A review on biomechanics of the hallux valgus pathology and its surgical treatments

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Abstract. The present paper aims at an interdisciplinary field, regarding biomechanics aspects of the Hallux Valgus, which is a frequent deformity in our days. Owing to the importance of the study theme and the social impact, we consider it very important that the state of the art should be as detailed as possible, due to this condition being frequent in women and older people. The review will target recent research of the biomechanics of the foot, the test subjects being in normal conditions and also patients affected by Hallux valgus deformities; likewise, it will define important geometrical elements, which are required for the engineering approach of the issue. As well, the 3D modelling of the condition will be taken into consideration, beside with the surgical procedures and conservative treatments. Another important aspect covered in the paper is regarding the research and CAE simulations using the FEM, alongside with the work stands developed in this area. The bibliographic research found on the most important journals and databases shall be synthesized and structured in order to highlight the big picture of a specific research regarding a future PhD thesis.

1. Introduction
The following paper aims to present an interdisciplinary approach of the Hallux Valgus subject. Since the contributions brought by the Engineering are more and more useful to Medicine and that the networking between the surgeons from the Orthopedic Department and the engineers from the Sibiu Faculty of Engineering is very lucrative, we found it convenient to work together, in order to implement engineering methods more frequently. The engineering study of the Hallux Valgus deformity involves several aspects, such as: biomechanics approach, loads study, Computer aided design, surgery simulations etc.

Our main goal aimed with this article is to synthesize the information in the medicine and biomechanics fields regarding the Hallux Valgus subject, to ease the following approaches, of course, it will be taken into account the establishment of the courses for a complete research in the biomechanics domain. Accomplishing a comprehensive bibliographic study is another important purpose due to its requirement for further transposition of the data to engineering methoding, therefore we can conclude that our main objectives are:

- Shifting the medical theme of the Hallux Valgus to the engineering area by accomplishing an elaborate study of the anatomical issue;
- Study the geometrical approach of the issue for a better comprehension of the displacements;
- Research and synthesize the biomechanics of the deformity - towards the mechanical loading state;
Elaboration of Computer aided design models alongside with Finite element analysis of the Hallux Valgus deformity and its treatments.

2. The foot - anatomy and biomechanics

In order to accomplish correct bioengineering studies a first important step is to comprehend the biomechanics and anatomy of the issue, only in this way, approaching the issue with engineering methods and principles is possible. This structure is very interesting from mechanical point of view, being extremely complex, although it’s relatively small sized. The complexity is due its plurality of bones, muscles, ligaments and nerve endings. The 26 bones, 33 joints and all the other previously mentioned elements assure several functions such as: bipodal gait, body propulsion and shock absorption during running or jumping [1, 2].

Due to the fact that an average person walks approximately 200,000 kilometers and that the foot could be affected by loadings varying between 1-4 of its bodyweight, for example in running and jumping the loadings are maximum, the foot is protected by a special architectural structure from stress related injuries [3, 4].

The main parts of the foot from anterior to posterior are: forefoot, midfoot and hindfoot, detailed in figure 1.

Talus and calcaneus are the two hindfoot bones. The talus is the bone jointing two important bones of the inferior member, Tibia and Fibula. The joint between these three bones is called ankle joint and in provides the vertical plane movement of the foot: up and down. As well, the talus joints with the calcaneus through the subtalar joint, which assures the pendulum foot motion: left-right. Further, the hindfoot is connected with the next structure, the midfoot, which is composed by 5 bones: cuboid, navicular and three cuneiforms, working together as a group. The previously mentioned bones describe the tarsal region of the foot and joint through the tarsal-meatatarsal rigid joint with five long bones, named metatarsals. Each one of the five bones joint with the phalanges; which are groups of two or three bones (two for the first finger and three for the others) [5, 6]. The metatarsal and phalanges region form together the forefoot. The positioning of the bones and joints is illustrated in figure 2.

