankle joints in the sagittal plane of the examined (dashed green line - right leg; red line to a point - left leg; the control group - solid blue line).

When analyzing the movements of the ankle joint of the studied group in the sagittal plane, there is a pronounced increase in the angle of flexion at the time of rolling over the ankle joint and a significant decrease in the angle of extension at the time of separation of the foot from the support before the transfer phase.

A clear example is the flexion-extension graph of the foot in the central nervous system in a patient with complicated Freiberg's disease - severe arthrosis of the second metatarsophalangeal joint in combination with a valgus deformity of the 1st toe. These changes are reflected in the graph (Fig. 2).

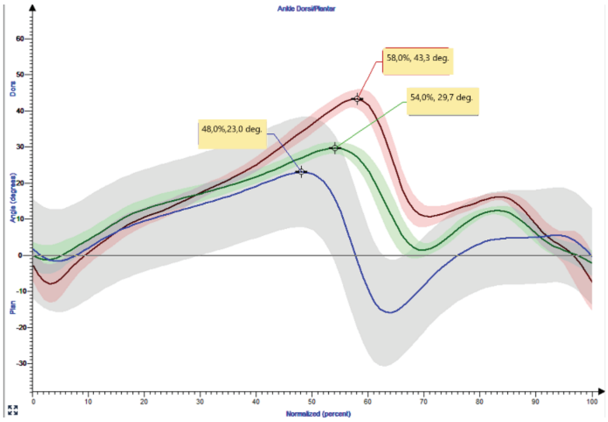

Figure 2. Increase in the angle of dorsiflexion ankle joint in both phases of the gait cycle (red line - left side of the body; green line - right side of the body; blue line - averaged data from the control group of the study.

These violations of the GC should be regarded as a reaction of the body to the pain syndrome, and the desire to limit the load on the painful areas of the supporting surface of the foot. When analyzing the movements of the 3D model of the subjects, a significant increase in the lateral displacement of the distal end of the vertical axis of the lower leg was revealed, which indicates an increase in the valgus position of the knee joints in both phases of the GC, more pronounced in the support phase. In 18 patients, a valgus installation of the left knee joint was diagnosed, and in 11 patients - the right one. When studying the transfer phase of the GC, a valgus position of the left knee joint was registered in 16 cases, and in 9 cases a similar situation was with the right knee joint. Varus position of the knee joints in the support phase was observed only in the one patient.

One patient suffering from arthrosis of the first metatarsophalangeal joint was characterized by a pronounced increase in supination in the phase of support on the diseased foot and a decrease in supination on the healthy one, but there was no decrease in the angle of extension

In the main group, relative to the control group, 15 patients showed an increase in the external rotation of the hip in both phases of the GC, and the inversion of the anterior part of the feet was increased in 13 cases of its deformation.

From the kinetic characteristics, the reaction of the support during the passage of the studied AMT along the dynamic platform was studied.

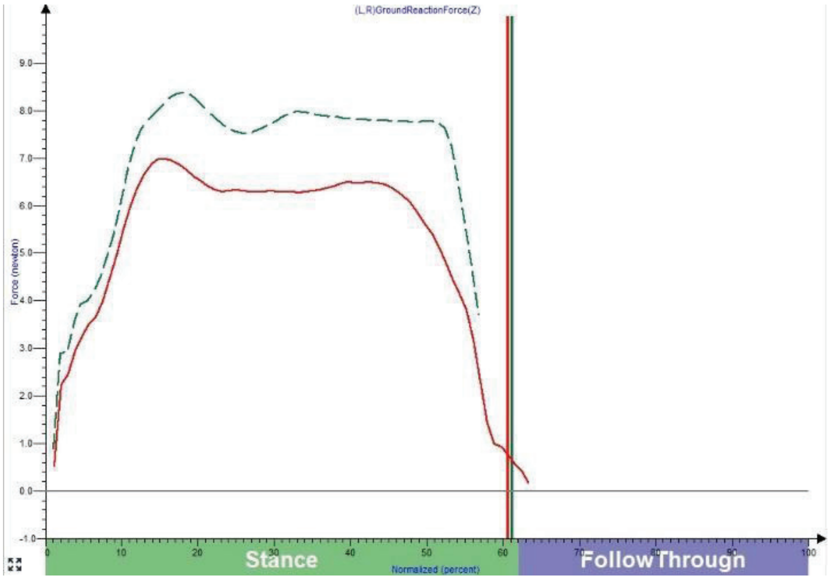

Figure 3. Vertical component of the ground reaction force of the test group (red solid line - left leg, green dotted line - right).

