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Long Hallucal Tendon Force Vectors and First Metatarsophalangeal Deformity After Hallux Valgus Surgery

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Abstract

Background: Recurrence is one of the most common complications following hallux valgus surgery. Moreover, hallux varus occurs in cases of overcorrection. We aimed to quantitatively measure, using radiographic examination, the dynamics of the soft tissues that act on deformities (recurrence of valgus and occurrence of varus) after the surgery.

Methods: This retrospective single-institution study included 60 patients (98 feet) who underwent hallux valgus surgery between 2009 and 2018. According to radiographic findings of the foot under weightbearing conditions at postoperative month 1, we examined the tendons' pathway and calculated the forces on the first metatarsophalangeal joint, which we termed the deformity force angle (DFA). We compared whether there was a significant difference in DFAs between the groups in which deformities occurred and those in which deformities did not occur after correction. In addition, the DFA was compared to known radiographic measurements of hallux valgus recurrence (hallux valgus angle, distal metatarsal articular angle, intermetatarsal angle, and sesamoid position) to assess association with recurrence.

Results: We observed a significant difference in the DFA between patients with and without hallux valgus recurrence ($P < .001$) and between those with and without hallux varus ($P < .001$) based on standing radiographs taken at a minimum of 6 months postoperation. For predicting the deformities, the areas under the curve were 0.863 (hallux valgus recurrence) and 0.831 (hallux varus occurrence), respectively, which was greater than other factors evaluated. The DFA values greater than 9.5 degrees and less than 5.5 degrees were associated with the recurrence of valgus and occurrence of varus, respectively.

Conclusion: In our study, DFA was associated with hallux valgus recurrence when it exceeded 9.5 degrees and hallux varus when it was less than 5.5 degrees. Moreover, in the hallux valgus surgery we performed, a DFA from 5.5 to 9.5 degrees appeared to be a "safe zone" for preventing early deformity after surgery.

Level of Evidence: Level III, prognostic.

Keywords: hallux valgus, hallux varus, tendons, metatarsophalangeal joint, recurrence, radiography, correction

Introduction

The recurrence of hallux valgus is a common complication after corrective hallux valgus surgery. Moreover, hallux varus occurs in cases of overcorrection. Reportedly, the recurrence of hallux valgus occurs in 4% to 25% of cases,[1,7,11,16-20] whereas hallux varus occurs in 2% to 17% of cases.[3]

Various factors have been associated with the recurrence of hallux valgus, some of which can be assessed radiographically, namely, preoperative hallux valgus angle (HVA),[12] insufficient HVA correction,[19] preoperative intermetatarsal angle (IMA),[13] preoperative and postoperative sesamoid position,[11] preoperative distal metatarsal articular angle (DMAA),[17] and a round-shaped metatarsal head.[10] All these risk factors focus only on the radiographically visible skeleton. Thus, the influence of the soft tissues is not properly considered in predicting postoperative complications or identifying the correction criteria for preventing the same.

