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Do First Ray-Related Angles Change Following Subtalar Arthroereisis in Pediatric Patients? A Radiographic Study

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Abstract: Introduction: Subtalar Arthroereisis (STA) is a surgical intervention for pediatric flexible flatfoot (PFF), primarily targeting hindfoot alignment by limiting excessive subtalar eversion. However, its effects on forefoot parameters remain underexplored. This study aims to investigate radiological changes following STA in pediatric patients. Materials and Methods: A retrospective analysis was conducted on consecutive patients treated with STA for PFF. First ray-related angles, including Hallux Valgus Angle (HVA) and InterMetatarsal Angle (IMA), alongside hindfoot radiological parameters such as Meary, Calcaneal Pitch, and Costa Bartani angles, were assessed. Subgroup analysis by gender was performed, and correlations between demographic and pre-operative radiological parameters were examined. Results: Forty-one patients (81 feet) with a mean age of 11.6 years were included, with a mean follow-up duration of 6.4 months. No significant differences were observed in first ray-related angles pre- and post-operatively, with mean IMA changing from 7.97° to 7.18° and mean HV angles from 9.51° to 8.66°. Noteworthy improvements were seen in flat foot angles, including Meary, Calcaneal Pitch, and Costa Bartani angles, postoperatively. Age subgroup analysis revealed similar trends in IMA and HVA changes between Group A (operated before peak growth) and Group B (operated later). Higher preoperative angles tended to improve, while lower preoperative IMA and HVA tended to worsen postoperatively, all remaining within normal ranges. Conclusion: STA showed positive radiological outcomes for PFF treatment, while negligible changes in first ray-related angles were observed. Age subgroup analysis indicated similar trends regardless of operation timing. Higher preoperative angles tended to improve, while lower preoperative angles tended to worsen postoperatively, despite all falling within non-pathological ranges. Further research is warranted to confirm this correlation.

Keywords: subtalar arthrorisis; pediatric; flatfoot; hallux valgus angle; intermetatarsal angle

1. Introduction

Subtalar arthroereisis (STA) is one of the surgical options for Pediatric Flexible Flatfoot (PFF), offering various techniques and implant choices. The fundamental principle of STA involves limiting excessive subtalar eversion through the insertion of a device into the sinus tarsi, thereby preserving the natural alignment between the talus and calcaneus during bone remodeling [1].

Subtalar eversion is associated with forefoot deformities, such as hallux valgus, while PFF, characterized by hindfoot pronation during gait, disrupts midtarsal joint locking, resulting in increased intermetatarsal angle (IMA) and progressive instability of the first metatarsophalangeal joint [2].

Despite ongoing debates regarding the optimal management of PFF in children, numerous studies have documented satisfactory radiographic and clinical outcomes, along with high patient satisfaction rates, following STA [3]. Existing studies primarily focus on radiographic parameters of the hindfoot, overlooking potential changes in other areas. Given the influence of the subtalar joint on the midfoot and forefoot, it is plausible that correcting flatfoot deformity may result in changes in forefoot parameters, particularly at the first ray. While previous studies in adults have investigated radiographic changes in the first ray following flatfoot deformity correction [4,5], with controversial results, no similar investigations have been conducted in pediatric patients with flexible flatfoot.

This study aims to investigate whether there are changes in radiological parameters associated with first-ray deformity assessment following surgical correction of PFF using STA, focusing specifically on measuring HVA and IMA.

2. Materials and Methods

2.1. Study Design

A retrospective cross-sectional study was carried out on individuals who underwent STA using bioabsorbable polymeric endo-orthotic implants for symptomatic PFF. The research was conducted by the Declaration of Helsinki [6].

2.2. Patients

Inclusion criteria encompassed individuals who underwent STA with a bioabsorbable polymeric endo-orthotic implant (BFFI® Novagenit S.R.L., Italy) between April 2020 and March 2022 at a single institution. Eligible patients were aged between eight and fifteen years at the time of surgery, presenting symptomatic idiopathic flexible flatfoot as the primary indication.

Exclusion criteria included generalized joint hyperlaxity, neurogenic or neuromuscular disorders, posttraumatic flatfoot, rigid flatfoot, clubfoot sequelae, history of lower limb surgeries, comorbidities, Achille's tendon lengthening (ATL), and incomplete radiographic assessments.