Normally, the vertical component of the support reaction has a characteristic form of a two-humped curve with two maximum and one minimum peaks. The first maximum peak occurs in the interval of 13-14% of the GC at the beginning of the single support period. The second maximum corresponds to the end of the period of a single support and falls on 46-47% of the GC, when the foot retains contact with the support only with its anterior part. In the presented graph (Fig. 3) in the study group, there is a practical absence of the second maximum peak of the vertical component of the support reaction at the moment when the force application vector passes through the heads of the metatarsal bones.

4. DISCUSSION AND CONCLUSION

The GC is limited to the period of time from the beginning of contact of the foot with the support surface until the beginning of the next contact of the same foot with the support surface. The characteristics of the gait are individual for each person, and its value depends on the height of the person, which determines the length of the lower limbs. The base of the step or the width of the step is the horizontal distance between the centers of the ankle joints. This indicator characterizes the area of support and increases, for example, when the balance is disturbed, i.e. the loss of a sense of stability. There were no pronounced changes in the step base in patients of the main group (Table 1). In some patients with existing complaints about a specific foot, a paradoxical increase in the lameness index (rhythm coefficient) on the contralateral limb was noted as a result of the study. When analyzing the kinematic data, it was revealed that all the subjects had violations of the biomechanics of movements in the joints of the lower extremities. From the data obtained from the control group of healthy subjects, it follows that at the end of the support phase, when the forefoot is rolled, the body weight falls only on the distal part of the supporting foot. The anterior arch, in turn, is flattened, and the anterior part of the foot is spread out along the plane of the support. Then the foot is raised on the distal part, ceases to rest on the anterior part of the tarsus, and the vector of force application passes through the heads of the metatarsal bones. It was noted that in patients with metatarsalgia, there is a sharp decrease in extension in the ankle joint in the support phase and an increase in flexion in both phases of the GC. We found that in the movements of the foot in the sagittal plane in the group of patients with valgus deviation of the first toe, a significant increase in the maximum flexion of the anterior part of the foot was revealed compared to the control group (Fig. 1). Similar data are described by Wataru Kawakami et al. [11], however, one of their criteria for selecting patients was the absence of pain in the presence of anterior foot deformity, and only young patients with an average age of 21 years took part in the study.

Rattanaprasert and co-authors [12], studying the gait of a patient with an old rupture of the posterior tibial tendon (PTT) by 3-D imaging and comparing the result with the data of 10 healthy patients, revealed excessive flexion of the forefoot at 70% of the support phase of the GC, before lifting the heel from the floor. The conclusion of the observation was a significant decrease in the stiffness of the medial arch of the foot after the rupture of the PTT. With the loss of the medial arch and the stability of the middle part of the foot, the Achilles tendon, apparently, becomes ineffective in transferring the load to the anterior part of the foot in patients with PTT dysfunction [13]. We observe similar data of an increase in the flexion of the forefoot in our study. However, among the patients examined by us, there was no revealed pathology of PTT and damage to the Achilles tendon.

In the terminal stage of deformity, constant pain causes a pathological change in gait, and severe hallux valgus and balance disorder are a common cause of falls in elderly patients [14]. The increase in flexion in the study group can be explained by an increase in the tension of the anterior-tibial muscle group and the advance of the tibia forward in order to lengthen the time of rolling over the ankle joint in order to delay the transfer of body weight to the anterior, affected by pathology, part of the foot. The decrease in the angle of extension at the moment of separation of the foot from the support may depend on a decrease in the activity of m.triceps surae in order to reduce the time of rolling through the anterior part of the foot and accelerate its separation from the support. Thus, an increase in the flexion angle and a decrease in the extension angle serve as a mechanism for reducing the load on the anterior part of the feet in the study group. This can be confirmed by the practical absence of the second peak of the maximum of the vertical component of the support reaction in the study group.