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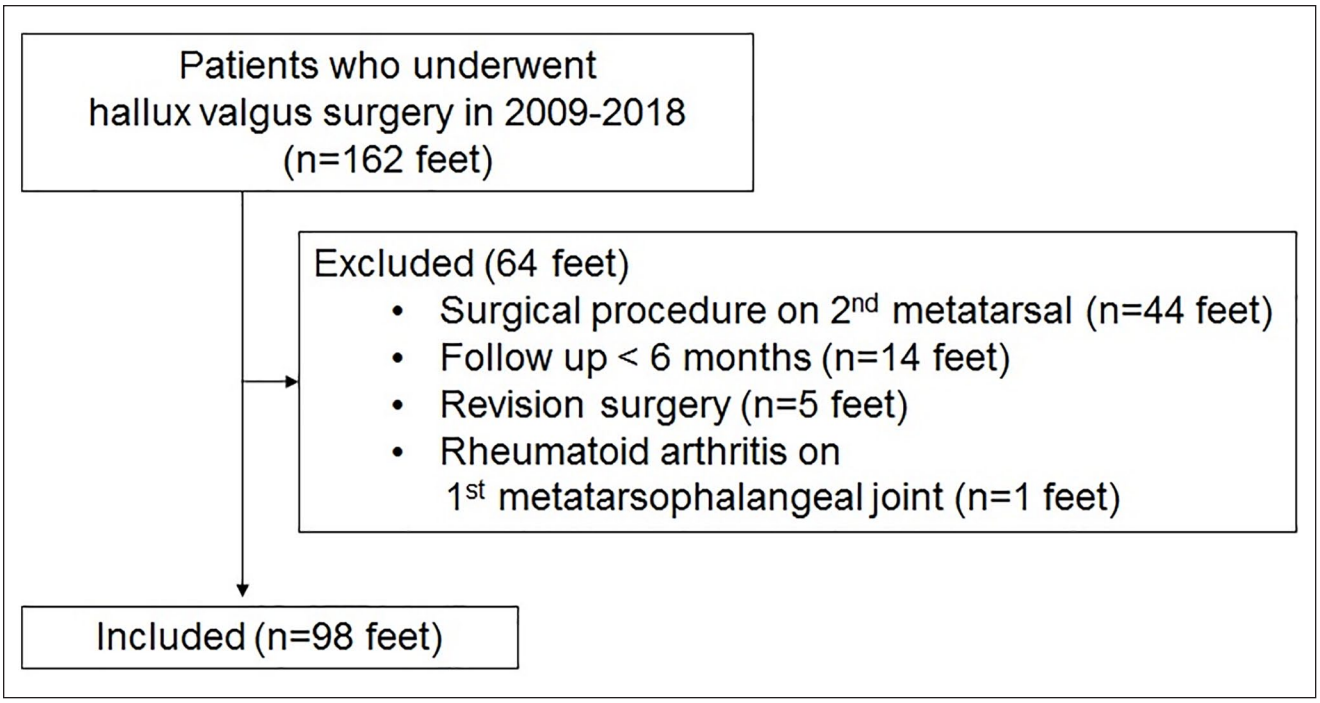

Figure 1. The enrollment of patients.

We hypothesized that tendon force to tilt the hallux to one side after hallux valgus surgery is one of the factors in the recurrence of hallux valgus or development of hallux varus after the surgery. Thus, this study aimed to measure the tendon force through radiographic examination to prove the above hypothesis, and consequently predict and prevent the above-mentioned adverse complications.

Material and Methods

The present study was approved by an institutional review board (number 2020-1399). This retrospective single-institution study included 104 patients (162 feet) who underwent hallux valgus surgery between 2009 and 2018. The inclusion criteria were age >18 years, previous hallux valgus surgery, and availability of more than 6 months for follow-up data. Exclusion criteria were (1) patients who received any other form of surgical procedure (eg, Weil osteotomy, hammer toe operation) on the lesser toes of the same foot to prevent secondary effects on the measured angles[6]; (2) those with soft tissue problems (history of tendon rupture, genetic diseases); and (3) those having cerebral palsy, poliomyelitis, rheumatoid arthritis, diabetes-related Charcot arthropathy, hallux rigidus, or infection.

Finally, 60 patients (98 feet) were included in the analysis, after excluding 44 patients (64 feet) who did not meet the inclusion criteria (Figure 1).

Operative Technique

All surgeries were performed according to a standardized protocol, as described below, by one orthopaedic surgeon with a fellowship in foot and ankle surgery.

The patient was placed in the supine position. Through the first web space dorsal approach, lateral release of the first metatarsophalangeal joint was done initially with adductor tenotomy and metatarsal-sesamoid capsular release. The degree of lateral release was such that the first toe was slightly deviated inward from the neutral position to by about 5 degrees varus, and the final check of the balance was confirmed after all procedures were completed. The first ray alignment became neutral in simulated weightbearing conditions. With an additional medial approach, a T-shaped incision on medial capsule was made and a 5- to 8-mm wide vertical limb of the capsule was removed. Bunionectomy was performed using an oscillating microsaw, cutting parallel to the medial aspect of the first metatarsal shaft. After this soft tissue procedure, distal chevron metatarsal osteotomy was performed and the metatarsal head was translated laterally by 5 to 9 mm. For patients with a large DMAA, its simultaneous correction was attempted by rotating the distal fragment medially. To fix the displaced distal fragment, two to three 1.1-mm Kirschner wires were inserted from a point 2 cm proximal to the osteotomy site, according to intraoperative stability of fixation. Additional capsulorrhaphy was performed with the pronated toe in

