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Classification of Hallux Valgus Using Conjugated Deformity

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Abstract

Hallux valgus is a complex deformity of the forefoot. It is the result of multiple effects of endogenous and exogenous etiological factors with different degrees of influence. The degree of hallux valgus deformity was assessed by radiological values of hallux valgus (HVA) and intermetatarsal (IMA) angle. Thus, each hallux valgus deformity corresponds to a pair (HVA, IMA) of hallux valgus angle (HVA) and intermetatarsal angle (IMA) values in the plane of the deformity. The intensity of the point position vector S (HVA, IMA) in the deformation plane determined by the relation $d = |\boldsymbol{OS}| = \left(\text{HVA}^2 + \text{IMA}^2\right)^{\frac{1}{2}}$ represents the absolute (conjugate) value of the power deformities. The goal of the article is to explain the advantage of the definition of the degree of hallux valgus deformity using its absolute (conjugate) value, and then to show that the degree of deformity defined in this way enables a better classification of deformities for all values of the HVA and IMA angles. Furthermore, in this article, applying the definition of conjugate deformity, analytical expressions were constructed for the assessment of the average value of deformity correction after operative treatment, as well as the error assessment of deformity correction after operative treatment. All obtained results were checked on a sample of 396 operatively treated feet.

Keywords

Conjugated Deformity, Hallux Valgus, Classification, Deformity Correction

1. Introduction

Hallux valgus is a relatively common and multifaceted complex deformity of the forefoot, which is manifested by moving the big toe away from other toes, which leads to a hammer-like deformation of the other toes, altered load transfer and the appearance of painful clavus on the plantar side. At the same time, there is a lowered and widened front forefoot, which is accompanied by inflammatory changes and pain in the places of load bearing and contact with shoes that are difficult to use, and the aesthetic effect is also significant, especially in women who are otherwise more often affected by this deformity. Etiologically, it is a result of the multiple actions of congenital (endogenous) and exogenous etiological factors with different degrees of influence, and it increasingly seems to be a combination of anomalies and acquired deformity [1] [2] [3] [4].

These are complex pathological anatomical changes that result in a double angular deformity of the first column of the foot dominated by a valgus displacement of the big toe with an increased hallux valgus angle (HVA) and an unstable metatarsophalangeal joint, and variation of the first metatarsal bone (1st MT) with an increase in the intermetatarsal angle (IMA) and instability of the first metatarsocuneiform joint [1] [4] [5].

The third aspect of the complexity of this deformity is particularly challenging and relates to the concept of its surgical treatment. It aims to correct the deformity and establish biomechanically favorable anatomical relationships of the bony and joint structures of the front part of the foot and thus provide a dynamically stable foot function. So far, over 130 operative techniques and their modifications have been described, none of which has the potential to correct all components of the deformity [6] [7] [8] [9].

This is understandable when we consider the fact that, in reality, we do not have two exactly the same deformities, because as Burns [4] points out: "Each will have its own nuance."

So far, several algorithms and recommendations have been published regarding the choice of the appropriate surgical technique and their combinations, which are based on the application of the principles of surgical treatment and the experiences of teams of orthopedic surgeons and podiatrists [6]-[11].

The mentioned recommendations and reached consensuses made a great contribution, but at the same time, they are burdened by the subjective influence of authority, which is confirmed by the research of Pince et alin which over 100 academic-level orthopedic surgeons expressed their opinion regarding the choice of surgical method of treatment for a given case [12]. The assumption for choosing an adequate surgical method or their combined application is that the surgeon fully understands and perceives the pathological anatomical changes that primarily occur at the level of the first row (medial column) of the foot, *i.e.* from the medial cuneiform bone to the distal phalanx of the big toe for each case separately [13] [14].

Clinically and radiographically, the most striking part of the deformity is certainly valgisation of the big toe at the level of the metatarsophalangeal (MTPH) joint with an increased HVA (HVU > 15˚) and subluxation of the base of the proximal phalanx. In the case of a congruent relation of the articular bodies of this joint, it is a laterally directed articular surface of the head of the 1st MT, which with its axis forms an increased distal metatarsal articular angle (DMAA) [6] [7] [8] [11] [15], which is also a developmental anomaly like an endogenous etiological factor and is significantly more common in juvenile HVA [15].

In order to define the severity-the degree of hallux valgus deformity, a widely accepted classification was established according to the radiological values of HVA and IMA that define this double angular deformity [6] [16] [17].

1) Mild deformity, where the HVA is less than 30˚, and the IMA is less than 13˚.

2) Moderate deformity, where the HVA is less than 40˚, and the IMA is less than 20˚.

3) Severe deformity, where the HVA is greater than 40˚ and the IMA is greater than 20˚.

By consistently applying the above classification, we regularly end up in a situation where a significant number of analyzed cases cannot be classified in the proposed framework values and must be omitted from the planned statistical analysis solely because of the way in which the above classification was conceived. Thus, we have cases that, according to one parameter (eg HVA) belong to a moderate or severe degree, while, according to the values of the intermetatarsal angle (IMA) they belong to a mild degree of deformity.

This is especially important in research that aims to determine to what extent certain endogenous etiological factors (difference in the lengths of the MT bones distal to Maestro's line, the form of the first metatarsocuneiform joint, lateral angulation of the distal articular surface of the first MT bone have an impact on the development and severity of hallux valgus deformity as a whole and not only on individual components of the deformity [18]-[27]. For the same reasons, there are no analyses of the achieved surgical corrections of this deformity when the deformity is viewed integrally [17].

Since it is a double angulation deformity in which the anatomical relations at the level of two adjacent joints are disturbed and which have a mutual influence on the progression of the deformity [28], we consider it justified to find a solution that would enable an integral (conjugate) definition of the severity of this deformity.

It is important to emphasize that the analysis of the severity of deformity using its absolute (conjugate) value presented in the paper also relies on the widely accepted limit values of the relevant angles (HVA and IMA) of the deformity and the classification based on these values, but the advantage of the degree of deformity defined in this way is the possibility of classification of all cases regardless of the conjunction requirements specified in the classification conditions (1 - 3), which is not possible with the existing approach (**Table 1**).

2. Material and Method

After researching the relationship between HVA and IMA using geometric and analytical methods, the correctness of the obtained analytical formulas and geometric representations was tested on the sample of surgically treated feet. At the same time, the observational research is a descriptive-analytical study in which 396 operatively treated feet with pronounced hallux valgus deformity were analyzed which were treated at the Institute for Orthopedic Surgery "Banjica" in Belgrade. All patients, upon admission, provided their consent that the data from their medical records could be analyzed for research purposes and all applied aspects of the study were approved by the institution. This study was approved by the Ethics Committee of the Institute as well.

In order to perform the preoperative planning, an X-ray was taken in the AP (anteroposterior) and LL (latero lateral) position of the foot with a load at a 15˚ angle and from a distance of 1 m. On the X-ray images obtained before and after the operative treatment, measurements were made in accordance with the recommendations of the Ad Hoc Committee of the American Foot and Ankle Orthopedic Association (AOFAS) [29] and, in addition to other parameters, the following values were determined: [30].