![Figure 1. Foot partition. Picture illustrated and modified from [5].](image1)

![Figure 2. The bones and joints of the foot. Picture illustrated from [2].](image2)

The articulation of the medial and lateral sesamoid bones (located on the inferior side of the foot), the first metatarsal head (MTH) and the corresponding phalanx base, are summing up the First metatarsophalangeal joint (1 MTPJ). Because in this joint the movements have great amplitude, the sesamoid bones, first metatarsal and first phalanges are connected in the same synovial capsule [7].

The 1 MTPJ has its mechanical mobility within the traverse and sagittal planes. The vertical and traverse axis are consisting the two main axes of the joint. The metatarsophalangeal joint has a...
complex structure (condylar), which has repercussions regarding the rotational motions of it. Those types of movements are impossible without harming the joint.

The backward bending and contracting of the foot is called dorsiflexion, and such a movement is done by the 1 MTPJ as well, there are three main components of motion which can be separated during it: rolling motion, sliding motion and finally compression motion. During gait, the angle between metatarsal axis and phalangeal axis could have significantly values of 50-60 degrees, as shown in figure 3 [8].

![Figure 3](image1.png)

**Figure 3.** Dorsiflexion of the 1 MTPJ during gait.

![Figure 4](image2.png)

**Figure 4.** The main tendons which link the proximal phalanx. Illustrated and modified from [11].

The anatomy of the 1 MTP joint is a complex structure consisting from bones mentioned above but also from small ligaments and soft-tissue, attached to the head of the metatarsal (MTH) and phalanx. The first MTH is located into a concave cavity, surrounded by soft-tissue. The medial and lateral support is provided by the tendon attachments in order to supplement the ligamentous structures [2], [9]. The most important tendons which link the proximal phalanx are: Flexor hallucis longus (FHL), the adductor hallucis oriented in two directions (oblique and transverse) and finally the flexor hallucis brevis, which anchor the sesamoid bones to the foot [4]. The propulsion is provided with the required stability by the abductor hallucis and the flexor hallucis brevis, illustrated in figure 4 [2]. Several factors are required for the correct biomechanical function of the flexor halluc: stability and flexion of the assembly consisting of first metatarsal and first cuneiforms as a single bone structure (first ray), standard function of the sesamoid bones and adequate activity of the muscles which stabilize the 1 MTPJ [10].

### 3. Pathoetiology and development of hallux valgus

#### 3.1. Epidemiology of Hallux Valgus

The Hallux Valgus (HV) is a frequent pathology of the Hallux, with propensity towards feminine gender; it can be considered a manifestation of the flat forefoot. Based on recent studies, almost 1 out of every 10 people might be affected by this deformity with a women-men ratio of about 9:1 [12].

The leading factors of the Hallux Valgus are still unclear, but plenty of intrinsic and extrinsic aspects such as uncomfortable sharp shoes, overweight or static deformations of the foot inflict the apparition of it [13].

#### 3.2. Genetic factors

Some inherited characteristics have been presumed to predispose people to Hallux Valgus, plenty of genetic related features such as specific foot type and joint hypermobility might be relevant to HV [9]. Mom-to-child transmission has been found in over 90% of subjects with a family background, in terms of juvenile HV [14].
Racial differences have been found as well between black Africans and whites, with a slightly prevalence of the HV in whites. The ratio is estimated to 2:1 detrimental to the whites [9].

### 3.3. Biomechanical factors

The pathoetiology and development of HV is strongly related to the biomechanics of the first ray. During propulsion, it is strongly required a stable and congruent MTP joint, although there is no interference between tendon attachments and the first metatarsal. The metatarsophalangeal joint articulations have a condylar structure which occurs to being enough to keep from happening the sesamoid subluxation, in terms of joint reaction force of the metatarsosesamoid.

Subluxation is engaged by the unloading of the metatarsosesamoid joint and this may occur by raising the Metatarsal head by the laterally loaded body weight [9]. There are plenty of displacements which occur in a chain reaction in engaging the HV, which are illustrated in figure 5 regarding the adduction, abduction and flexion and in figure 6 for the deviations and rotations.

