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Factors influencing the speed of correction speed of distal tibial valgus deformity in children with percutaneous epiphyseodesis using transphyseal screw

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ABSTRACT

Introduction: The distal tibial valgus deformity in children mimics a hindfoot valgus and is observed in several conditions of both non-neurogenic and neurogenic origin. The deformity can only be detected with radiological examination and can be safely and effectively corrected in children with medial percutaneous epiphysiodesis using transphyseal screws (PETS). The aims of the study are: 1. to determine the correction rates of the distal tibial valgus deformity due to different pathologies, 2. to examine the correction rate in relation to the age at implantation, severity of the initial deformity and the duration of implantation, 3. and types of foot deformities associated with the deformity.

Materials and methods: A retrospective study was done on children who underwent a PETS for a distal tibial valgus deformity. The lateral distal tibia angle 89° ± 3° on ankle mortice x-rays was taken as normal. An analysis of variance and covariance was done to investigate differences in parameters between aetiologies and relations between parameters respectively.

Results: Following exclusion of 191 limbs, 155 limbs in 104 children were included the study, 5 groups could be identified: Idiopathic, ICP (cerebral palsy), MMC (Meningomyelocele), Dysmelia, MHE (multiple hereditary exostosis). The mean age at implantation of all patients was 10.9 ± 1.4 years. The average correction of 0.45° ± 0.08°/month with no significant differences in the correction rates between groups. However, the correction rates were dependent on the age, the initial deformity and the duration of treatment. The incidence of a valgus foot deformity was 86.4 %.

Conclusion: The correction rates of the distal tibial valgus deformity following PETS are variable and depend, on the age at implantation, duration of treatment and initial deformity. The spectrum of foot deformities associated with distal tibial valgus deformity, especially a high prevalence of valgus foot deformity warrants an ankle mortice x-ray.

Level of Evidence: Level III, retrospective study

1. Introduction

The distal tibial valgus deformity is reported as an uncommon deformity [1]. In paediatric age group, it has however been described in association with several conditions of both non-neurogenic and neurogenic origin. The reason for the development of this deformity remains unclear [2]. The deformity has been reported in children in association with idiopathic genu valgum and idiopathic clubfoot [3,4,5], spina bifida [6,7,8] and cerebral palsy [9]. Its association with multiple hereditary exostosis (MHE) is well-known [4,6,7,10,]. Apart from these conditions, it occurs in in several other conditions [11,12,13,14,15,16,17]. It is prevalent in 67 % of idiopathic clubfoot [4] and 45–54 % of MHE [18]. The prevalence of this deformity due to aetiologies remain unknown. Due to its association with several

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disease conditions, several patho-mechanisms may be responsible for the development of this deformity [2,11,15, 19].

The presence of a foot deformity might make the detection of an underlying ankle valgus impossible [3]. It may provoke a fibula-calcaneal impingement and may be responsible for pain, ankle dysfunction and osteoarthritis [20], therefore justifying the need for an early treatment. The deformity may be corrected in children with a hemiepiphyseodesis of the distal medial tibia using either a percutaneous transphyseal screw (PETS) or a 2-holed plate, with both methods giving similar and satisfying results [21]. Some papers investigated the effect of the aetiological cause or age at implantation on the correction rates. The limitations of these studies are, small number of patients [21,22] and grouping together a wide variety of aetiologies [3]. Hence, there is a need to examine these questions in a larger collective of patients.

The study objectives were to: 1. assess correction rates of distal tibial valgus deformity in children following PETS based on various aetio-pathologies, 2. investigate potential correlations between correction rate and age at implantation, initial deformity severity, and treatment duration, and 3. explore the association between foot deformities and distal tibial valgus deformity. Our hypotheses are: 1. the correction rate of distal tibial valgus deformity following PETS is influenced by its underlying aetiology, 2. the correction rate is inversely proportional to age at implantation, severity of the initial deformity, and proportional to treatment duration, and 3. valgus foot is the most common associated deformity.

2. Materials and methods

A retrospective study was done using hospital database in children who underwent PETS for a distal tibial valgus deformity between 2008 - 2021. The study was exempted from the ethics committee of the Bavarian medical council (Nr. 2023–1176) due to its retrospective. The inclusion criteria were: children with a distal tibial valgus deformity, hemi-epiphysiodesis with a cannulated screw, availability of pre-implantation and pre-explantation ankle mortice view radiographs. Children in whom the correction was in progress at the time of study, non-availability of radiographs, and hemi-epiphyseodesis using 8-plates were excluded from the study. Further, children with distal tibial valgus deformity due to syndromes (20 different syndromes) and miscellaneous conditions such as hemimelia, Neurofibromatosis, Osteogenesis Imperfecta, Fibrous Dysplasia, Renal Rickets, congenital posterior-medial bowing of tibia and fibula were excluded from the study.