supination. If residual deformity persisted after distal chevron metatarsal osteotomy and accompanying soft tissue procedures, Akin phalangeal osteotomy was performed, based on the judgment of the surgeon. For patients with residual toe pronation, complete osteotomy and reduction of the pronated toe was performed. The surgery was completed after checking for residual deformity or soft tissue imbalance.

Radiographic Evaluation

All radiographic examinations were performed in a single hospital. Foot anteroposterior (AP) radiographs were taken preoperatively and postoperatively at 1, 3, and 6 months and at 1 year.

Preoperative HVA,[12] DMAA,[17] IMA,[13] and sesamoid bone position[11] were measured on foot AP radiographs taken the day before surgery with the patients in a weightbearing state. In addition, the postoperative sesamoid bone position, DFA, was measured at 1 month postoperatively, and the final HVA was measured on foot radiographs taken at the outpatient clinic at the last follow-up visit to assess the presence of a deformity (hallux valgus recurrence or hallux varus occurrence). Minimum follow-up was 6 months. All measurements were performed by weightbearing radiographs.

The HVA, IMA, DMAA are defined in Figure 2. The sesamoid position was graded from 1 to 7 as proposed by Hardy and Clapham.[4]

The final radiograph measurements after surgery of HVA greater than 15 degrees were categorized as hallux valgus recurrence,[15] whereas measurements less than 0 degrees were categorized as hallux varus occurrence.[3]

Calculation of the Effects of Soft Tissue Based on the Deformity Force Angle

During the surgical procedure, the capsule and ligaments were balanced, and in the process, the adductor hallucis muscle was tenotomized. On the other hand, when the extensor hallucis longus (EHL) is displaced to one side and contracts, it not only extends the toe but also tends to adduct or abduct it, thus making a deformation toward hallux valgus or varus. The flexor hallucis longus (FHL) tendon, which retains its relationship with the sesamoids, moves laterally or medially while becoming a dynamic deforming force.[2] Therefore, based on the judgment that the flexor and extensor hallucis longus muscles play a major role in the deformation, the force of the flexor and extensor hallucis longus muscles acting on the first metatarsophalangeal joint was measured through foot AP radiograph with weightbearing. The 2 tendon tracts on the midfoot under a weightbearing state were drawn using ultrasonography findings (Figure 3A and B). After performing skin marking by placing a wire on the tendon tracts, a foot AP radiograph image was obtained in the weightbearing state, which confirmed that the FHL and EHL tendon tracts passed through the center of the lateral cortex of the medial cuneiform of the midfoot (Figure 4A and B). Finally, the 2 tendons' tracts could be inferred on weightbearing radiographs by connecting the center of the lateral cortex of the medial cuneiform (Figure