The institutional database was systematically searched to identify eligible patients.

2.3. Implant Characteristics, Operative Technique, and Post-Operative Protocol

The utilized implant (BFFI® Novagenit Srl, Mezzolombardo (TN) Italy) was a bioabsorbable Poly-L-lactic acid (PLLA) endo-orthotic extra-articular device, classified as extraosseous sinus tarsi stents (EOTTS) [1]. The implant consisted of two components: an outer cylindrical body (plug) and an internal cylindrical body (screw). The surgical procedure adhered to the previously reported method [7]: a 1 cm incision was performed on the skin overlying the distal-central part of the sinus tarsi. Specialized blunt rods, incrementally increasing in size, were inserted in the same direction to prepare the sinus tarsi for implant placement. The diameter of the final rod matched the optimal size of the implant. Two small retractors were utilized to open the skin and retinaculum fibers, aiding in the placement of the outer cylinder of the implant using a universal introducer. Subsequently, the inner screw was inserted to expand and secure the implant.

Postoperatively, the feet were immobilized with a cast for the initial 4 weeks: no weight bearing was permitted for the first 2 weeks, followed by a progressive weight bearing over the subsequent 2 weeks. After 4 weeks, casts were removed, and patients were permitted to walk with regular shoes. The postoperative protocol advised against high-risk activities, jumping, and running for the first 5-6 months while permitting swimming and stationary biking.

2.4. Outcomes

The primary objective was to assess significant differences in forefoot radiological parameters pre and post-STA. HVA and IMA were measured on preoperative and 6-month follow-up radiographs under full weight-bearing conditions. Normal ranges for the parameters were defined as follows: HVA angles < 15° [8]; IMA angles < 9° [8].

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The secondary aim was to observe hindfoot radiological parameters modifications after STA, measuring Meary's Angle (MA), Calcaneal Pitch angle (CP), and Moreau Costa Bertani angle (MCB) on pre-operative and 6-month follow-up radiographs. Normal ranges for the parameters were defined as follows: MA [9] between -4° and +4°; CP [9] angle between 18 and 20°; MCB [10] angle between 115 and 125°.

The tertiary objective was to investigate any possible correlations between angular variations of the first ray and preoperative patients' characteristics. Patients were categorized into two groups based on surgery timing concerning peak growth, considering literature indicating peak growth velocity occurs at 11.5 years in females and 13.5 years in males [11]. Patients were classified as Group A if operated on before reaching peak growth and Group B if operated on later.

Measurements were conducted on preoperative and 6-month follow-up radiographs by two independent orthopedic surgeons, and interobserver reliability was evaluated. All measurements were performed on calibrated images with the PACS® system (GE-Healthcare, Chicago, IL, USA).

Six months was considered the minimum time to deem the condition stabilized and to allow weight-bearing without pain, as patients can typically resume sports activities at this time.

2.5. Statistics

The statistical unit in this study was represented by each individually operated foot. A post hoc power analysis was conducted to ensure a sufficient sample size for detecting clinically relevant differences between pre-and post-operative radiographic values. Assuming a significant difference in HVA measurement requires a minimum 5-degree difference [12], and in IMA measurement requires a minimum of +/-3.60 degrees [13] of difference between two measurements, a sample size of at least 70 feet was calculated.

Intra-observer reliability was assessed using intraclass correlation coefficients (ICCs) for continuous data, with a Cronbach's alpha exceeding 0.80 signifying perfect reliability. Cohen's kappa coefficient was calculated to measure inter-observer reliability. Variables resulting from radiological scores were reported as mean values, standard deviations (SD), and ranges.

The normality of the distribution for continuous variables was assessed using the Shapiro-Wilk test. After confirming normal distribution, paired T-tests were conducted to compare preoperative and final follow-up radiological parameters.

The potential correlation between the two variables was assessed using Pearson's test. Local estimated scatterplot smoothing was performed to visualize the correlation between the changes in radiological parameters between pre and post-operation and the pre-operative deformity or the age of the patients at the time of surgery.

Statistical significance was defined as $P < 0.05$, and all statistical analyses were performed using Jamovi software (The Jamovi project - jamovi Version 1.6, 2021).