The revealed predominant valgus installations above the located joints in both phases of the GC are associated with the individual valgus position of the lower segments of the limb. The valgus position of the knee joints, especially in the support phase, is a prerequisite for the development of deformities of the foot, and the deformation of the foot itself can contribute to an increase in the valgus position of the knee. The root cause and consequence of the development of deformities of the lower segments of the leg have not yet been fully established and, in all probability, are combined and interdependent.

At the same time, a decrease in the flexion-extension amplitude in the ankle joint leads to a forced reduction in the length of the step and half-step, and also increases the time spent on the GC. Thus, the influence of kinematic data on the space-time characteristics of the GC is explained. To date, the diagnostic results and the determination of indications for the surgical method are based on static research methods [15, 16]. Three-dimensional video analysis of gait and 3-D modeling of movements can be an objective method for obtaining more reliable diagnostic data, as well as functional treatment results.

As is known, the decision on the choice of a surgical intervention method is based on a comprehensive and maximally complete study of each specific situation. The method makes it possible to determine the indications for osteotomy of the small rays of the foot to transfer the load to the balance points of the foot - the heads of the first and fifth metatarsal bones.

The deformation of the feet, as well as the chronic background pain syndrome associated with this deformation, has a clear impact on the GC. Patients with foot deformity slow down the step speed, while the cadence decreases, the double support period increases and the step length shortens. The most obvious observed changes in the structure of the GC are associated with a certain type of deformation. A sharp decrease in extension in the ankle joint at the moment of separation of the foot from the support and an increase in flexion in both phases of the GC. A decrease or absence of the second peak of the maximum of the vertical component of the support reaction are typical symptoms and consequences of deformities of the anterior part of the foot, accompanied by metatarsalgia.

Anatomical distortions of the osteoarticular apparatus of the foot lead to changes in its kinematics, as well as the kinematics of the ankle, knee and hip joints. The method can allow you to plan surgery more accurately, determine the need for osteotomy of the small rays of the foot. Three-dimensional video analysis of gait and 3-D modeling of movements in the pre- and postoperative period can be an objective method for obtaining reliable functional results of treatment.

AUTHORS' CONTRIBUTIONS

S. Dianov and L. Udochkina developed the idea and the theory of the article. P. Gureev and O. Vorontcova carried out the experiment and performed the computations. All authors discussed the results and created the final manuscript.

ACKNOWLEDGMENTS

We thank the staff of the Center three-dimensional research of biomechanics of Astrakhan State University for the organizing of the research process. The article was created within the framework development programs of the Astrakhan State University of the Priority 2030 program.