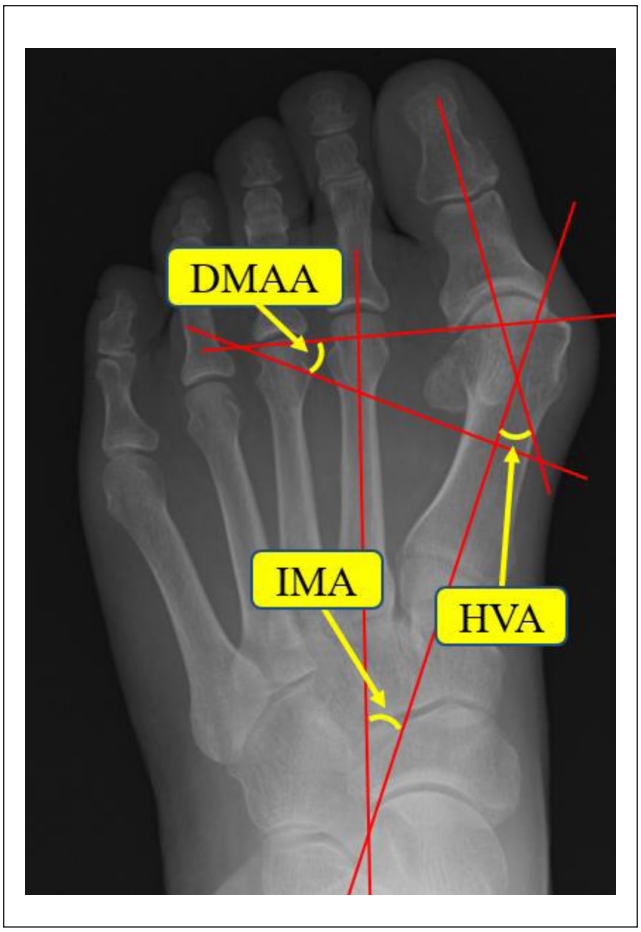

Figure 2. Radiographic assessment of hallux valgus. The HVA was defined as the angle between the longitudinal axis of the first metatarsal bone and that of the proximal phalanx. The preoperative longitudinal axis of the first metatarsal bone and proximal phalanx was defined as the line connecting the center of the proximal diaphysis and the distal diaphysis. The postoperative longitudinal axis of the first metatarsal bone and proximal phalanx was defined as the line connecting the center of the proximal articular surface and the center of the distal articular surface. The IMA was defined as the angle between the longitudinal axis of the first and second metatarsals. The longitudinal axis of the second metatarsal bone was defined as the line connecting the center of the proximal and distal diaphysis. The DMAA was defined as the angle between a line perpendicular to the longitudinal axis of the first metatarsal and a line delineating the orientation of the articular surface of the metatarsal head. AP, anteroposterior; DMAA, distal metatarsal articular angle; HVA, hallux valgus angle; IMA, intermetatarsal angle.