1) Hallux valgus of the angle (HVA, **Figure 1**), obtained by the axis of the 1st MT bone and proximalphalanx shows the degree of movement of the thumb away; and up to 15˚ is considered a normal finding; a mild deformity is considered with an angle up to 30˚; a moderate deformity is one ranging from 30˚ to 40˚; a severe one is the one in which the HVA is greater than 40˚ [6] [15].

2) The intermetatarsal angle (IMA, **Figure 1**), obtained by the axis of the 1st and 2nd MT bones shows the degree of internal displacement of the first metatarsal bone. and up to 9˚ is considered a normal finding; if the IMA is up to 13˚; a mild deformity is the one up to 13˚; a moderate one ranges from 13˚ to 20˚; a severe one is when the IMA is greater than 20˚ [6].

3. Results and Discussion

3.1. Preliminary Analysis

The decision on the degree of deformity based on the radiologically assessed values of the angles HVA and IMA uses the truth of the following conjunctions as a criterion.

If the conjunction $0˚ < HVA < 15˚ \wedge 0˚ < IMA < 9˚$ is valid, then the area for making a decision on the degree of deformity geometrically represents a rectangular area defined by the product of the segments [0; 15[, [0; 9[, and in that case, the finding is considered to be normal (the area marked with FN) (**Figure 2**).

If the conjunction $15˚ \leq HVA < 30˚ \wedge 9˚ \leq IMA < 13˚$ is valid, the decision-making area is a rectangular area determined by the product of the segments [15; 30[,[9; 13[i and it is considered that the deformity is of a mild degree (area marked with MD), If the conjunction $30˚ \leq HVA < 40˚ \wedge 13˚ \leq IMA < 20˚$ is valid, the decision-making area geometrically represents a rectangular area determined by the product of the segments [30; 40[, [13; 20[, and it is considered

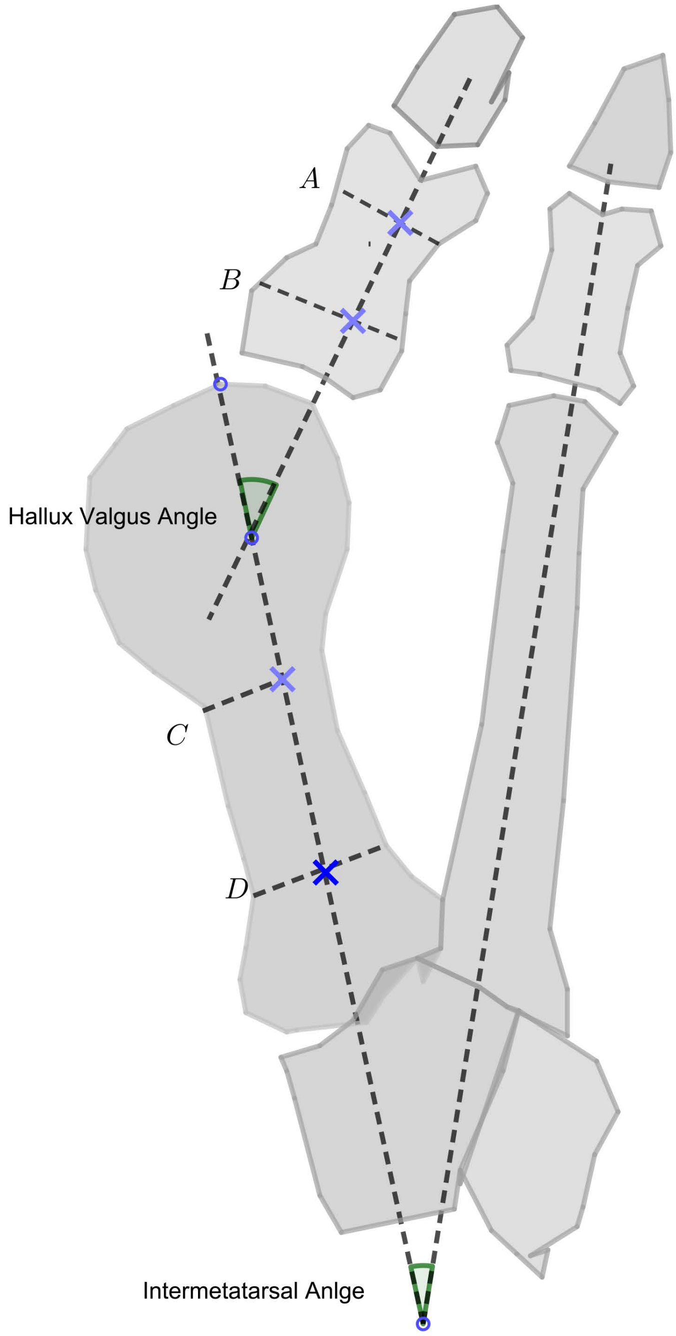


Figure 1. Basic radiological parameters in the measurement of the deformity assessment.

that the deformity is of a moderate degree in that case (area marked with MoD) (**Figure 2**).

If the conjunction HVA ≥ 40˚ ^ IMA ≥ 20˚ is valid, the decision-making area geometrically represents a rectangular area and it is considered that in that case there is a severe degree of deformity (area marked with SD) (**Figure 2**).

Let us note that in the case of the code, the specified conjunction is not fulfilled, the decision on the degree of deformity is not clearly determined, that is, those cases remain outside the domain of the decision-making area. So, for example, if = 13˚ and IMA = 10˚, the decision on the degree of deformity in that case remains outside the rectangular area that indicates that the finding is normal (Figure 3). This gives us a justified reason to "broaden" the area for the decision on the degree of deformity, so that such cases are included in the decision.

As an example of the classification of the degree of deformity based on the accuracy of the conjunction (values of the angles HVA, IMA), a sample of 396 surgically treated feet was analyzed. The analysis showed that 49.50% of the total considered deformities in the sample were classified in accordance with the requirements of the conjunction, (those cases can be seen on the diagonal), while for the other cases only one of the classification conditions was met, *i.e.* the conjunction is incorrect, so the classification is impossible (Table 1). From the results in Table 1, we see that, for example, in the area of mild deformity, in addition to 71 correctly classified cases, there are also some of the cases in the column (when 9˚ ≤ IMA < 13˚) or in the row when 15˚ ≤ HVA < 30˚, but it is not possible to distinguish which cases are these, because they do not meet the classification requirements. It is similar in other cases of classifying deformities based on the values of the angles HVA and IMA and the specified conjunctions.

Therefore, with this method of classifying deformities, the problem of undefinedness and inaccuracy arises, so in most cases, the classification of the degree (severity) of the deformity is accompanied by approximation and uncertainty [28].

In addition, the need to include a larger number of results by classification is also the need to increase the reliability of conclusions about examining the connection of deformity with other factors affecting the deformity (e.g. the period of development of the deformity, the influence of etiological factors on the development of the deformity, etc.) which are in the focus of the study of this

Table 1. Classification of deformities of surgically treated feet in the sample based on the values of the IMA and HVA angles and the fulfillment of the criteria.