As per the hospital protocol a standard ankle mortice view X-ray were routinely obtained in all patients referred to the outpatient department for limb or foot deformities (Fig. 1). Patient demographic parameters, aetiology causing the valgus deformity, presence or absence of a foot deformity, chronological age at surgery, side of the deformity, chronological age at explantation were recorded. The presence of an open growth-plate was confirmed on the ankle X-rays. Estimation of the skeletal age of the child was not routinely practiced before surgery. The lateral distal tibia angle (LDTA) was measured as the lateral angle between the joint surface of talus to the longitudinal axis of the tibia. LDTA between 89° ± 3° was taken as normal [23]. A PETS was indicated when the LDTA was below 86° and the surgery was performed using 5 mm incision below the medial malleolus using a fully threaded stainless-steel cannulated screw. Depending on the severity of the deformity, all children were followed-up clinically and radiologically in the outpatient's department at 3 to 6-month intervals. The screw was removed when the LDTA was at least 90° or earlier due to closure of the growth-plate. Where possible, a slight overcorrection up to 92° was aimed to allow for loss of correction after explantation due to 'rebound' phenomenon. The underlying foot deformity was corrected in a second sitting at the time of explantation of PETS as it is the standard hospital practice (Fig. 5). All children were clinically followed up until end of growth, observing the hind- and forefoot in standing. Repeat ankle X-rays were only performed when the hindfoot or a forefoot deformity was clinically observed and routine follow-up ankle x-rays were not performed due to ethical reasons.

Fig. 1. Ankle mortice view. The vertical line is drawn along the long axis of the tibia. The transverse line is drawn along the superior border of the talus. The lateral distal tibial angle (LDTA) is measured as the lateral angle between vertical and the horizontal line, which in this case measures 78.9°.

3. Statistical analysis

A one-way analysis of variance (ANOVA) was used to analyse differences in the parameters listed in Table 1. This was done using the function "anova1" in MatLab 2020b (The MathWorks®, Natick, MA, USA) including post-hoc tests. To investigate whether the correction velocity differs with age, preoperative LDTA and duration of treatment an analysis of covariance was done with the function "aoctool" in MatLab 2020b using separate line fits for each group with no constraints. P-Value of < 0.05 was taken as significant.

4. Results

Between 2008 and 2021, PETS of the distal medial tibia was performed in 346 limbs, of which 191 limbs (116 limbs due to lack of correction in progress or non-availability of X-rays and further 75 limbs with syndromes and miscellaneous conditions) were excluded. Therefore, 155 limbs in 104 children were included in the study. There were 70 males (116 limbs) and 34 females (39 limbs). 53 children had a bilateral procedure and 49 a unilateral procedure. The children were divided into 5 groups depending on the aetiology causing the deformity: 1 – idiopathic, 2 – Infantile cerebral Palsy (ICP), 3 – Meningomyelocele (MMC), 4 – Multiple Hereditary Exostosis (MHE) and 5 – bone dysplasia. The number of ankles and the mean age at implantation in each group are provided in Table 1. The mean age at implantation of the entire collective was 10.9 ± 1.4 years. One-way ANOVA indicated that the age of patients between

Table 1
Showing the number of limbs (N) in each group, age at implantation, pre-implantation and pre-explantation lDTA (**l**ateral **D**istal **T**ibia **A**ngle), average correction in degrees, time of correction in months and correction rate/month. The values in the brackets show the standard deviations.