According to Lelievre, the congenital adduction of the first Metatarsal bone (MT1), the hypermobility of the tarsometatarsal joint and the unusual length of the metatarsal bones are the main factors of the Hallux Valgus [15]. The abduction angle of the Hallux might reach 90° and the Hallux could mount over the second finger.

![Figure 5](image1.png) **Figure 5.** Adduction of MT1. Picture illustrated from [15].

![Figure 6](image2.png) **Figure 6.** Valgus deviation (A), rotation of Hallux (B), Varus deviation of the 1st Metatars (C). Picture illustrated from [15].

### 3.4. Other factors

Factors such as trauma, joint diseases and some neurological conditions such as Parkinson’s disease, which disturb the normal functioning of the foot, may occur to HV; being considered etiological elements [6]. Recent research articles claim that there is a bounding between the HV deformity and metatarsal pain by measuring and recording several parameters such as rate of loading, duration and area of contact, during dynamic gait [16].

Regarding the symptomatology of the deformity, in premature phases, patients feel a vague pain in the Metatarsophalangeal joint, but in evolved forms, the pain may expand up to the calves.

### 4. Approach of the Hallux Valgus deformity

#### 4.1. Hallux Valgus geometrical classification

For a better assessment of the bunion condition, certain angles must be measured, such as: the Hallux valgus angle, the Intermetatarsophalangeal angle, the Interphalangeal angle, but there is also a series of observation items regarding the Tibialsesamoid position. The most important of them are the Hallux...
Valgus Angle (HVA) and the Intermetatarsophalangeal Angle (IMA), which are determined as following:

- The Hallux Valgus Angle is defined by the two longitudinal axes - one of the proximal phalanx and the second one of the first metatarsal. For healthy subjects the HVA is less than 15°, but for increased values, it characterizes a hallux valgus deviation.
- The Intermetatarsophalangeal Angle is between the longitudinal extension of the first and second metatarsals axis. The normal values of this angle are less than 10° [17, 18].

The mentioned angles (HVA and IMA) are presented in figure 7 alongside with their normal values.

**Figure 7.** Normal values of the HVA and IMA.

The radiographic exam usually requires the basic AP (anteroposterior) and LL (lateral) x-rays, in order to state the Hallux Valgus type and for scheduling the eventual surgical correction.

In 1960, based on the congruity of the 1st MP joint, Pigott classified HV into 3 types:

- Congruous joint (1st Type)
- Deviated non congruous joint (2nd Type)
- Subluxated joint (3rd Type), as shown in figure 8.

**Figure 8.** The three types of HV, based on Pigott. Picture illustrated from [19].
A second classification was made by LaPortain 1974, which was later issued in 1999. The deformity could be classified in three categories, starting from mild, with a lapse between 15 to 20 degrees, continuing with moderate, between 20 and 40 degrees and finally, severe above 40 degrees, relating to the Hallux Valgus Angle [20]. The LaPorta classification has its benefits due to the fact that can classify the tibial sesamoid position relative to the first metatarsal bisector by assessing the dorso-plantar projection, ranging from normal to most laterally shifted [21].

In the early 2000s, researchers established the basic elements and values in hallux abducto valgus (HAV), establishing the first IMA as normal for values lower than 10°, mild for values ranging from 10° to 11°, moderate for angles between 11° to 16° and severe for values above 16° [22].

According to the latest research, the triplane method is the most accurate one relating to distinguishing the Hallux Abducto Valgus (HAV), besides the 2-dimensional algorithms, this method includes the frontal plane. This method takes into consideration the anatomic findings and the status of the MTPJ, concluding with recommendations regarding the treatment as well.

The first type (Class 1) has the following anatomical aspects: the HV and IM angles are increased but there is no evident pronation at the first metatarsal on AP X-ray or sesamoid axial X-ray, although, the sesamoids might be subluxed. Regarding the MTPJ status, the first class HV does not have any kind of medical or imagistic evidence of degenerative joint disease, and the algorithm recommend an osteotomy to the metatarsal or a correction on the Lisfranc joint.