3. Results

Forty-one patients, corresponding to 81 feet, were identified, and included in the study. Among these patients, 14 (34.1%) were females. The mean age of the population at the time of surgery was 11.6 ± 1.71 years, ranging from 8 to 15 years. Demographic details of the patients are presented in Table 1. All patients were treated by the same surgeon.

The average follow-up duration for radiological assessment was 6 months. Subgroup analysis was conducted, considering patients' gender, age, and growth potential at the time of surgery.

No intraoperative complications occurred. Regarding postoperative complications, three children experienced delayed wound healing, which resolved within a week after cast removal with no residual effects. Additionally, five children reported residual pain after cast removal, which had completely disappeared at the 8-week follow-up examination. There was no need for revision surgery among the patients. A total of 40 out of 41 patients (97.5%) underwent a single-stage bilateral procedure, while only 1 patient (2.5%) had surgery exclusively on the right foot.

Intra-observer reliability showed excellent values, with an ICC of 0.91. Inter-observer reliability was also excellent with a Cohen's kappa coefficient of 0.89.

Concerning the measurements of first ray-related angles, no significant difference was observed between the preoperative and postoperative measurements (Table 1).

Table 1. Differences in angle values between preoperative and postoperative measurement.

	Mean	Median	Standard deviation	Minimum	Maximum
Age	11.7	11.5	1.3	10	15
Meary difference	6.53	6.21	8.76	-7.1	28.4
Calcaneal pitch difference	2.76	0.4	7.92	-11.4	27.9
Costa Bartani difference	13.1	14.1	11.4	-6.8	33.7
Kite angle difference	3.94	4.18	5.76	-7.07	16.7
IMA preop	8.7	8.98	2.14	4.9	13.6
IMA difference	-0.994	-1.19	2.8	-9.11	4.9
HVA preop	13.6	11.6	10.8	1.3	47.6
HVA difference	-2.02	0.555	9.28	-30.9	6.99

Regarding hindfoot related angles, Meary, Costa Bartani e calcaneal Pitch showed an improvement but no significant difference was observed between the preoperative and postoperative measurements (Table 1).

For what may concern age differences, in group A, including patients before peak growth, the mean IM angle changed from 8.07 degrees (SD 3.04; range 3.10-23.4) to 7.16 degrees (SD 2.16; range 1.50-13.4) and the mean HV angle changed from 8.34 degrees (SD 7.95; range 0.00-47.6) to 8.02 (SD 8.05; range 0.0-42.8). In Group B, including patients after peak growth, the mean IM angle changed from 7.71 degrees (SD 2.13; range 4.80-13.6) to 7.22 degrees (SD 2.51; range 1.10-11.5) and the mean HV angle changed from 12.80 degrees (SD 8.24; range 1.40-31.90) to 10.5 (SD 6.85; range 1.0-22.70). None of these changes were statistically significant. Furthermore, no correlation was found between age and post-operative parameter changes, as observed in the locally estimated scatterplot smoothing (LOESS) plots, neither in male nor in female patients. Correlation between age, sex, and changes in IMA and HVA are shown in Figures 1 and 2 for girls and Figures 3 and 4 for boys.

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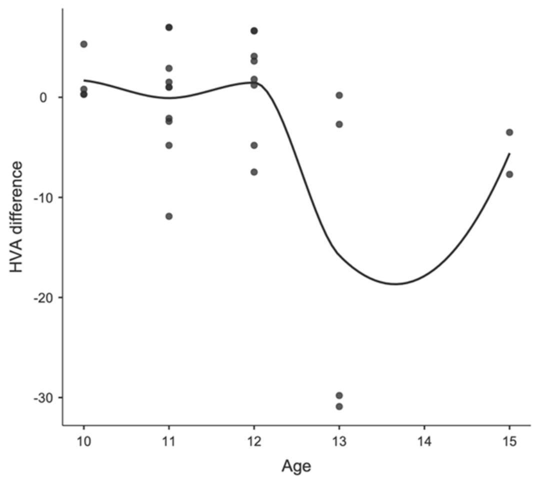

Figure 1. Correlation between age and HVA difference in girls.