	1. Idiopathic	2. ICP	3. MMC	4. MHE	5. Bone dysplasia	p - ANOVA	post-hoc tests
Number of Limbs (N)	46	27	43	18	21	N/A	N/A
Limbs in males	38	22	29	11	16	N/A	N/A
Age at implantation [Years]	11.7 (2.5)	12.1 (2.4)	9.0 (2.5)	12.1 (2.6)	10.2 (2.9)	< 0.001 *	3 vs. 1,2,4
Pre lDTA [°]	83.3 (2.5)	81.1 (3.9)	78.3 (5.3)	79.8 (3.8)	78.3 (5.1)	< 0.001 *	1 vs. 3,4,5
Pre lDTA [°]	89.8 (3.7)	87.7 (4.2)	87.7 (6.1)	85.3 (5.6)	84.8 (5.4)	0.001 *	1 vs. 4,5
Correction [°]	6.4 (4.4)	6.6 (4.8)	9.4 (5.8)	5.4 (3.7)	6.5 (6.3)	0.024	-
Duration [Months]	12.1 (6.2)	13.0 (8.9)	17.8 (7.5)	17.9 (8.1)	33.6 (26.0)	< 0.001 *	5 vs. 1,2,3,4
Correction velocity [°/Month]	0.57 (0.33)	0.54 (0.46)	0.56 (0.37)	0.39 (0.33)	0.43 (0.37)	0.293	-

groups were significantly different ($p < 0.001$). Post-hoc analysis indicated that the children in MMC group were significantly younger than the children in other groups.

The screw was placed as targeted on both views in all limbs. The mean pre-implantation and pre-explantation values of LDTA of the entire patient collective were 80.2° ± 2.1° and 87° ± 2.0°. The average degree of correction of LDTA in the entire collective was 6.6° ± 1.0° and the average time of correction was 19.3 ± 9.6 months with an average correction of 0.45° ± 0.08°/month. The pre-operative valgus deformity was significantly different between groups ($p < 0.001$). Post-hoc test indicated differences between group 1 and groups 3–5. Groups with diagnosis MMC, MHE and bone dysplasia showed severe deformity with mean LDTA < 80°. There was a significant correction of the deformity following PETS as indicated by the main effect of the treatment ($p < 0.001$) across groups. The mean values of pre-implantation and pre-explantation LDTA, average degrees of correction, average correction time and average correction/month along with standard deviation values in all 5 groups are presented in Table 1. The variance for correction velocity was not significant ($p < 0.293$), indicating that correction velocity was not different across diagnoses.

To investigate whether the homogeneous slopes assumption was supported by the data, an additional model was tested allowing the associations between age, duration of treatment, pre-operative LDTA and correction velocity across 5 aetiologies. Results indicated that slopes between age and correction velocity, as well as preoperative LDTA and correction velocity and duration of treatment and correction velocity did significantly vary across aetiologies, (all $p < 0.001$), suggesting that the different aetiologies did not have the same relationship to velocity of correction of the deformity and that the assumption of homogeneous slopes is violated. The slopes are shown in Figs. 2,3 and 4 and the corresponding analysis of

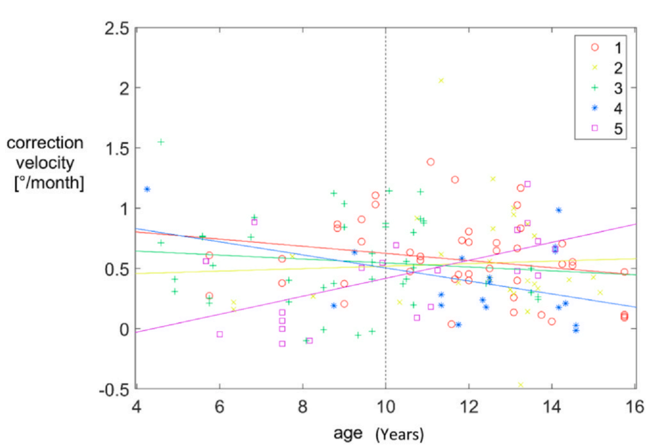

Fig. 2. Linear regression graphs of the correction velocity of predictor age, The patient's groups were: 1. Idiopathic 2. Infantile Cerebral Palsy, 3. Meningomyelocele, 4. Multiple Hereditary Exostosis 5. Bone Dysplasia.

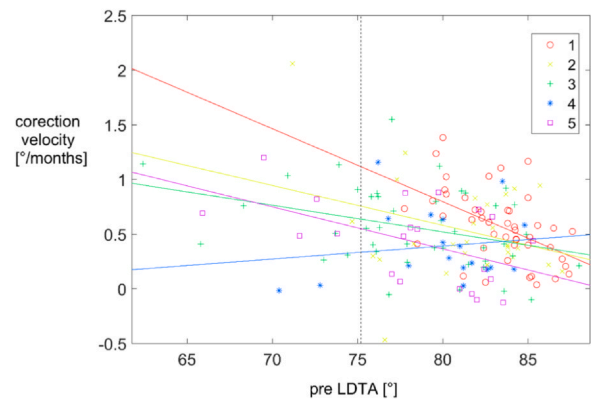

Fig. 3. Linear regression graphs of the correction velocity of predictors preoperative LDTA. The patient's groups were: 1. Idiopathic 2. Infantile Cerebral Palsy, 3. Meningomyelocele, 4. Multiple Hereditary Exostosis 5. Bone Dysplasia.