Criteria			IMA				*N* = 396 p
			IMA < 9˚ *N* = 14, 3.5%	From 9˚ to 13˚ *N* = 151, 38.1%	From 13˚ to 20˚ *N* = 217, 54.8%	From 20˚ and above *N* = 14, 3.5%	
HVA	HVA < 15 *N* = 1, 0.3%	Count	0	1	0	0	χ^2 (9, 396)\ = 81.200, Sig = 0.000 Cramer's V = 0.261
		% of Total	0.0%	0.3%	0.0%	0.0%	
	from 15 to 30, *N* = 125, 31.6%	Count	11	71	43	0	
		% of Total	2.8%	17.9%	10.9%	0.0%	
	from 30 to 40 *N* = 185, 46.7%	Count	3	65	114	3	
		% of Total	0.8%	16.4%	28.8%	0.8%	
	from 40 and above *N* = 85, 21.5%	Count	0	14	60	11	
		% of Total	0.0%	3.5%	15.2%	2.8%	

Legend: HVA-hallux valgus angle, IMA-intermetatarsal angle, N-number of cases.

complex process.

3.2. Definition of a Conjugated Hallux Valgus Deformity

Each hallux valgus deformity corresponds to a pair of HVA and IMA angle values. We say that the state (degree) of hallux valgus deformity is assessed by the pair (HVA, IMA).

Let us denote with $\mathcal{H} = \{\text{HVA} \mid \text{HVA} \geq 0\}$ the set of values of hallux valgus angles (HVA), and with $\mathcal{I} = \{\text{IMA} \mid \text{IMA} \geq 0\}$ the set of values of IMA angles expressed in degrees. The Cartesian product $\mathcal{D} = \mathcal{H} \times \mathcal{I} = \{(\text{HVA}, \text{IMA}) \mid \text{HVA} \in \mathcal{H} \wedge \text{IMA} \in \mathcal{I}\}$, of the sets $\mathcal{H}$ and $\mathcal{I}$ determines the plane, the elements of which are all ordered pairs (HVA,IMA) of the values of the angles HVA and IMA.

Let us introduce a definition.

Definition 1: The function $\mathsf{d} : \mathcal{H} \times \mathcal{I} \to \mathbb{R}^+$ from the Cartesian product of the sets $\mathcal{H}$ and $\mathcal{I}$ to the set of non-negative real numbers defined by the formula

$$\mathsf{d} = \mathsf{d}(\text{HVA}, \text{IMA}) = \left(\text{HVA}^2 + \text{IMA}^2\right)^{\frac{1}{2}},$$

which associates each pair $(\text{HVA}, \text{IMA}) \in \mathcal{H} \times \mathcal{I}$ with a non-negative real number $\mathsf{d} \in \mathbb{R}^+$ so that the following is valid:

1) $d(\text{HVA}, \text{IMA}) \geq 0$;

2) $d(\text{HVA}, \text{IMA}) = 0 \Leftrightarrow \text{HVA} = 0 \wedge \text{IMA} = 0$;

3) if $d(\text{HVA}, \text{IMA}) \in \mathcal{D}$ then it is that $d(\text{IMA}, \text{HVA}) \in \mathcal{D}$ and the following is valid $\mathsf{d}(\text{HVA}, \text{IMA}) = d(\text{IMA}, \text{HVA})$, is called the *conjugate hallux valgus deformity*.

The plane $\mathcal{D}^* = \mathcal{H}^* \times \mathcal{I}^* = (\mathcal{H} \times \mathcal{I}) \setminus [0,15] \times [0,9]$ represents *the plane of deformation*, and the rectangular area $[0,15] \times [0,9]$ is the set the values of the angles HVA and IMA, for which the deformity rating (HVA, IMA), determined by the values of those angles, is considered a *normal finding*.

The elements of the plane $\mathcal{D}^*$ are the points S (HVA, IMA) corresponding to the values of the angles HVA and IMA. Geometrically, the deformity $\mathsf{d} \in \mathcal{D}^*$ determined by the values of the angles HVA and IMA is represented by the point position vector S (HVA, IMA), and its absolute value (conjugate deformities) equals to the intensity of the radius vector $\boldsymbol{r} = \boldsymbol{OS}_p$, of the position of that point (**Figure 2**).

If we introduce the symbols $x = \text{HVA}, y = \text{IMA}$, for simplicity of writing, the conjugate deformation determined with the intensity of the position vector of the point S(HVA, IMA), is then

$$d = |\boldsymbol{r}| = |\boldsymbol{OS}| = \sqrt{\text{HVA}^2 + \text{IMA}^2} = \sqrt{x^2 + y^2} \tag{1}$$

That the hallux valgus deformity is determined with the position of the point before the operative treatment is indicated with $S_p(x_p, y_p) \in \mathcal{D}^*$, and after the operative treatment it is indicated with the position of the point $S_o(x_o, y_o) \in \mathcal{D}^*$ in the plane of the deformity (**Figure 2**). Therefore, each foot deformity $\mathsf{d} \in \mathcal{D}^*$, in the plane of the deformity $\mathcal{D}^*$ corresponds to one pair of values of the angles HVA and IMA, *before the surgery*, represented by the ordered pair (x_p, y_p), and after the *surgery*, represented by the ordered pair (x_o, y_o).

3.3. Classification of a Hallux Valgus Deformity Based on the Definition of a Conjugated Deformity

Note the points $S_N(15,9), S_B(30,13), S_U(40,20) \in \mathcal{D}^*$ which correspond to the limit values of the angles HVA = 15, 30, 40 and IMA = 9, 13, 20 in accordance with the current classification, in the plane of deformity (**Figure 2**).

Definition 2. When $\text{HVA} \in [0,15)$ and $\text{IMA} \in [0,9)$, hallux valgus is assessed with the point $S_p(\text{HVA}_p, \text{IMA}_p) = (x_p, y_p)$ in the plane of the deformity for which the intensity of the position vector the following inequality appliesholds

$$\begin{aligned} |\boldsymbol{OS}_p| &= \sqrt{\text{HVA}_p^2 + \text{IMA}_p^2} = \sqrt{x_p^2 + y_p^2} \\ &< |\boldsymbol{OS}_N| = \sqrt{15^2 + 9^2} = \sqrt{306} \approx 17.5^\circ \end{aligned} \tag{2}$$

we classify it as a *normal condition* (the finding is normal) (**Figure 2**).