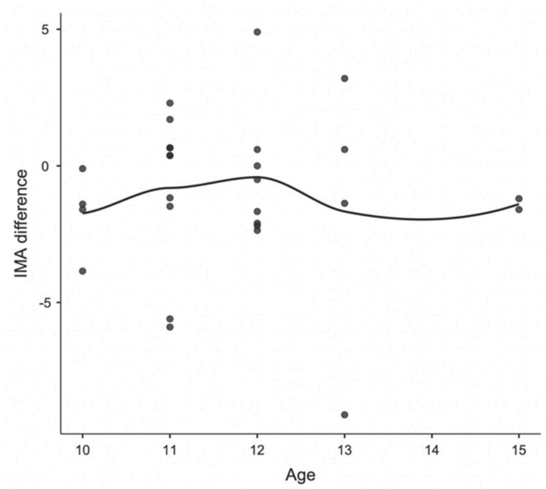

Figure 2. Correlation between age and IMA difference in girls.

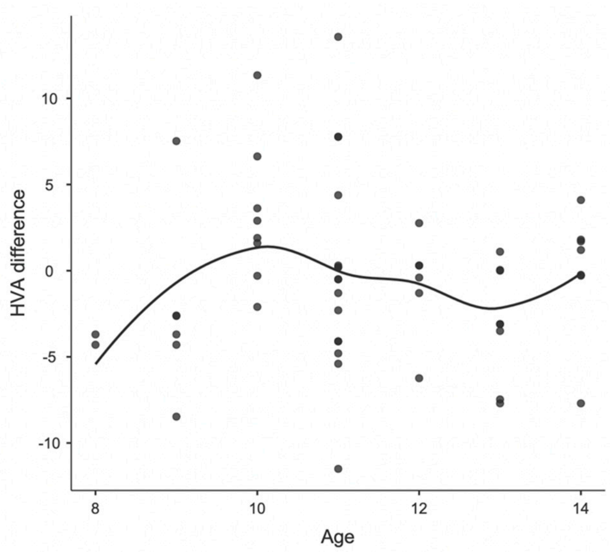

Figure 3. Correlation between age and HVA difference in boys.

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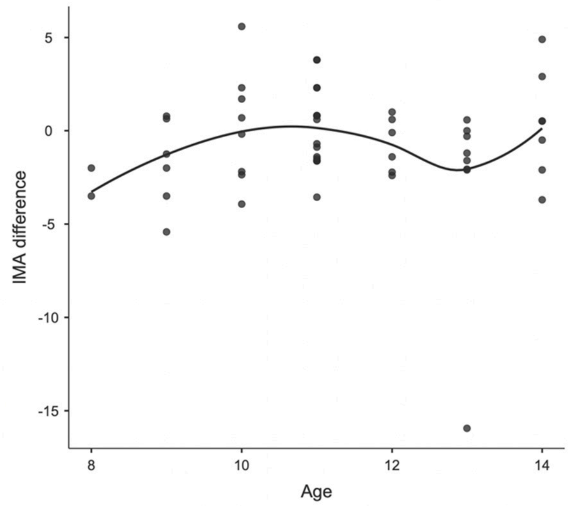

Figure 4. Correlation between age and IMA difference in boys.

Regarding a possible correlation between preoperative values and first-ray related angles, a significant correlation was observed between the pre-operative IMA and the change in IMA before and after surgery (see Figures 5 and 6), as well as between the pre-operative HVA and the change in HVA before and after surgery (Figures 7 and 8).

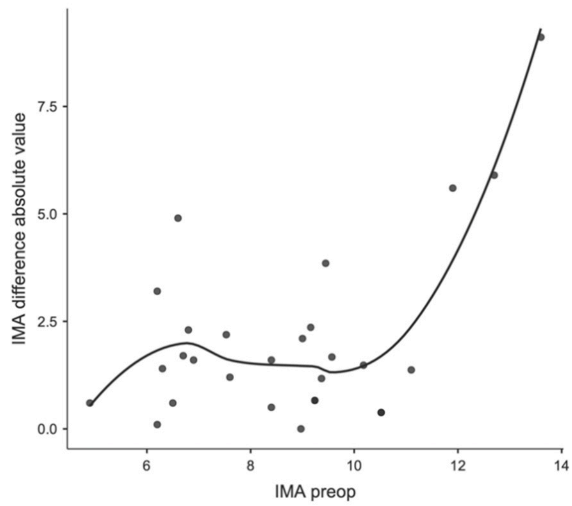

Figure 5. Locally estimated scatterplot smoothing between preoperative IMA and IMA change at the post-operative control, expressed as absolute values.