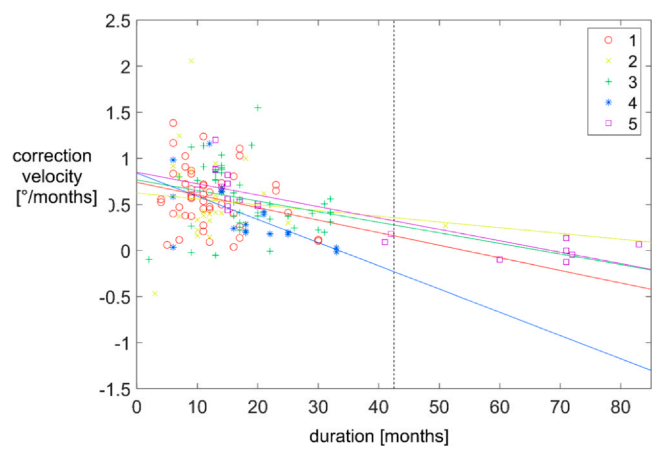

Fig. 4. Linear regression graphs of the correction velocity of duration of treatment. The patient's groups were: 1. Idiopathic 2. Infantile Cerebral Palsy, 3. Meningomyelocele, 4. Multiple Hereditary Exostosis 5. Bone Dysplasia.

covariance values for slopes and intercept values for the following 3 equations in Table 2.

Age: correction velocity $=(-0.0189+\textit{slope})\ \textit{age}+(0.7944+\textit{intercept})$.

Duration: correction velocity $=(-0.0189+\textit{slope})\ \textit{duration}+(0.9158+\textit{intercept})$.

Initial LDTA: correction velocity $=(-0.0261+\textit{slope})\ \textit{duration}+(2.6889+\textit{intercept})$.

Fig. 2 demonstrates that for groups 1, 3 and 4 the correction velocity was negatively related to the age, so that the lower the age the more rapid the correction. Detailed post-hoc analysis indicated any significant differences. However, in bone dysplasia group, the slope suggests that the earlier the age at implantation, the slower the correction velocity.

Table 2
Analysis of covariance coefficients for age, duration and initial LDTA.

Diagnoses	Age [Years]		Duration of treatment [Months]		Initial LDTA	
	slope	intercept	slope	intercept	slope	intercept
1. Idiopathic	−0.0107	0.1263	−0.0407	3.4477	0.0052	−0.1760
2. ICP	0.0292	−0.3779	−0.0104	0.8085	0.0126	−0.2936
3. MMC	0.0025	−0.0854	0.0017	−0.2152	0.0074	−0.1494
4. MHE	−0.0352	0.2507	0.0380	−3.2484	−0.0063	−0.0754
5. Bone Dysplasia	0.0934	−1.1211	−0.0124	0.7543	0.0065	−0.0665

The pre-operative LDTA shows for most groups (except for Multiple Hereditary Exostosis) a negative relation with the correction velocity (Fig. 3) The lesser the LDTA (more valgus) the larger the correction velocity. Post hoc analysis revealed a significant difference between bone dysplasia, ICP and idiopathic groups, in these groups, the initial LDTA had a greater impact on the correction velocity.

For the factor duration of implantation all slopes are negative suggesting that the longer the duration the slower the correction velocity. There were no significant differences between groups (Fig. 4).

Irrespective of the aetiological diagnosis, several expressions of valgus foot deformity were often associated with the distal tibial valgus deformity and was seen in 134 limbs. Other foot deformities include clubfoot, cavus and equines foot deformities. In 21 limbs no foot deformity was seen.

5. Discussion

The results of the study did not confirm the first hypothesis, the idiopathic, ICP, MMC, MHE and bone dysplasia groups did not show any significant differences in the correction velocities. However, despite not being significantly different, the groups MHE and bone dysplasia showed an average slower correction velocities. The second hypothesis was also found to true for all groups, except bone dysplasia. In 4/5 groups the correction rate was inversely proportional to age at implantation, directly proportional to the initial valgus deformity. In all the 5 groups, the rate of correction was inversely proportional to the duration of implantation. The valgus foot deformity was the most common associated foot deformity proving the third hypothesis as correct.