The second class is divided into 2 subclasses (A and B), with the same MTPJ status and anatomical findings beside the metatarsal pronation and sesamoid status. Class 2A is described by evident pronation of the first metatarsal on AP X-rays but the sesamoids are not subluxed and the treatment recommendations are: triplane correction including the 1 MT inversions, with or without lateral capsulotomy.

The difference between class 2A and 2B is strictly related to the sesamoids status, which are subluxed in the second subclass. The treatment for this case is alike the previously mentioned one, but imply in addition before correction a conservative lateral capsular release.

The third class is distinguished from the others by being characterized with an increased Hallux Valgus angle and metatarsus adductus over 20°. Its main treatment recommendations consist in plane correction of the second and third metatarsal, Lisfranc correction or metatarsal osteotomy.

The final class from this classification has medical imagistic evidence of degenerative joint disease and increased values of Hallux Valgus and intermetatarsal angle but there is no pronation of the first metatarsal. The surgical recommendation for the 4th class consists in arthrodesis of the first metatarsophalangeal or even joint arthroplasty.

4.2. Geometrical references

In order to make a correct biomechanical approach from dimensional and geometrical point of view, certain pieces of information regarding the axis and planes of the human body must be presented.

The most frequently used system in the body biomechanics is the triortogonal system, which consists of 3 planes, each one mutually perpendicular, as following: the sagittal plane, the transversal plane and the frontal plane, illustrated in figure 9.

The sagittal plane is a vertical plane which crosses the body, dividing it into two perfectly symmetrical sides, reason for what it is called the bilateral symmetry plane. The two mentioned parts are left and right.

The secondary plane is horizontal, and it is called transversal plane. This plane crosses the body on its height midline, dividing it into to asymmetrically parts, superior or cranial and inferior or caudal.

The third plane is vertical, positioned parallel with the forehead, and it’s called frontal. It divides the body into anterior (front) and posterior (back) parts.

The intersection of these planes is defining the axis of the human body. Therefore, the intersection of the sagittal and transversal describes the sagittal axes, with two poles, one anterior and one posterior, describing the body’s thickness. The transversal line is described by the intersection of the transversal and frontal plane, with two opposite planes, left and right, describing the width of the body.
The third line is the result of the sagittal and frontal plane intersection, named the longitudinal axis, having a superior and inferior pole. The position of the superior pole is on the top of the head and the inferior one is located on the sole [24, 25].

![Figure 9. Axes and planes of the human body.](image)

Obviously, the intersection of the three axes previously defined, describes the origin of the human body reference system, which concur with its symmetry center.

Other important terminology must be defined for a better comprehension of the problematic, this terms are found in specialized literature are very useful in geometrical describing: proximal – for elements located closer to the joints and distal for elements positioned further from them, or volar for describing hand elements and plantar for the foot ones.

Those geometrical elements have their usefulness in dimensional and geometrical defining of bones, and especially for describing their movements, translations and rotations, and even for some displacements owed by pathological conditions.

Relatively to this main reference system of the human body, it can be defined by translating and rotating movements, secondary coordinate systems, which are necessary for the required biomechanics elements studied. For example, for a foot study, it can be defined in an incipient phase a coordinate system by moving the main one to the ground surface. The origin of the new system is the projection of the main one on the sole, having its planes and axis parallel to the body’s. A more comprehensive view of the system is illustrated in figure 10.

![Figure 10. The ground reference coordinate system (Gcs) of the foot.](image)
Starting from this approach, for a better understanding of the displacements that cause the Hallux Valgus deformity, we decided to place several coordinate systems in points which we consider important. Those coordinate systems are associated with the human reference planes previously presented.

The main reference coordinate system is located on the frontal and sagittal planes and the XoZ plane is associated with the ground system (Gcs), as presented in the previously image [24].