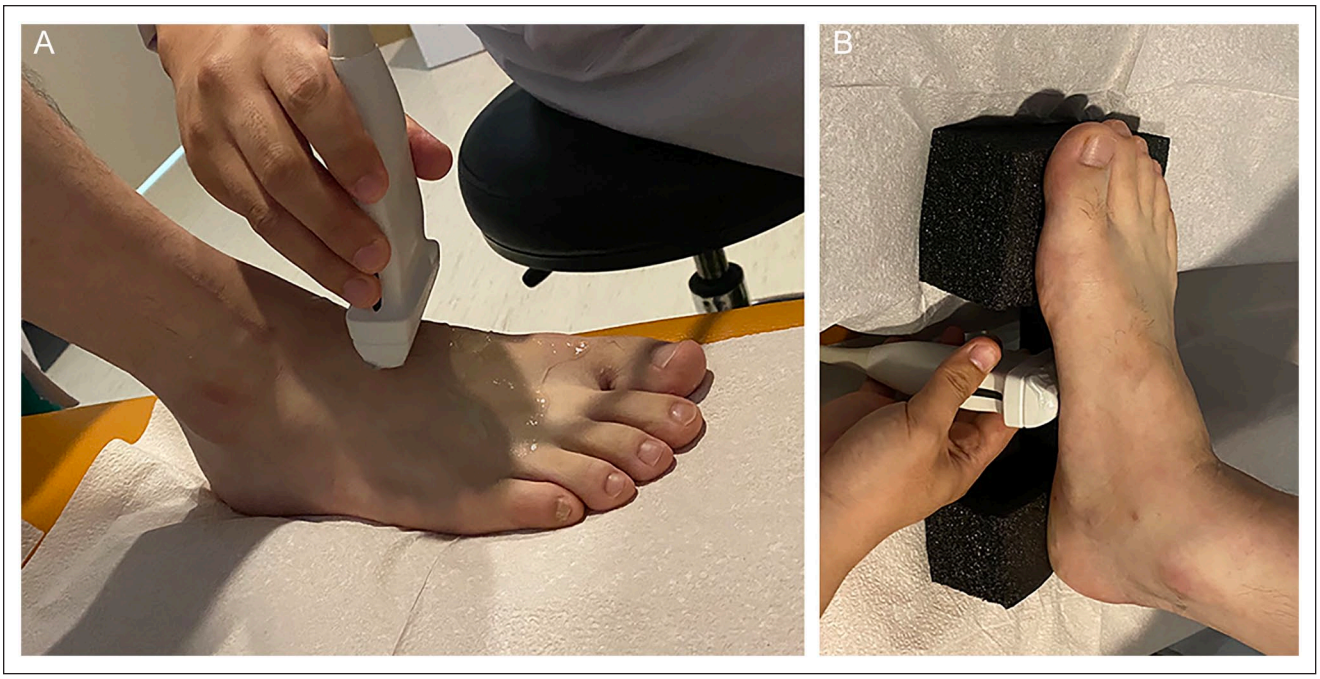

Figure 3. (A) Clinical image obtained by performing ultrasonography of EHL under weightbearing state. The EHL tract was drawn using these ultrasonography findings. (B) Clinical image obtained by performing ultrasonography of FHL under weightbearing state. The FHL tract was drawn using these ultrasonography findings. EHL, extensor hallucis longus; FHL, flexor hallucis longus.

5, point b) and the center of the base of the first distal phalanx (Figure 5, point a), the insertion site of the 2 tendons. The axis of the first toe was defined as the line connecting the center of the base of the first distal phalanx and the center of the first metatarsal head (Figure 5, point c). A geometric device was used to determine the best-fit circle (circle Q) that matched the metatarsal head, and then the center was found. Circle Q was defined as a circle that has 3 points of contact with the metatarsal head, including the medial edge, the top, and the lateral edge.[10] The deformity force angle (DFA) was defined as the angle between these 2 lines (Figure 5). The DFA measured as above was used to calculate the torque affecting the hallux.

$$\begin{aligned} Torque \;=\; & distance\ between\ the\ force\ application \\ & point\ and\ the\ center\ of\ rotation\ (moment \\ & arm) \times force\ acting\ on\ the\ axis\ at\ 90^\circ \\ & [muscle\ force \times sine(DFA)] \end{aligned}$$

The distance between the force application point and the center of rotation was defined as the length of "the axis of the first toe" (Figure 5). In the case of the force acting on the axis at 90 degrees, the force of the EHL, FHL (Figure 5, dashed arrow), was multiplied by a sine(DFA) (Figure 5, dotted arrow).

This study excluded patients with muscle force problems, including soft tissue disorders, cerebral palsy, and poliomyelitis. Therefore, it was assumed that the amount of muscle force would not cause a significant difference. Additionally, to obtain a similar value of torque that can be applied in clinical practice, the torque was calculated through the length of "the axis of the first toe" (L) × sine(DFA) while excluding the size of muscle force that is difficult to measure in clinical practice. To make the calculation simpler, the value of the length of "the axis of the first toe" (L) × sine(DFA) was approximated from the DFA using the mathematical calculations (see Appendix). Through this process, it was possible to conclude that DFA can indicate the approximate torque.

Statistical Analysis

Each measurement was checked by 2 orthopaedic surgeons using a double-anonymized method. To evaluate the reliability of the measured values, each evaluator measured each value twice and calculated the intraclass correlation coefficients. The measured values of the first and second evaluators were compared to calculate the interclass correlation coefficients. The calculated correlation coefficients were classified as very low (less than 0.25), low (0.26-0.49), moderate (0.50-0.69), high (0.70-0.89), or very high (more than 0.90).[9]

To assess the differences in age, follow-up duration, and sex, t and χ^2 tests were used. The t test was used to compare

Figure 4. AP radiograph image of the weightbearing foot. (A) The wire was placed on the EHL tract and a weightbearing foot AP radiograph image was obtained, which confirmed where the EHL passed on the midfoot. The black dots indicate the proximal and distal points of the line drawn using ultrasonography findings, and the arrow indicates the center of the lateral cortex of the medial cuneiform. (B) The wire was placed on the FHL tract and a weightbearing foot AP radiograph image was obtained, which confirmed where the FHL passed on the midfoot. The black dots indicate the proximal and distal points of the line drawn using ultrasonography findings, and the arrow indicates the center of the lateral cortex of the medial cuneiform. AP, anteroposterior; EHL, extensor hallucis longus; FHL, flexor hallucis longus.

differences in each index (HVA, IMA, sesamoid position, DMAA, DFA) between the recurrence and nonrecurrence groups. And independently, the differences in DFA between the groups with and without hallux varus were also compared using the *t* test. The level of significance was set at $P < .05$.