All points $S_p(x_p, y_p)$ whose radius position vectors satisfy the inequality (2) and describe conditions when the hallux valgus deformity does not exist, *i.e.* when the finding is normal. If we mark that set of points with $\mathcal{D}_{NN}$ (**Figure 2**) then it is

$$\mathcal{D}_{NN} = \left\{ (x_p, y_p) \in \mathcal{H}^* \times \mathcal{I}^* \mid |\boldsymbol{OS}_p| = \sqrt{x_p^2 + y_p^2} < |\boldsymbol{OS}_N| = \sqrt{306} \right\} \tag{3}$$

Definition 3. When $\text{HVA} \in [15^\circ, 30^\circ)$ and $\text{IMA} \in [9^\circ, 13^\circ)$, hallux valgus is assessed with the point $S_p(\text{HVU}_p, \text{IMU}_p) = (x_p, y_p)$ in the plane of the deformity, and for the intensity of its position vector $\boldsymbol{OS}_p$ the following inequality holds

$$\begin{aligned} |\boldsymbol{OS}_N| &= \sqrt{306} \approx 17.5 \le |\boldsymbol{OS}_p| = \sqrt{x_p^2 + y_p^2} \\ &< |\boldsymbol{OS}_B| = \sqrt{30^2 + 13^2} = \sqrt{1069} \approx 32.7^\circ \end{aligned} \tag{4}$$

and we classify it as a *milddeformity.* All points $S_p(x_p, y_p)$ of the plane $\mathcal{D}^*$ whose intensity of the position vector is met with the inequalities (4) describe mild deformities. Those points lie within the part of the circular ring located in the first quadrant (marked BD in **Figure 2**. If we label that set with $\mathcal{D}_{BD}$ then it is

$$\begin{aligned} \mathcal{D}_{BD} = \Big\{ (x_p, y_p) \in \mathcal{H}^* \times \mathcal{I}^* \mid 17.5^\circ \approx \sqrt{306} = |\boldsymbol{OS}_N|^2 \le x_p^2 + y_p^2 \\ < |\boldsymbol{OS}_B|^2 = \sqrt{1069} \approx 32.7^\circ \Big\} \end{aligned} \tag{5}$$

Definition 4. Let $\text{HVA} \in [30^\circ, 40^\circ)$ and $\text{IMA} \in [13^\circ, 20^\circ)$. The hallux valgus deformity assessed by the point $S_p(\text{HVA}_p, \text{IMA}_p) = (x_p, y_p)$ in the plane of deformity $\mathcal{D}^*$ and for the intensity of its position vector $\boldsymbol{OS}_p$ the following inequalities apply

$$
\begin{aligned}
&\left|\boldsymbol{OS}_B\right| = \sqrt{1069} \approx 32.7^\circ \le \left|\boldsymbol{OS}_p\right| = \sqrt{x_p^2 + y_p^2} \\
&< \left|\boldsymbol{OS}_U\right| = \sqrt{40^2 + 20^2} = \sqrt{2000} \approx 44.7^\circ
\end{aligned} \tag{6}
$$

and we consider it a *moderate deformity*. All points $S_p\left(x_p, y_p\right)$ of the plane $\mathcal{D}^*$ which are determined to be of the moderate deformity, lie within the part of the ring defined by inequalities (6) and are denoted as

$$
\mathcal{D}_{UD} = \left\{\left(x_p, y_p\right) \in \mathcal{H}^* \times \mathcal{I}^* \mid 32.7^\circ \approx \left|\boldsymbol{OS}_B\right|^2 \le x_p^2 + y_p^2 < \left|\boldsymbol{OS}_U\right|^2 \approx 44.7^\circ\right\} \tag{7}
$$

Definition 5. When $\text{HVA} \in \left[40^\circ, \text{Max}_{\text{HVU}}\right)$ and $\text{IMA} \in \left[20^\circ, \text{Max}_{\text{IMU}}\right)$, the hallux valgus deformity is assessed by point $S_p\left(\text{HVA}_p, \text{IMA}_p\right) = \left(x_p, y_p\right)$ in the plane of deformity $\mathcal{D}^* = \mathcal{H}^* \times \mathcal{I}^*$ and for the intensity of its position vector in point S_p, $\boldsymbol{OS}_p$, the following inequality applies

$$
\left|\boldsymbol{OS}_p\right| = \sqrt{x_p^2 + y_p^2} \ge \left|\boldsymbol{OS}_U\right| = \sqrt{2000} \approx 44.7^\circ \tag{8}
$$

and we consider it a *severe deformity*.

We define the set $\mathcal{D}_{TD}$ of all points $S_p\left(x_p, y_p\right)$ of the plane $\mathcal{D}^*$ that determine a severe deformity and that lie inside of an open circular ring and for which the following inequalities (8) are valid, as follows.

$$
\mathcal{D}_{TD} = \left\{\left(x_p, y_p\right) \in \mathcal{H}^* \times \mathcal{I}^* \mid x_p^2 + y_p^2 > \left|\boldsymbol{OS}_U\right|^2 \approx 44.7^\circ\right\} \tag{9}
$$

Let $S_{p1}\left(x_{p1}, y_{p1}\right)$ and $S_{p2}\left(x_{p2}, y_{p2}\right)$ be the two points corresponding to the deformities d_1 and d_2 in the plane $\mathcal{D}^*$, respectively.

Definition 6. Conjugate deformities $d_1 \equiv S_{p1}\left(\text{HVA}_{p1}, \text{IMA}_{p1}\right)$ and $d_2 \equiv S_{p2}\left(\text{HVA}_{p2}, \text{IMA}_{p2}\right)$ belong to the same category if and only if their position vectors of corresponding points S_{p1} and S_{p2} have equal intensities, *i.e.* if and only if the following equality holds

$$
d_1 = \left|\boldsymbol{OS}_{p1}\right| = \sqrt{\text{HVA}_{p1}^2 + \text{IMA}_{p1}^2} = \sqrt{\text{HVA}_{p2}^2 + \text{IMA}_{p2}^2} = \left|\boldsymbol{OS}_{p2}\right| = d_2. \tag{10}
$$

for $\text{HVA} \in \left[0, \text{Max}_{\text{HVU}}\right)$, and $\text{IMA} \in \left[0, \text{Max}_{\text{IMU}}\right)$.

The categories of hallux valgus deformity classified based on the definition of the conjugate deformity are summarized in **Table 2**, together with the limits of the category and the corresponding values of the angles HVA and IMA. The results are shown in **Table 2**. We can see that each pair of values of the angles HVA and IMA, which defines the category of the degree of deformity, has been replaced with one value of the conjugate deformity. A comparison of the classification of the degree of deformity classified on the basis of the definition of conjugate deformity and on the basis of the values of the angles HVA and IMA, of a sample of 396 surgically treated feet is shown in **Table 3**.

First, for all the measured values of the angles HVA and IMA using the formula $d = \sqrt{\text{HVA}^2 + \text{IMA}^2}$, the values of the corresponding conjugate deformities were calculated, and then by applying the definitions (2 to 5), the degree of deformity was determined. For the sake of comparison, the results of this classification are opposed to the classification based on the limit values of the specified angles (**Table 3**).

Table 2. Classification of the degree of deformity based on the values of the angles and the intensity of the position vector *i.e.* (conjugate deformity values).