A first coordinate system will be placed in the talocrural joint (ankle) and it will be considered the main reference and all the movements will be associated with it. This system will be further referred to as Talocrural Coordinate System - Tcs. Due to the fact that the Hallux Valgus Angle is crucial in the decision making regarding the surgical method, we considered proper to place another system in the intersection of the longitudinal axis of the first metatarsal and the extension longitudinal axis of the second metatarsals, which we named Angular Coordinate System - Acs. The final and the most relevant to the subject in discussion, is the Displacement Coordinate System - Dcs, placed on the metatarsophalangeal joint, exactly where the whole pathological condition has its origins. The three coordinate systems are presented more specific in figure 11:

![Figure 11. Setting up the 3 main coordinate systems: Tcs, Acs, Dcs, relatively to the Gcs.](image)

4.3. FEA considerations
The Finite Element Analysis is an Engineering approach of the medical issue, established for the simulation of the behavior of a part or an assembly under specific conditions, in our case, this element plays a crucial role in developing and designing adequate models. Plenty of data is needed to begin such a study, such as mechanical properties of the bones, loads and tension state etc.

Due to the fact that the structure of the bone is complex, engineers had to make several researches to determine the most precise pattern that provided its properties and roles.

In terms of biomechanical research, lately was adopted in clinical applications the subject specific finite element analysis of the skeleton. Reproducing the subject specific models by processing the information from the X-ray images is one of the most popular methods. This method is based on interpreting the resulted computer tomography images’ grey tones using mathematical relationship between them and their mechanical correspondent. This process will lead to obtaining important data regarding bones’ mechanical properties [26, 27].

Due to the fact that the bones affected by the studied deformity are mostly trabecular bones, their properties will be presented in brief.

Considering the fact the real bone structure is not homogenous, having rough areas (cortical) and trabecular ones (with different densities) the mechanical characteristics such as Young’s Modulus must be correlated with them. This specific action is necessary for performing correct analysis regarding the bone, or the bone-implant assembly [28]. Accurate determination has a high
difficulty, due to the fact that the heterogeneity and because of the trabecular struts, which are very small sized. In order to establish a Young’s modulus estimation, plenty of methods were used, regarding the testing of single trabeculae from mechanical point of view, nanoindentation or ultrasonic testing [29, 30].

Another important aspect which must be taken into consideration is the load status of the foot, during posture and gait. Clinical applications require a good comprehension of the functional biomechanics of the foot and ankle, information which is also vital for an accurate engineering approach [31]. The procedure’s workflow has 3 steps:

- Data gathering of 3D foot kinematics and kinetics during gait;
- 3D modelling;
- Finite Element Analysis of internal stresses and loads [32].

![Figure 12. Workflow of the procedure. Picture illustrated from [32].](image)

4.4. Principles of treatment

The suitable treatment methoding is picked according to the severity of the displacement. Mild cases are befitting for non operative treatments, the so called conservative treatments, but more severe one require surgical interventions. Therefore, a much more efficient solution for mild cases of Hallux Valgus is the conservative alternative, due to the fact that the patient can return to his activities much faster and it’s less pricy [33]. Special footwear, orthotic and plenty of exercises are the main techniques involved by this method. The main exercises are for strengthening and mobilization of the affected elements, which are performed mostly in the sitting position by the patient, for a better overview, such a exercise program will be exemplified: abducting the hallux, which literally involves taking far away the hallux from the 2nd phalanx [34, 35].

Although these conservative methods could have effects only for the mild cases, the severe types of HV were assigned by Mann with their suitable surgery. The following paragraphs present the soft-tissue, bony and combined soft-tissue-bony Hallux Valgus surgical treatment procedures. In order to pick the suitable surgical method of treatment of the HV, Mann described a remarkable algorithm, which was recently was transmuted into a more easily comprehensive scheme, recreated in figure 13 [21, 36].

The decision making starts from the status of the 1 MTPJ, which can be congruent, incongruent or arthritic. In the first case, if the Hallux valgus interphalangeus (measured between long axis of distal
phalanx and proximal phalanx) is above 10° will lead to a Akin osteotomy, if the IM angle is above 15° but the HV angle is under 45°, the suitable treatment will be an Chevron or Scarf osteotomy.