The receiver operating characteristic (ROC) curves comparing sensitivity and specificity were used to determine the optimal reference values that best predicted postoperative hallux valgus or hallux varus. The cut-off values were determined based on the largest sum of the sensitivities and specificities. Higher areas under the ROC curves (AUCs) were considered to demonstrate better discriminatory abilities as follows: excellent discrimination, AUC ≥ 0.90; good discrimination, $0.80 \leq$ AUC < 0.90; fair discrimination, $0.70 \leq$ AUC < 0.80; and poor discrimination, AUC of < 0.70.[8] We also compared AUCs of DFA with other factors that showed significant results as predictors based on the

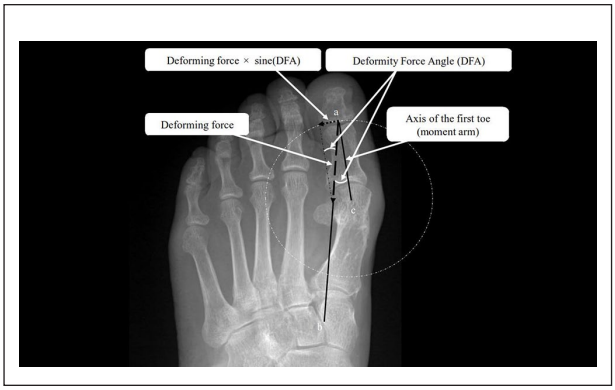

Figure 5. AP radiograph of the weightbearing foot. The force acting on the axis of the big toe at 90° is measured by multiplying the muscle force (dashed arrow) by sine(DFA) (dotted arrow), while the torque is calculated by multiplying the force by the length of the moment arm, that is, the length of the axis of the first toe. AP, anteroposterior; DFA, deformity force angle; EHL, extensor hallucis longus; FHL, flexor hallucis longus.

bootstrap test. All statistical analyses were performed using the R software (version 4.0.5).

Results

Postoperatively, the rate of hallux valgus recurrence was 21% (21 feet of 98 feet), the rate of hallux varus was 14% (14 of 98 feet), and there were no cases of AVN, pin loosening, or nonunion based on the last radiograph. The intra- and interobserver reliabilities of the radiographic measurements are shown in Table 1. The preoperative sesamoid position showed high interobserver and very high intraobserver reliabilities, whereas the postoperative sesamoid position showed moderate interobserver and high intraobserver reliabilities. Other factors showed very high reliabilities according to the correlation coefficients.

There were no significant intergroup differences in demographic data (Table 2). The mean follow-up period was 21.2 (range, 7.4-90.6) months. The preoperative HVA and DFA differed significantly between the hallux valgus nonrecurrence and recurrence groups ($P = .048$ and $P < .001$, respectively) (Table 3). Regarding the preoperative HVA, which showed a significant difference, the cutoff was 38.5 degrees and the AUC of the ROC was 0.651. In the case of DFA, the cutoff was 9.5 degrees and the AUC was 0.863. The *P* value for comparing the 2 AUCs was 0.008, where under the alternative hypothesis, the true difference in AUC is not equal to 0.

The DFA differed significantly between the hallux varus nonoccurrence and occurrence groups ($P < .001$) (Table 3). The cutoff values obtained through the ROC analysis was 5.5 degrees, with an AUC of 0.831.

Table 1. Intra- and Interobserver Reliabilities of Radiographic Measurements.

	Interobserver Reliability (95% CI)	Intraobserver Reliability (95% CI)
Preoperative HVA	0.967 (0.927-0.982)	0.989 (0.979-0.994)
Preoperative DMAA	0.961 (0.946-0.972)	0.994 (0.992-0.996)
Preoperative sesamoid position	0.772 (0.696-0.832)	0.913 (0.881-0.937)
Preoperative IMA	0.904 (0.739-0.952)	0.977 (0.961-0.985)
Postoperative sesamoid position	0.610 (0.491-0.762)	0.798 (0.729-0.851)
Postoperative DFA	0.954 (0.936-0.967)	0.953 (0.935-0.966)
Final HVA	0.902 (0.865-0.929)	0.988 (0.984-0.992)

Abbreviations: DFA, deformity force angle; DMAA, distal metatarsal articular angle; HVA, hallux valgus angle; IMA, intermetatarsal angle.