Degree of deformity (Category)	Based on the value of the angles		Based on the conjugate deformity $\lvert \boldsymbol{OS} \rvert = \sqrt{\text{HVA}^2 + \text{IMA}^2}$, (˚)
	HVA, (˚)	IMA, (˚)	
The finding is normal (FN)	<15˚	<9˚	$\lvert \boldsymbol{OS} \rvert < 17.5^\circ$
Mild Deformity (MD)	from 15˚ to 30˚	from 9˚ to 13˚	$17.5^\circ \le \lvert \boldsymbol{OS} \rvert < 32.7^\circ$
Moderate Deformity (MoD)	from 30˚ to 40˚	from 13˚ to 20˚	$32.7^\circ \le \lvert \boldsymbol{OS} \rvert < 44.7^\circ$
Severe Deformity (SD)	40˚ and above	20˚ and above	$\lvert \boldsymbol{OS} \rvert \ge 44.7^\circ$

Legend: HVA-hallux valgus angle, IMA-intermetatarsal angle, N-number of cases.

Table 3. Classification results based on the value of the angles HVA and IMA, and the value of the conjugated deformity.

Value of angles HVA and IMA (method M1)	Classification (method M1) N (%)	Not classified by method M1	Value of conjugate deformity (method M2)	Classification (method M2) N (%)
[0, 15) × [0, 9)	0 (%)	1	<17.5˚	2 (0.5%)
[15, 30) × [9, 13)	71 (17.92%)	54	from 17.51 to 32.70	155 (39.1%)
[30, 40) × [13, 20)	114 (28.79%)	71	from 32.71 to 44.70	196 (49.5%)
[40, Max_{HVU}) × [20, Max_{IMU})	11 (2.8%)	74	from 44.7 and above	43 (10.9%)
Total	196 (49.49%)	200	Total	396 (100%)

Legend: HVA-hallux valgus angle, IMA-intermetatarsal angle, N-number of cases.

The obtained results (Table 3) show that a total of 196 (49.49%) cases were correctly grouped by the classification of deformities according to the limit values of HVA and IMA (method M1), while all 396 (100%) cases were correctly grouped by the classification based on the conjugate deformity (method M1) among the cases of the surgically treated feet, *i.e.* we definitely know which category each deformity belongs to.

4. Application of a Classification Based on the Conjugate Degree of Deformity

4.1. Deformity Correction Analysis

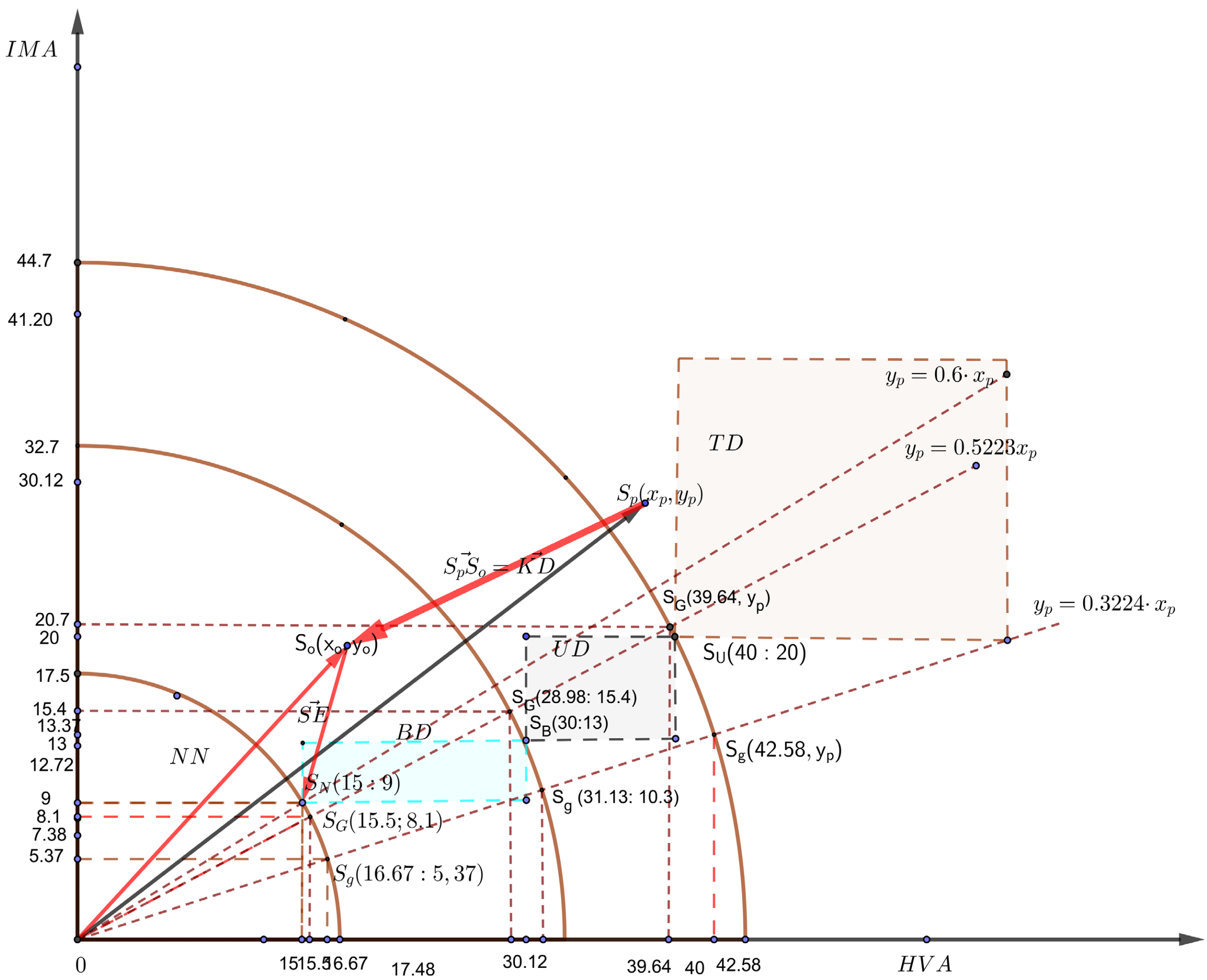
Under *the correction of foot deformity* using surgical method M, we mean the mapping (transformation) that maps (translates) the deformity determined by the state $S_p(x_p, y_p) \in \mathcal{H}^* \times \mathcal{I}^*$ into the deformity determined by the state $S_o(x_o, y_o) \in \mathcal{H}^* \times \mathcal{I}^*$ That is $\mathcal{K}_M : S_p(x_p, y_p) \to S_o(x_o, y_o)$ or $S_o = \mathcal{K}_M(S_p)$. Each correction of the deformity entails a change in the values of the angles HVA and IMA, which determine that deformity.

Geometrically, a foot deformity correction is a vector $\boldsymbol{S_p S_o}$ whose starting point $S_p(x_p, y_p)$, corresponds to the assessment of the degree of deformity determined by the values of the angles $x_p = \text{HVU}_p, y_p = \text{IMU}_p$ prior to the surgical treatment, and the end point $S_o(x_o, y_o)$ corresponds to the degree of the foot deformity after the surgical treatment using the surgical method M.