In the case of a incongruent first MTP joint, alongside with an 10-15° IM angle and the value of the HVA under 30°, the only surgical treatment shall be the Chevron osteotomy, for values over 15° of the IMA and under 45° regarding de HVA, the treatment will be strictly the scarf or chevron osteotomy. Besides of all the mentioned findings, if the patient has an arthritic first tarsometatarsal joint, it should be taken into consideration a modified lapidus procedure.

Finally, in case of an arthritic 1st MTP joint, the treatment shall be a fusion of the first MTP joint.

Figure 13. Hallux Valgus Treatment - reissued after Mann. [21], [36], [37].

A thorough review of the surgical techniques has been done, focusing on the osteotomy procedures since their suitability for engineering approaches. We have chosen to present the scarf osteotomy procedure to illustrate the necessary steps of such a surgical treatment, because, as illustrated in the scheme, is the only one suitable for both moderate and severe deformities, and those are the main types of HV which require surgical interventions. The mentioned treatment method is made at the diaphyseal level of the bone aided by a horizontally directed displacement osteotomy Z-shaped. The term “scarf” refers to jointing of two pieces’ ends and this specific medical procedure is illustrated in figure 14 and has the following steps:

1. Osteotomy cuts;
2. Lateral displacement;
3. Repositioning the bone parts for correcting the deviation;
4. Fastening of the osteotomy with two minifragment screws [36].

Figure 14. The five steps of the scarf osteotomy procedure.
Picture illustrated from [36].

Besides the scarf osteotomy there are also other procedures which are preformed, such as: the crescentic, chevron and Ludloff, osteotomies. Those are done when the patient is no suitable for the scarf osteotomy; these types of situations are less frequent. The scarf osteotomy, alongside with the other three interventions’ brought up are presented in figure 15 in terms of osteotomy cuts and fastening methods.
For the proximal crescentic osteotomy (1), the cut is done parallel with the frontal plane, as for the proximal chevron osteotomy (2), the cut is L-shaped, both requiring a single screw for the fastening. The Ludloff osteotomy (3) has an angular cut and requires two screws, displaced in converse directions. Finally, the scarf osteotomy (1) demands a Z-shaped cut of the bone, the fastening being done with two minifragment screws [36].

Figure 15. Metatarsal shaft osteotomies.
Picture illustrated from [36].

Proximal osteotomy is also necessary in most hallux valgus deformities that require a distal soft-tissue procedure but this procedure is not recommended if excessive valgus posturing, above the HVA angle 15 degrees [36, 38].

5. Conclusions
As noted, this article aims a detailed bibliographic research regarding a very frequent medical condition, Hallux Valgus. Studying, synthesizing and structuring the data regarding the axial deviation of the foot are very important for several reasons:

- The first reason is that the biomechanics of the deformity and the afferent treatment methods are an interdisciplinary field which involves in-depth studies. The interest area which is referred to is in relation to analytical approaches, alongside with CAD-CAE research regarding geometric, dimensions, reference systems, 3D modelling systems or the applied simulation technologies for the Hallux Valgus research, in the event of prosthesis and necessary surgical interventions;
- The second reason is the favourable social impact that the study will have, considering that this deformity causes unbearable pain alongside with the high frequency of it in women and older people;
- Another reason is linked to the increasing surgical accuracy by training the doctors with surgery simulations on virtual or 3D printed models;
- The final reason is the interdisciplinary research of the two fields, medical and engineering. The principle followed for this approach is that “the whole is much more than the sum of its parts”, which will lead to superior results.