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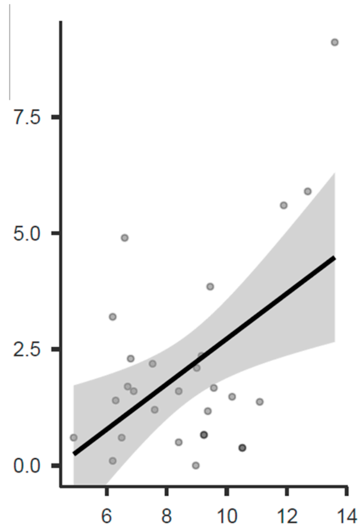

Figure 6. Correlation between preoperative IMA and IMA change at the post-operative control, expressed as absolute values.

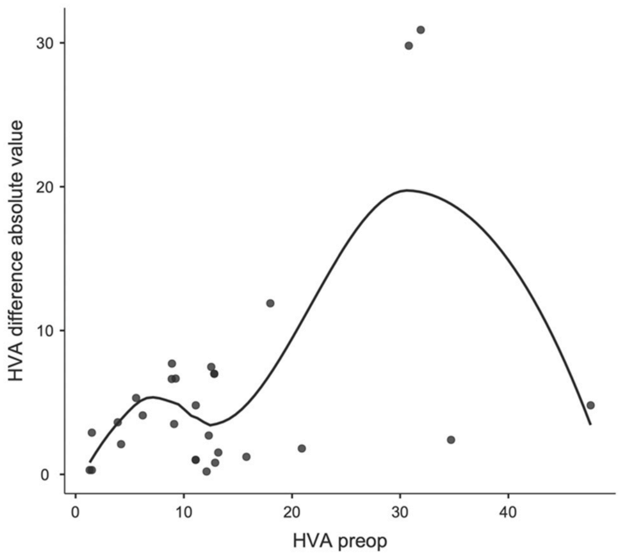

Figure 7. Locally estimated scatterplot smoothing between preoperative HVA and HVA change at the post-operative control, expressed as absolute values.

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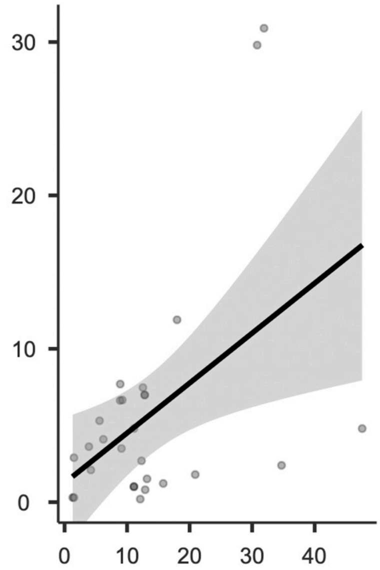

Figure 8. Correlation between preoperative HVA and HVA change at the post-operative control, expressed as absolute values.

4. Discussion

Flatfoot affects various angular parameters, yet no study has specifically investigated the impact of a surgical procedure for hindfoot correction in children as STA, on first ray-related radiological parameters.

Previous investigations in adults have shown varying outcomes regarding radiographic changes in the first ray following deformity correction surgery [4,5]. Wang et al examined patients with Adult Acquired Flatfoot Deformity (AAFD) who underwent soft tissue and bony procedures, including medializing calcaneal osteotomy and Cotton osteotomy [5]. They hypothesized that following AAFD surgery, reduction in HVA may occur due to first metatarsal bone supination. However, medializing calcaneal osteotomy may also potentially lead to HVA augmentation due to factors such as abductor hallucis weakening, while Cotton osteotomy may result in medial ray elongation. Postoperative findings revealed an improvement in the tibial sesamoid position, yet an average 4-degree increase in HVA was observed. These findings suggest that while initial first metatarsal bone supination post-surgery may be linked to medial soft tissue reconstruction and medializing calcaneal osteotomy, it may also result in HVA elevation due to abductor hallucis weakening and medial ray elongation. Additionally, the complex multiplanar corrective effects of these procedures may not be fully captured by two-dimensional radiographic parameters, and soft tissue imbalance could contribute to HV deformity pathogenesis. Matsumoto [4] retrospectively analyzed hallux alignment changes in 37 feet treated with double or triple arthrodesis of the hindfoot for AAFD. Unlike their counterparts, authors reported a reduction in the HVA following flatfoot correction surgery.