The vector intensity $\left|\boldsymbol{S}_p\boldsymbol{S}_o\right| = \left|\boldsymbol{KD}\right|$ corresponds to the *value of the surgical correction of the foot deformity* $S_p\left(x_p, y_p\right)$ (**Figure 2** and **Figure 3**), is calculated according to the formula

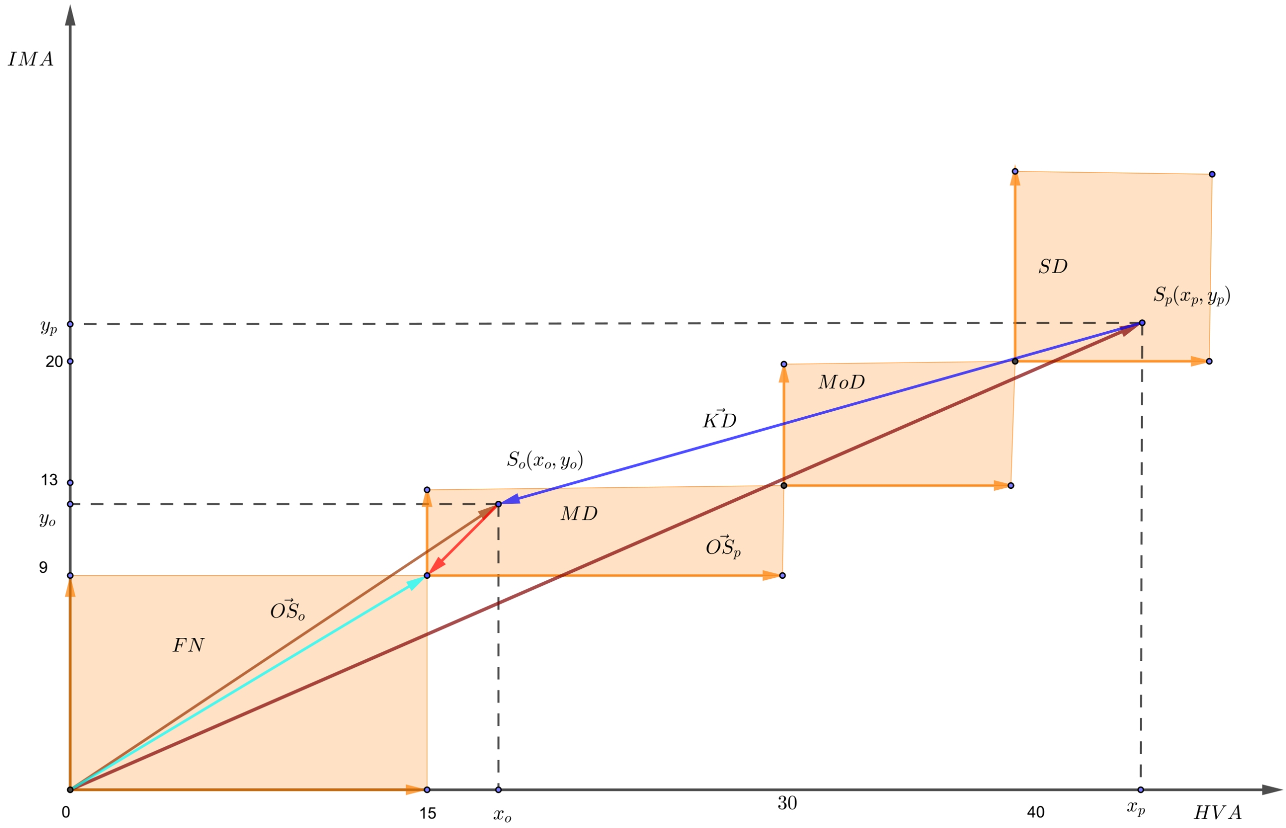
$$\begin{aligned} KD = \left|\boldsymbol{KD}\right| &= \sqrt{\left(\text{HVA}_p - \text{HVA}_o\right)^2 + \left(\text{IMA}_p - \text{IMA}_o\right)^2} \\ &= \sqrt{\left(x_p - x_o\right)^2 + \left(y_p - y_o\right)^2} \end{aligned} \quad (11)$$

Let $\left(x_{p1}, y_{p1}\right), \left(x_{p2}, y_{p2}\right), \left(x_{p3}, y_{p3}\right), \cdots, \left(x_{pN}, y_{pN}\right)$ be the measured values of the HVA and IMA angles, respectively, in N feet prior to the surgical treatment, and $\left(x_{o1}, y_{o1}\right), \left(x_{o2}, y_{o2}\right), \cdots, \left(x_{oN}, y_{oN}\right)$ be the corresponding values of those angles after the surgical treatment, treated by method M, respectively. If KD_i marks the correction of the deformity $\left(x_{pi}, y_{pi}\right)$, of foot $i = 1, 2, 3, \cdots, N$ to the deformity $\left(x_{oi}, y_{oi}\right)$, then the correction of deformity in a sample of N feet, that



Legend: FN-normal finding, MD-mild deformity, MoD-moderate deformity, SD-severe deformity, HVA-halluv valgus angle, IMA-intermetatarsal angle.

Figure 2. Deformity categories based on definitions and range of deformity values before and after surgery.



Legend: FN-normal finding, MD-mild deformity, MoD-moderate deformity, SD-severe deformity, HVA-halluv valgus angle, IMA-intermetatarsal angle.

Figure 3. Geometric construction of a hallux valgus deformity correction.

was achieved with the surgical method, (marked KD_M), is equal to the average value of the deformity correction achieved on N feet, *i.e.*

$$KD_M = \frac{1}{N}\sum_{i=1}^{N} KD_i = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\left(\text{HVA}_{pi} - \text{HVA}_{oi}\right)^2 + \left(\text{IMA}_{pi} - \text{IMA}_{oi}\right)^2} \quad (12)$$

or, shorter

$$KD_M = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\left(x_{pi} - x_{oi}\right)^2 + \left(y_{pi} - y_{oi}\right)^2} \quad (13)$$

As an illustrative example of the application of formulas (12) and (13), the deformity correction was calculated on a sample of $N = 396$ surgically treated feet using the Chevron and Golden methods. The results are shown in **Table 4**, and the calculated values for Mean and Standard Deviation are expressed in degrees.

The T test of independent samples assessed the significance of the difference in the calculated average values of deformity correction using the surgical method of Chevron and the one according to Golden. It was shown that there is a statistically significant difference in the average value of the degree of deformity correction in the sample, $t(N = 394) = -7.918$, Sig. = 0.000.

Table 4. Results of calculating the average value of the correction of deformities using Chevron and Golden surgical methods on a sample of 396 feet, with an assessment of the significance of the difference in corrections.

Surgical treatment	*N*	Mean (Me)	Standard deviation (SD)	Stan. error of mean (Se)	Min.	Max.	T (df = 394)	p
Chevron	209	16.5748	8.59274	0.59437	0.00	48.10	−7.918	0.000
According to Golden	187	23.1086	7.73222	0.56544	3.93	48.58		
Total	396	19.6602	8.81476	0.44296	0.00	48.58		

Legend: N-number of cases, Min-minimum, Max-maximum, T-degrees of freedom, p-probability value.