Analyzing the researches presented in this paper, which are the start point of an ample research, we structured a number of certain research objectives, as following:

- Designing the 3D models of the bones affected by the Hallux Valgus deformity;
- Elaboration of a generalized model with the mentioned bones, assembled with constraints, in Skeleton systems, for healthy subjects and for subjects affected by Hallux Valgus;
- Accomplishing 3D simulations that include all the geometrical and dimensional possibilities of the deformity;
- Designing by Rapid Prototyping of several physical models, starting from the considerations previously mentioned, with the purpose to submit them to mechanical testing;
- Parameterized 3D modelling of the surgical strategies, alongside with their afferent simulations;
- Finite Element Analysis of the deformity and the treatment methods as well;
- Specific experimental research.
  We consider that the approached field is interesting and there is plenty of potential in accomplishing high interdisciplinary research results.

References
[1] Robinson A, Bhatia M, Eaton C and Bishop L 2009 Prospective comparative study of the Scarf and Ludloff osteotomies in the treatment of hallux valgus Foot Ankle Int. 30 955
[2] Valmasy R L 1996 Clinical biomechanics of the lower extremities (St. Louis [u.a]: Mosby) p 1
[3] Alazzawi S, Suke M, King D and Vemulapalli K 2017 Foot and ankle history and clinical examination: A guide to everyday practice World J. Orthop 8 21
[4] Ferner H and Staubesand J 1982 Sobotta atlas of human anatomy (10th ed.) (In Ferner Helmut bStaubesand Jochen (Eds.) Munich: Urban & Schwarzenberg) p 327
[5] Fraissler L, Konrads C, Hoberg M, Rudert M and Walcher M 2016 Treatment of hallux valgus Deformity EFTOR Open Reviews 1 295
[6] Hansen S T 2000 Functional reconstruction of the foot and ankle (In Hurley R, Seigafuse S L and Marino-Vasquez D (Eds.), Philadelphia u.a: Lippincott Williams & Wilkins) p 1
[7] Haines R W and McDougall A 1954 The anatomy of hallux valgus (Lancet) p 1308
[8] Klemola T 2018 Flexible Hallux Valgus. Results of a new surgical technique (University of Oulu, Faculty of Medicine: Medical Research Center Oulu; Oulu University Hospital) p 19
[9] Perera A M, Mason L and Stephens M M 2011 The pathogenesis of hallux valgus J. Bone. Joint. Surg 93 1650
[10] Root M L, Orien W P and Weed J H 1977 Forefoot deformity caused by abnormal subtalar joint pronation (Los Angeles: Clinical Biomechanics Corporation) p 349
[11] Wesker K 2007 Thieme Atlas of Anatomy: General Anatomy and Musculoskeletal System (New York, Thieme, Stuttgart. Copyright (2005) by Georg Thieme Verlag)
[12] Xu H, Jin K, Fu Z, Ma M, Liu Z, An S and Jiang B 2015 Radiological Characteristics and Anatomical Risk Factors in the Evaluation of Hallux Valgus in Chinese Adults Chin. Med. J 128
[13] Donatelli R 1985 Normal Biomechanics of the Foot and Ankle J. Orthop Sports. Phys. Ther. 7 91
[14] Coughlin M J and Jones C P 2007 Hallux valgus: Demographics, etiology, and radiographic Assessment Foot Ankle Int. 28 759
[15] Pop S P, Gergely I, Russu O M and Roman C O 2013 Elemente de ortopedie (Elements of orthopedics) (ed. II, ISBN 978 973-169-259-3)
[16] Cheng C, Wang Q F, Guo J C, Li D D, Fan Y B and Wen J M 2019 The biomechanical relationship between Hallux Valgus Deformity and Metatarsal Pain Journal of Healthcare Engineering 2020
[17] Xu H, Jin K, Fu Z, Ma M and Liu Z 2015 Radiological Characteristics and Anatomical Risk Factors in the Evaluation of Hallux Valgus in Chinese Adults Chinese medical journal