REFERENCES

1. A.K. Buldt, G.S. Murley, P. Levinger et al., Are clinical measures of foot posture and mobility associated with foot kinematics when walking, in: J. Foot Ankle Res., Springer Nature, USA, 2015, vol. 8, pp. 63. https://doi.org/10.1186/s13047-015-0122-5
2. K. Deschamps, I. Birch, K. Desloovere, G.A. Matricali, The impact of hallux valgus on foot kinematics: a cross-sectional, comparative study, in: Gait Posture, Elsevier, Amsterdam, Netherlands, 2010, vol. 32, pp. 102-106. https://doi.org/10.1016/j.gaitpost.2010.03.017
3. U. Waldecker, Metatarsalgia in hallux valgus deformity: a pedographic analysis, in: J. Foot Ankle Surg., vol.41, 2002, Springer Nature, USA, pp. 300-308. https://doi.org/10.1016/s1067-2516(02)80048-5
4. J. Wen, Q. Ding, Z. Yu, W. Sun, Q. Wang, K. Wei, Adaptive changes of foot pressure in hallux valgus patients, in: Gait Posture, Elsevier, Amsterdam, Netherlands, 2012, vol. 36, pp. 344-349. https://doi.org/10.1016/j.gaitpost.2012.03.030
5. W.M. Glasoe, D.J. Nuckley, P.M. Ludewig, Hallux valgus and the first metatarsal arch segment: a theoretical biomechanical perspective, in: Phys. Therapy, 2010, vol. 90, pp. 110-120. https://doi.org/10.2522/ptj.20080298
6. K.S. Shih, H.L. Chien, T.W. Lu, C.F. Chang, C.C. Kuo. Gait changes in individuals with bilateral hallux valgus reduce first metatarsophalangeal loading but increase knee abductor moments, in: Gait Posture, Elsevier, Amsterdam, Netherlands, 2014, vol. 40, pp. 38-42. https://doi.org/ 10.1016/j.gaitpost.2014.02.011
7. S. Nix, M. Smith, B. Vicenzino, Prevalence of hallux valgus in the general population: A systematic review and meta-analysis, in: J. of Foot and Ankle Research, Springer Nature, USA, 2010, vol. 3, p. 21. https://doi.org/10.1186/1757- 1146-3-21
8. A. Nishimura, N. Ito, S. Nakazora, K. Kato, T. Ogura, A. Sudo, BMC Musculoskelet Disord, Springer Nature, USA, 2018, vol. 29, p. 174. https://doi.org/10.1186/s12891-018-2100-0.PMID:29843683
9. J. Klugarova, M. Janura, Z. Svoboda, Z. Sos, N. Stergiou, M. Klugar, Hallux valgus surgery affects kinematic parameters during gait, in: Clinical Biomechanics, Bristol, Avon, 2016, vol. 40, pp. 20-26. https://doi.org/10.1016/j.clinbiomech.2016.10.004
10. U.K. Hofmann, M. Götze, K. Wiesenreiter, O. Müller, M. Wünschel, F. Mittag. Transfer of plantar pressure from the medial to the central forefoot in patients with hallux valgus, in: BMC Musculoskelet Disord, Springer Nature, USA, 2019, vol. 20, pp. 149. https://doi.org/10.1186/s12891-019-2531-2
11. W. Kawakami, M. Takahashi, Y. Iwamoto, K. Shinakoda, Coordination among shank, rearfoot, midfoot and forefoot kinematic movement during gait in individuals with Hallux Valgus, in: Journal of Applied Biomechanics, Springer Nature, USA, 2018, vol. 23, p. 21. https://doi.org/10.1123/jab.2017-0319
12. C. Neville, A.S. Flemister, J. Houck, Total and distributed plantar loading in subjects with stage II tibialis posterior tendon dysfunction during terminal stance, in: Foot Anklev, Springer Nature, USA, 2013, vol. 34, pp. 131-139. https://doi.org/ 10.1177/1071100712460181
13. H.B. Menz, S.R. Lord, Gait instability in older people with hallux valgus, in: Foot Ankle, Springer Nature, USA, 2005, vol. 26, pp. 483-489. https://doi.org/ 10.1177/107110070502600610

14. S. Chopra, K. Moerenhout, X. Crevoisier, Characterization of gait in female patients with moderate to severe hallux valgus deformity, in: Clinical Biomechanics journal, 2015, vol. 30, pp. 629-635. https://doi.org/10.1016/j.clinbiomech.2015.03.021
15. N.Z. Dennis, S. Das De, Modified Mitchell's osteotomy for moderate to severe hallux valgus - an outcome study, in: Journal Foot Ankle Surgery, 2011, vol. 50, pp. 50-54. https://doi.org/ 10.1053/j.jfas.2010.10.005
16. A. Martinez-Nova, R.Sanchez-Rodriguez, A. Leal-Muro, J.D. Pedrera-Zamorano, Dynamic plantar pressure analysis and midterm outcomes in percutaneous correction for mild hallux valgus, in: Journal Orthopedics Research, John Wiley & Sons, USA, 2011, vol. 29, pp. 1700-1706. https://doi.org/ 10.1002/jor.21449