4.2. Deviation of Deformity Correction from the Normal State

Let the deformity prior to the surgical treatment be assessed with the point $S_p\left(x_p, y_p\right)$, and let the the deformity after the operative treatment and the performed correction be assessed with the point $S_o\left(x_o, y_o\right)$ and let $S_N(15,9)$ be the point that describes the normal state. The difference between the deformity $S_o\left(x_o, y_o\right) \in \mathcal{H}^* \times \mathcal{I}^*$ after the surgical treatment by method M and the condition which is considered normal, $S_N(15,9)$, can be conditionally called the error of the surgical treatment of the foot deformity, and let us mark it with (*SE*).

This quantity represents the deviation of the obtained values of the HVA and IMA angles after the surgical treatment from the limit values for the normal state and represents the resultant of the errors, SE_{HVU} and SE_{IMU}.

From the triangle $\Delta OS_N S_o$ the following equality applies (**Figure 2** and **Figure 3**)

$$\boldsymbol{OS}_0 + \boldsymbol{S}_o\boldsymbol{S}_N = \boldsymbol{OS}_N \tag{14}$$

From which it follows that $\boldsymbol{S}_o\boldsymbol{S}_N = \boldsymbol{OS}_N - \boldsymbol{OS}_0$. From here, after shortening, we get the formula for calculating the deviation of the correction of the deformity from the normal state after the surgical treatment, *i.e.* the formula for calculating the correction error

$$SE = \left|\boldsymbol{S}_o\boldsymbol{S}_N\right| = \sqrt{\left(\text{HVA}_o - 15\right)^2 + \left(\text{IMA}_o - 9\right)^2} \tag{15}$$

Or shorter, according to the earlier mentioned designations

$$SE = \left|\boldsymbol{S}_o\boldsymbol{S}_N\right| = \sqrt{\left(x_o - 15\right)^2 + \left(y_o - 9\right)^2} \tag{16}$$

The correction error of N treated deformities $\left(x_{p1}, y_{p1}\right), \left(x_{p2}, y_{p2}\right), \cdots, \left(x_{pN}, y_{pN}\right)$ with the surgical method M, (marked SE_M), is defined as the average value of the correction errors of individual deformities, *i.e.* the following applies

$$ER_M = \frac{1}{N}\sum_{i=1}^{N} ER_i = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\left(x_{oi} - 15\right)^2 + \left(y_{oi} - 9\right)^2} \tag{17}$$

As an illustrative example, the deformity correction error was calculated on our sample of 396 surgically treated feet. A comparison of the obtained results for the surgical methods Chevron and the one according to Golden are shown in Table 5. The results are expressed in degrees. The average error value for 209 surgically treated deformities using the Chevron method was Me = 7.5 degrees with SD = 5.36 degrees, and for 187 surgically treated feet using the one according to Golden, the average correction error was Me = 6.07 degrees with SD = 3.49 degrees (Table 5).

4.3. Calculation of the Deformity Correction Rate

The correction of the deformity of the *i* foot represents the intensity of the vector $\boldsymbol{S}_{pi}\boldsymbol{S}_N = \boldsymbol{UDF}_i$ whose starting point $S_{pi} = \left(x_{pi}, y_{pi}\right)$ corresponds to the values of the angles $x_{pi} = \text{HVA}_{pi}, y_{pi} = \text{IMA}_{pi}$ prior to the surgical treatment, and the endpoint $S_N\left(15^\circ, 9^\circ\right)$ represents the point when the findings are normal.

So, if UDF_i is the intensity of the vector $\boldsymbol{S}_{pi}\boldsymbol{S}_N$, then, according to the symbols in Figure 2 and Figure 3, the following formula applies

$$UDF_i = \left|\boldsymbol{UDF}_i\right| = \left|\boldsymbol{S}_p\boldsymbol{S}_N\right| = \sqrt{\left(x_{pi} - 15\right)^2 + \left(y_{pi} - 9\right)^2} \tag{18}$$

Total deformity for the measured values of the angles HVA and IMA; $\left(x_{p1}, y_{p1}\right), \left(x_{p2}, y_{p2}\right), \left(x_{p3}, y_{p3}\right), \cdots, \left(x_{pN}, y_{pN}\right)$, respectively, in *N* feet prior to the surgical treatment by method M, represents the average value of the deformity of individual feet, which can be written in the form

$$UDF_M = \frac{1}{N}\sum_{i=1}^{N} UDF_i = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\left(x_{pi} - 15\right)^2 + \left(y_{pi} - 9\right)^2}$$

The rate of the deformity S_{DFi} correction in the foot *i*, is now

$$s_{DFi} = \frac{KD_i}{KD_i + SE_i} = \frac{KD_i}{UDF_i} = \frac{\sqrt{\left(x_{pi} - x_{oi}\right)^2 + \left(y_{pi} - y_{oi}\right)^2}}{\sqrt{\left(x_{pi} - 15\right)^2 + \left(y_{pi} - 9\right)^2}} = \sqrt{\frac{\left(x_{pi} - x_{oi}\right)^2 + \left(y_{pi} - y_{oi}\right)^2}{\left(x_{pi} - 15\right)^2 + \left(y_{pi} - 9\right)^2}} \tag{19}$$

Let a collection of *N* deformities treated by method M be given. The correction rate of deformities $\left(x_{p1}, y_{p1}\right), \left(x_{p2}, y_{p2}\right), \left(x_{p3}, y_{p3}\right), \cdots, \left(x_{pN}, y_{pN}\right)$ using the surgical method of treatment M represents the average value of the correction

Table 5. Deformity correction error on a sample of surgically treated foot deformities using the Chevron and Golden methods.

Surgical Method	N	Mean (Me)	Median (Md)	St.Dev. (SD)	Min	Max
Chevron	209	7.5554	6.4031	5.36171	0	35.69
According to Goldenu	187	6.0750	5.3853	3.49935	0	25.71
Total	396	6.8563	5.8310	4.63162	0	35.69

Legend: N-number of cases, Min-minimum, Max-maximum.

rates of individual feet, *i.e.*

$$s_{DF} = \frac{1}{N}\sum_{i=1}^{N} s_{DFi} = \frac{1}{N}\sum_{i=1}^{N}\frac{KD_i}{KD_i + SE_i} = \frac{1}{N}\sum_{i=1}^{N}\frac{KD_i}{UDF_i} = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\frac{\left(x_{pi}-x_{oi}\right)^2+\left(y_{pi}-y_{oi}\right)^2}{\left(x_{pi}-15\right)^2+\left(y_{pi}-9\right)^2}} \quad (20)$$

4.4. Application of the Absolute Value of the Deformity in Monitoring the Period of Its Development

Example 1: An example of calculating the rate of deformity correction determined by the application of the surgical treatment method is shown in **Table 6**. The table shows the results of calculating the average rate of foot deformity correction treated with the Chevron surgical method, $N = 209$, and the one according to Golden, $N = 187$. In the analyzed sample, the deformity correction rate using the Chevron surgical treatment method was Me = 67.68%, with a standard deviation of SD = 19.169%, and the surgical treatment according to Golden was Me = 78.53% with SD = 12.367%.Therefore, by applying the absolute value of the severity of hallux valgus deformity, a new approach is enabled in the analysis of the achieved overall correction of the deformity expressed by the rate of change in the values of the HVA and IMA angles of this complex deformity (**Table 6**).