This study on the valgus deformity of the distal tibia is the largest in the literature with 155 PETS procedures in 104 children, allowing better statistical analysis of results. Some studies in the literature did not group the patient collective based on the aetiology causing the deformity, while others did [22,24]. The large number of patients in each of the 5 study groups and the exclusion of 75 limbs with uncommon aetiologies makes the results of the study reliable. For combined aetiologies, correction rates of 0.37°/month have been reported [21,22,24,25], which is less than 0.45°/month seen in this study. Stevens et al. also reported higher correction rates (0.6°/month) in their collective [3]. The variations in the correction rates in different studies could be due to the differences in the aetiological mix of patients in individual studies. This highlights the need for grouping the patient collective depending on the aetiology causing the deformity.

Aetiology-specific correction rates have been reported in the literature for MMC, MHE and ICP [6,10,24,26]. However, the numbers of limbs in these studies were much small than those in this study. Table 3 depicts different studies with patient collective and correction rates. Six of the nine studies in the table have mixed aetiologies, making the results of those studies incomparable with the current one. The correction rates for MHE in this study was 0.37°/month. The results of this study were supported by those from 2 further studies [10,24]. However, Rupprecht et al. reported higher correction rates of 0.58°/month [26]. In MMC, Bayhan et al. reported in 18 ankles correction rates of 0.87°/month [6]. In the present study with 43 ankles, we noted far lower correction rates of 0.56°/month. The extremely low correction rate of < 0.05°/month observed in 4 limbs in this study partly contribute explain the differences in results. Other studies reported much lower correction rates, 0.24°/month in 7 limbs and 0.38°/month in 13 limbs [22,24]. Similarly, for ICP, the correction rates of 0.56°/month in 22 limbs in this study were similar to that reported by Rupprecht et al., in 14 limbs, but lower than those of Chang et al. (0.9°/month in 4 limbs) [22,24].

Table 3
Showing the correction rates of the valgus deformity of the distal tibia following the PETS in the literature. MHE = Multiple Hereditary Exostosis, N = Number of ankles.

Author	Year	Aetiology	Rate of correction (°/Month)
Chang et al. (N = 63)	2015	Mixed	0.37
Rupprecht et al. (N = 21)	2015	Mixed	0.65
Bayhan et al. (N = 18)	2014	Spina bifida	0.87
Driscoll et al. (N = 35)	2014	Mixed	0.55
Driscoll et al. (N = 58)	2013	MHE	0.37
		Non- MHE	0.51
Rupprecht et al. (N = 15)	2011	MHE	0.58
Davids et al. (N = 29)	1997	Mixed	0.59

We included children with distal tibial valgus deformity with no systemic disease in the idiopathic group. Only 2 studies included idiopathic groups in their patient collective without defining the criteria [22,24]. The current study reported correction rates of 0.54°/month, which were similar to that reported by Rupprecht et al. [22]. However, Chang et al. reported only 0.38°/month [24].

In the literature the average age at surgery was between 10–12 years but was in general lower for MMC [24,27]. The lower age at surgery in children with MMC indicates that the deformity develops early in age. A short fibula has been reported to be the cause [2]. Correction rates in relation to age at surgery has been only studied for MHE. While van Oosterbos et al. described a positive correlation between speed of correction and age [28], Macneille et al. noted that correction rate peaked between 10 – 11 years [27]. Non-linear growth characteristics of growth in children is the possible reason for this observation. The fastest growth in a child occurs during puberty. On contrary, this study showed faster correction rates at early age of surgery in all groups, except in bone dysplasia. The deformity in bone dysplasia is caused by the deformation of the epimetaphyseal region under load [29], and differs from other aetiologies, where asymmetric growth is the cause. This pathological process is the probable reason for the lack of correlation between age at implantation and correction rates.

We assumed that the severe the initial deformity, the slower the correction velocity. In contrary to our assumption, faster correction rates were seen with severe initial deformity in 4/5 groups. Only group MHE showed slower correction rates. To our knowledge, this question has not been investigated until now. A valgus deformity of the distal tibia in MHE is often associated with an exostosis in the metaphysis of the lateral side of the distal tibia. Its role of MHE in the development of valgus deformity of the ankle is not clear, as the deformity is seen only in 71 % of the subjects with exostosis at the distal tibia [30].