Table 2. Demographic Characteristics of Patients and Statistical Comparison.[a]

	Nonrecurrence	Recurrence	*P* Value
Hallux valgus, n	77	21	
Age, y	64.55 ± 4.84	63.29 ± 3.58	.269
Male	2	3	.110
Female	75	18	
Follow-up duration, mo	20.2 ± 13.2	22.0 ± 11.8	.572
Hallux varus, n	84	14	
Age, y	66.36 ± 6.30	63.93 ± 4.22	.184
Male	4	1	.708
Female	80	13	
Follow-up duration, months	22.4 ± 11.0	20.3 ± 13.1	.581

[a]Values are given as mean ± SD or absolute number, as appropriate.

Table 3. Results of Risk Factors for Hallux Valgus Recurrence and Hallux Varus Occurrence.[a]

	Nonrecurrence Group	Recurrence Group	*P* Value
Hallux valgus			
HVA	32.66 ± 8.05	38.14 ± 11.34	**.048**
IMA	15.56 ± 4.51	14.76 ± 5.06	.486
Preoperative sesamoid position	6.14 ± 1.00	6.14 ± 1.01	1.000
Postoperative sesamoid position	2.70 ± 1.37	3.00 ± 1.30	.373
DMAA	18.48 ± 11.85	21.81 ± 9.95	.242
DFA	6.18 ± 2.84	11.05 ± 3.56	**<.001**
Hallux varus			
DFA	4.00 ± 1.92	7.76 ± 3.53	**<.001**

Abbreviations: DFA, deformity force angle; DMAA, distal metatarsal articular angle; HVA, hallux valgus angle; IMA, intermetatarsal angle.
[a]Values are given as mean ± SD or absolute number, as appropriate.

Discussion

Postoperatively, the rate of hallux valgus recurrence was 21% (21 of 98 feet), the rate of hallux varus was 14% (14 of 98 feet). Although the incidence rate of hallux varus falls within the range because the incidence rate ranges from 2% to 17% depending on the study,[3] it cannot be denied that it is a high rate. However, even if 5 of 14 patients were defined as hallux varus, it was only –1 degree (3 feet) or –2 degrees (2 feet), and all 5 patients were satisfied with the outcome. And only 7 of 14 cases exceeded –5 degrees.

The occurrence of hallux valgus is known to be caused by various extrinsic (footwear, occupation, trauma) and intrinsic (hereditary, pes planus, hypermobility of the metatarsocuneiform joint, ligamentous laxity, Achilles tendon contracture, miscellaneous factors) causes, and accordingly,

various anatomic and radiographic factors should be considered.[2] Anatomically, factors acting on the hallux (muscles of the foot, ligaments, capsule)[14] and radiographically, HVA,[12] DMAA,[17] IMA,[13] sesamoid position,[11] and round-shaped metatarsal head[10] can be considered.

Hallux varus can rarely be congenital. But more frequently, it is a deformity acquired after either a surgical procedure or trauma.[2] In the case of iatrogenic hallux varus that occurs after hallux valgus surgery, the malalignment of EHL and FHL is known to play a role, and a transfer operation of EHL and FHL is sometimes performed if necessary.

Kaufmann et al found a linear correlation between preoperative deformity in terms of IMA, HVA, and DMAA and a loss of correction.[6] Also, Okuda et al[11] identified a relationship between incomplete reduction of the sesamoids and recurrence of hallux valgus, and Okuda et al[10] suggested that a positive round sign can be a risk factor for the recurrence of hallux valgus.

However, there has been no study on radiographic evaluation of EHL and FHL, which is considered to act as a cumulative deforming force of the metatarsophalangeal joint after hallux valgus surgery. Therefore, the direction of EHL and FHL in the radiographic examination, and its correlation with recurrence of hallux valgus and occurrence of hallux varus, were evaluated in this study.