Unlike Matsumoto's findings, our study did not show significant changes in first ray-related angles following STA intervention in pediatric patients. However, subsequent analyses conducted on the outcomes revealed noteworthy findings warranting further reflection.

Intra-observer and inter-observer reliability demonstrated excellent values, comparable to those reported in previous studies [13]. No significant changes exceeding +/-3.60 degrees in IM angles and +/-5 degrees in HV angles were observed. This cutoff was chosen to minimize X-ray misclassification, ensuring a misclassification risk of less than 5% [12,13]. While this conservative approach may reduce statistical sensitivity for significance, we emphasize the importance of maintaining scientific rigor in such studies.

The absence of statistically significant gender differences in angular parameter variations aligns with findings from other studies, which have reported a slightly better improvement in girls.

Similarly, we also observed a trend towards greater improvement in girls, although this trend was not statistically significant in our study [3].

Regarding the correlation between preoperative HVA and IMA values and post-intervention correction, lower initial angle values appear to be associated with a slight worsening postoperatively, while higher preoperative angular values tend to improve outcomes. These values are observed in individuals within the normal range, and in no case have they led to an increase in HVA beyond pathological values. Conversely, preoperative HVA and IMA values close to the threshold of pathology tend to exhibit higher postoperative correction values. The observed worsening of HVA values may be attributed to hallux abductor shortening due to hindfoot inversion secondary to STA, thereby reducing the varus action of this muscle. However, this consequence seems to be less influential in cases of more pronounced deformity at the first ray level: in this scenario, the beneficial effect of first ray supination likely outweighs the de-tensioning effect on the hallux abductor.

Finally, it is essential not to overlook how even minor variations in radiographic projection orientation or patient positioning during radiographic examination can influence the measurements obtained, regardless of the accuracy and reproducibility of the measurements taken. In this radiographic bias, due to purely geometrical reasons, larger angles are more affected, and therefore, they are more susceptible to influence. Hence, it is not impossible to assert that one of the reasons why larger preoperative angles are associated with greater variations between pre and postoperative states may partly be attributed to this factor. However, the fact that almost all patients with larger preoperative deformities experienced a reduction in angular parameters postoperatively suggests a genuine improvement in deformity only for this subgroup of individuals.

Limitations

Limitations of this study primarily stem from the relatively short follow-up period post-surgery, which is nonetheless consistent with similar studies by Wang and Matsumoto [4,5]. Additionally, after 6 months, patients were able to resume high-impact sports, suggesting that the clinical condition was sufficiently stabilized for a radiological evaluation. However, assessing the same angles at longer follow-up periods would be of interest. Furthermore, the study is constrained by its small sample size and the retrospective design. Despite conducting a post hoc power analysis to ensure an adequate sample size, limitations persist due to the focus on angular values and the absence of evaluation of sesamoid bone position. Although the intervention was expected to reduce first ray-related radiological deformities, no statistically significant differences were observed between preoperative and postoperative measurements. However, a significant correlation was found between preoperative deformity values and their change after surgery, suggesting that the intervention may primarily affect patients with pathological values. Furthermore, minor changes in radiological projections may have a disproportionate impact on higher radiological deformities, posing a challenge in accurately assessing outcomes. While weight-bearing foot CT scans may offer a solution in a scientific context, their practicality in clinical settings remains debatable.

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5. Conclusions

STA showed positive radiological outcomes for PFF treatment, while negligible changes in first ray-related angles were observed. Age subgroup analysis indicated similar trends regardless of operation timing. Higher angles tended to improve, while lower preoperative angles tended to worsen postoperatively, despite all falling within non-pathological ranges. Further research is warranted to confirm this correlation.

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