Fig. 5. Case – 1 (1a – 1e): A case of valgus deformity of the distal tibia in a 8 year old child with Meningomyelocele. Following the correction of the valgus deformity and at the time of explantation of the screw, the calcaneo-valgus foot deformity was corrected with Grice subtalar arthrodesis and a dorsal flexion osteotomy of the calcaneus. Case – 2 (2a – 2 f): A case of painful idiopathic flatfoot deformity in a 14-year-old healthy young child with valgus deformity of the distal tibia. In the first step, a PETS of the distal tibia was done. Following correction of the distal tibial valgus deformity the foot was corrected with tarsal triple osteotomy (calcaneal lengthening, calcaneal medial-shift osteotomy, and cotton cuneiform osteotomy), gastrocnemius recession and supra-malleolar rotation osteotomy.

The duration of the implantation showed an inverse relation, with the MHE group showing the greatest decline in the correction velocity with duration. The compression effect on the growth-plate following hemiepiphyseodesis can be modulated depending on the stiffness of the implant and amount of physis blocked [31]. PETS as with any other method of Epiphyseodesis does not only supress growth locally, but also causes a progressive transmission of compressive pressure in the growth-plate with time from medial to lateral. The longer the duration of the hemiepiphyseodesis, the greater is the 'compressive effect' spreading laterally in the growth-plate, thereby the growth suppression [32]. Martinez et al. experimentally induced a valgus deformity in rabbit limbs. He found following an initial increase of the valgus deformity which reached a plateau with time, that persisted until the end of growth. This is due to compression induced growth suppression beginning at the site of surgically induced growth suppression. A reversal of mechanism takes place in a hemiepiphyseodesis, where the correction slows with time.

There was a very high incidence (86.4 %) of a concurrent foot deformity due to the nature of diseases causing the deformity. Only 13.6 % of the limbs with distal tibial valgus deformity did not show any foot deformity although clinically a hindfoot valgus was noticed. In contradiction to previous studies which mention only pes planovalgus and clubfoot [2,4,33], a variety of foot disorders such as equino-varus, equino-valgus, calcaneo-valgus, pes cavus/ cavo-varus, equinus and over-corrected clubfoot deformity were found, highlighting the several aetio-pathological causes. A pes planovalgus deformity was the most common (43.2 %) and was spread out in all 5 groups, although it was seldom seen in MMC group. 67 % of the ankles in MMC group showed a calcaneo-valgus deformity characterised by the weakness of the calf-muscle. Considering the high incidence of foot deformities, one could speculate a causal relationship between foot deformity and the development of a distal tibial valgus deformity. In spite of 67 % of the idiopathic clubfeet having a ankle valgus deformity, Stevens et al. did not find any such causal association in their study of 33 patients [4]. Stevens et al. reported 11 foot procedures in 33 children, which were performed at the same time as the hemiepiphysiodesis of the distal tibia [3]. On contrary, we corrected the foot deformity in a second sitting at the time of explantation of PETS using several techniques ranging from arthroeresis, osteotomies to arthrodesis or combination techniques. The technique used to correct the foot surgery depended on the type and nature of the deformity, the pathology causing it, the flexibility of the deformity and the associated findings. Two exemplary cases are presented in Fig. 5. The results of this study would prompt us to look for an ankle valgus in every case of foot deformity. The effect of a foot deformity on the initiation or propagation the distal tibial valgus deformity and vice-versa must be investigated. Questions also remain unanswered as to how much deviation from normal LDTA is required to affect the function of the foot on long run and how the correction of the deformity affects the valgus foot deformity and function. These questions become important since 2 studies report 2 different normal values for LDTA; 89° ± 3° and 87.9° ± 2.2° [23,34].

The limitation of the study is its retrospective nature. Complications and recurrence/ rebound deformity were recorded but not further analysed, as this was not the purpose of the study. A large prospective multi-centre study must be done to determine true prevalence of the distal tibial valgus deformity with foot deformities in children and to determine the correction rates in most common aetiologies.

In conclusion, the aetiology of the distal tibial valgus deformity did not influence the correction rates but depended on age, the initial deformity of the distal tibia and duration of implantation. Considering the spectrum of foot deformities associated with distal tibial valgus deformity, ankle x-ray must be obtained in every case of foot deformity, especially a valgus foot deformity.

Ethical exemption for the study: YES

The study was exempted from ethical approval by the Bavarian medical council (Bayerische Landesärztekammer) due to the retrospective nature of the study (2023–1176).

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Declaration of Competing Interest

None.

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