[18] Bryant A, Tinley P and Singer K 2000 A comparison of radiographic measurements in normal, hallux valgus, and hallux limitus feet. J. Foot Ankle Surg. 39 39
[19] Gui J C, Hou M F, Shen H Q, Wang L M, Gu X J and Ma X 2001 X-ray evaluation of the normal and hallux valgus feet and it's clinical values (in Chinese) Chin. J. Orthop 21 137
[20] Laporta G, Melillo T and Olinsky D 1974 X-ray evaluation of hallux abducto valgus deformity J. Am. Podiatr. Med. Assoc. 64 544
[21] Mann R A and Coughlin M J 1999 Adult hallux valgus. in Surgery of the foot and ankle (7th ed.) (St. Louis: Mosby) p 159
[22] Condon F, Kalismer M, Conhyea D, O'Donnell T, Shaju A and Masterson E 2002 The first intermetatarsal angle in hallux valgus: an analysis of measurement reliability and the error involved Foot Ankle Int. 23 717
[23] Hatch J D, Santrock D R, Smith B, Dayton P and Weil Jr. L 2018 Triplane Hallux Abducto Valgus Classification J. Foot Ankle Surg. 57 972
[24] Cofaru I I 2013 Cercetări privind biomecanica deviațiilor axiale ale membrului inferior uman și dezvoltarea unor echipamente chirurgicale aferente (Research on biomechanics axial deviations of the member human inferior and the development of some related surgical equipment) (PhD thesis, Lucian Blaga University of Sibiu)
[25] Glasoe W, Phadke V, Pena F, Nuckley D and Ludewig P 2013 An Image-Based Gait Simulation Study of Tarsal Kinematics in Women With Hallux Valgus Phys. Ther. 93 10.2522/ptj.20130025
[26] Vicenzi M, Olsen S, Nolte L P and Burton K 2005 Extracting clinically relevant data from finite element simulations Clin. Biomech. 20 451
[27] Kaneko T S, Bell J S, Pejicic M R, Tehranzadeh J and Keyak J H 2004 Mechanical properties, density and quantitative CT scan data of trabecular bone with and without metastases. J. Biomech. 37 523
[28] Helgason B, Perilli E and Schileo E 2007 Mathematical relationships between bone density and mechanical properties: A literature review Clin. Biomech. 23 135
[29] Wu D, Isaksson P, Ferguson S J and Persson C 2018 Young’s modulus of trabecular bone at the tissue level: A review Acta Biomater. 78 1
[30] Suzuki T, Matsura Y, Yamazaki T and colab. 2019 Biomechanics of callus in the bone healing process, determined by specimen-specific finite element analysis Bone 132 115
[31] Horwood A 2019 The biomechanical function of the foot pump in venous return from the lower extremity during the human gait cycle: An expansion of the gait model of the foot pump Med. Hypotheses 129 109
[32] Scarton A, Guiotto A, Malaquias T, Spolaor F, Sinigaglia G, Jonkers I, Cobelli C and Sawacha Z 2017 A methodological framework for detecting ulcers’ risk in diabetic foot subjects by combining gait analysis, a new musculoskeletal foot model and a foot finite element model Gait and Posture 60 279
[33] Ferrari J, Higgins J and Prior T D 2004 Interventions for treating hallux valgus (abductovalgus) and bunions Cochrane Database Syst. Rev.: CD000964
[34] Srivastava S, Chockalingam N and El Fakhri T 2010 Radiographic angles in hallux valgus: comparison between manual and computer assisted measurements J. Foot Ankle Surg. 49 523
[35] Gul O K, Nilgun B and Ugur T 2015 Short-term effects of the kinesiotaping of pain and joint alignment in conservative treatment of the hallux valgus J. Manipulative Physiol. Ther. 38 564
[36] Canale S T, Azar F M, Beatty J H and Campbell W C 2017 Campbell's operative orthopaedics (Thirteenth edition, Philadelphia, PA : Elsevier, Inc.)
[37] Fraissler L, Konrads C, Hoberg M, Rudert M and Walcher M 2016 Treatment of hallux valgus Deformity EFORT Open Rev 2016;1:295-302.
[38] Chapman M W 2001 Chapman's orthopaedic surgery (Philadelphia: Lippincott Williams Wilkins)