Example 2: An example of the functional application of the representation of hallux valgus deformity using the intensity vector of the position of the point in the plane with coordinates that present the values of the angles HVA and IMA was shown by examining the relationship between the degree of deformity and the period of its development, shown in **Table 7**.

Such an approach enables s to graphically interpret the relationship between the deformity and the observed factor in the plane. As an illustration of the graphic interpretation, a scatter diagram of the deformity in relation to the period of its development is shown in **Figure 4**.

5. Conclusion

The classification of hallux valgus deformity based on the borderline radiological values of the HVA and IMA angles is not sufficient to reliably classify each case. On the contrary, the representation of the hallux valgus deformity by its conjugate

Table 6. Hallux valgus deformity correction rate in a sample of surgically treated foot deformities.

Surgical Method	N	Mean (Me)	Median (Md)	St.Dev. (SD)	Min.	Max.
Chevron	209	0.6768	0.7291	0.19169	0	1.0
According to Golden	187	0.7853	0.8054	0.12367	0.21	1.0
Total	396	6.7280	0.7752	0.17174	0	1.0

Table 7. Distribution of the degree of hallux valgus deformity measured in absolute value in relation to the period of development of the deformity.

Deformity assessed by absolute value		Period of deformity development (years) ≤5	6 - 10	11 - 15	16 - 20	21+	N = 396 p
Less than 17.50, N = 2, 0.5%	Count	0	2	0	0	0	χ^2 (12,396)-\ = 31.213, Sig = 0.002 Cramer's V = 0.162
	% within Deformity	0.0%	100.0%	0.0%	0.0%	0.0%	
	% within Period	0.0%	1.1%	0.0%	0.0%	0.0%	
	% of Total	0.0%	0.5%	0.0%	0.0%	0.0%	
From 17.50 to 32.69 N = 145, 36.6%	Count	51	61	24	8	1	
	% within Deformity	35.2%	42.1%	16.6%	5.5%	0.7%	
	% within Period	53.1%	33.2%	33.8%	22.2%	11.1%	
	% of Total	12.9%	15.4%	6.1%	2.0%	0.3%	
From 32.70 to 44.69 N = 206 52.0%	Count	40	103	37	22	4	
	% within Deformity	19.4%	50.0%	18.0%	10.7%	1.9%	
	% within Period	41.7%	56.0%	52.1%	61.1%	44.4%	
	% of Total	10.1%	26.0%	9.3%	5.6%	1.0%	
From 44.70 and more N = 43 10.9%	Count	5	18	10	6	4	
	% within Deformity	11.6%	41.9%	23.3%	14.0%	9.3%	
	% within Period	5.2%	9.8%	14.1%	16.7%	44.4%	
	% of Total	1.3%	4.5%	2.5%	1.5%	1.0%	
Total	Count	96	184	71	36	9	
	% of Total	24.2%	46.5%	17.9%	9.1%	2.3%	

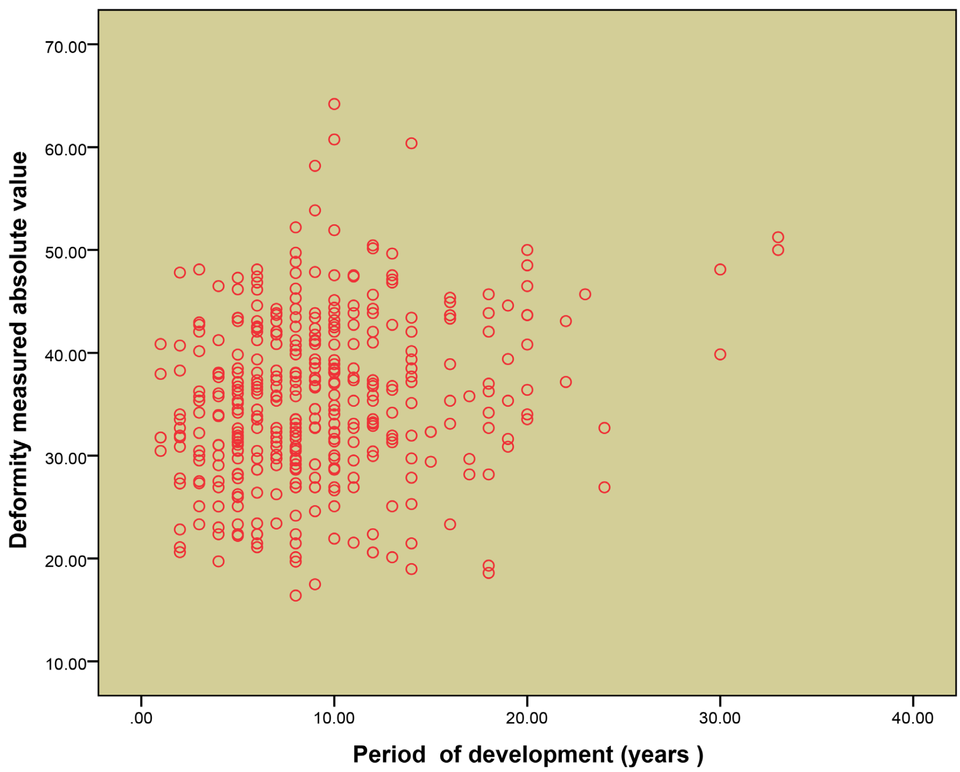


Figure 4. Scatter diagram of deformities in relation to the period of development.

(absolute) value allows us to classify each form of deformity according to a degree with high reliability, and besides, we express the degree of deformity with a quantitative value. The advantage of expressing the deformity with its conjugate value allows us to calculate the degree of correction of the deformity both in individual cases and at the sample level, either by monitoring the effects of applying one surgical method on the population or by comparing the results of the treatment of two or more methods. We believe that the application of absolute values (conjugated) of the deformity will significantly contribute to its understanding, and increase the degree of certainty in further research of both the influence of the etiological factors and the analysis of the results achieved with surgical correction.

6. Declarations

Ethics approval and consent to participate.

The authors confirm that informed consent was obtained from all subjects. The informed consent for subjects under 18 years was obtained from their parents/legal guardians.

The authors confirm that all research protocols were approved by the Ethics committee of the Institute of Orthopedics "Banjica" Belgrade, Serbia.

Availability of Data and Materials

All data and materials of the research are in possession of the corresponding author.

Authors' Contributions

N.S. used mathematical and logical argumentation and created mathematical formula for calculation of conjugated Hallux valgus deformity. M.S. defined the problem of standard classification of HV deformity, gave guidelines to solve the problem and named the deformity as conjugated. V.I. and D.V. reviewed the manuscript, giving suggestion for improvement.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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