Among the previously known risk factors for hallux valgus recurrence, the preoperative HVA and DFA differed significantly between the recurrence and nonrecurrence groups. Among them, DFA, newly defined in this study, better predicted hallux valgus recurrence than preoperative HVA. Furthermore, DFA correlated with the occurrence of postoperative hallux varus and had good predictive power. The valgus recurrence was predicted if DFA exceeded 9.5 degrees, whereas a varus occurrence was predicted if DFA was less than 5.5 degrees. Moreover, DFA can be checked by simulated weightbearing radiograph imaging before terminating the surgery. If DFA is not appropriate, reoperation or partial correction of the DFA through a web spacer could be considered. Correction of the DFA value to 5.5 to 9.5 degrees is correlated with a low occurrence of complications; this can help prevent deformities.

The DFA is also a valuable predictor when considering its high reproducibility. Although the sesamoid position before and after surgery showed moderate to high reliability, it was lower than other factors. For DFA, both interobserver and intraobserver reliability were very high at 0.954 and 0.953, respectively. Thus, DFA is a highly reproducible and useful factor. This was possible because the reference point on the radiograph was clear and the measurement process was simple.

Many measurement methods for the HVA, IMA, and DMAA have been proposed; in particular, the reference point of measurement differs before and after osteotomy.[16] This may cause confusion in the clinical application or further research on these values. However, in the DFA, the center of the base of the first distal phalanx, the center of the first metatarsal head, and the midpoint of the lateral cortex of the medial cuneiform are reference points that are not affected by surgery (eg, Akin, scarf, Ludloff, or chevron osteotomy); thus, there is no confusion in measuring the reference value. These characteristics of DFA provide a greater advantage than other factors (HVA, IMA, and DMAA) in terms of reflecting the hallux state after surgery.

One limitation of this study was that, as a simplified and 2-dimensionally calculated value, our consideration of other associated factors (pronation of hallux, shape of metatarsal head, the soft tissue constraints of the FHL and the EHL, etc) was insufficient. As the tracts in the midfoot where FHL and EHL passed were difficult to confirm using anatomy textbooks or previous clinical papers (cadaver study, image study, and so on), we conducted an additional study to determine where they passed. However, owing to the complexity of the process, it was not possible to proceed with the evaluation of all the feet, and the tracts of FHL and EHL were confirmed in only 11 representative adults. In the future, large sample studies are needed to confirm the tracts of EHL and FHL under weightbearing conditions. In the case of hallux valgus surgery patients in this study, there were many cases of follow-up loss if there was no discomfort. Accordingly, a rather short minimum follow-up period of more than 6 months was imposed. However, the loss of HVA or IMA correction after 3 months is known to be minor.[5,6] In this study, a group of patients with a follow-up period longer than 6 months, which is twice as long as this, was included; hence, it will not significantly affect the results. And among the factors known to be associated with the recurrence of hallux valgus, only limited representative factors known were included, but not all factors were included. Finally, as discussed above, DFA was measured without the size of the force, which is difficult to measure for each patient. Therefore, it may be appropriate to say that DFA represents the direction of the force rather than measuring the force itself. Nonetheless, it can ultimately predict postoperative hallux varus or its recurrence, regardless of whether it represents the force itself or the direction of the force. The retrospective nature of this study, the relatively small sample size, and the large SD of DFA results also were limitations of this study. However, when looking at the ROC curve and AUC, it was found that DFA was acting appropriately as a factor. And in addition to the *t* test, Wilcoxon signed rank test also showed significant difference between groups ($P < .001$). We think that a randomized controlled trial with a large sample is needed in the future.

In summary, in our cohort with the surgical technique we used to treat HV, DFA appeared to be a meaningful factor correlating with postoperative recurrence of hallux valgus or development of hallux varus, with cutoff values of 9.5 and 5.5 degrees, respectively.

Ethical Approval

Ethical approval for this study was obtained from an institutional review board (number 2020-1399).

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. ICMJE forms for all authors are available online.

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Supplemental Material

Supplementary material is available online with this article.

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