Fourth-Generation Percutaneous Transverse Osteotomies for Hallux Valgus

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Background: Fourth-generation percutaneous, or minimally invasive, hallux valgus surgery utilizes a transverse osteotomy to achieve deformity correction. There are only a small number of studies reporting the clinical and radiographic outcomes of transverse osteotomies, many of which have methodological limitations such as small sample size, limited radiographic follow-up, or use of non-validated outcome measures. The aim of this study was to provide a methodologically robust investigation of percutaneous transverse osteotomies for hallux valgus deformity.

Methods: We studied a prospective series of consecutive patients undergoing fourth-generation metatarsal extracapsular transverse osteotomy performed by a single surgeon (P.L.) between November 2017 and January 2023. The primary outcome was clinical foot function assessed using the Manchester-Oxford Foot Questionnaire (MOXFQ), a validated patient-reported outcome measure. Secondary outcomes included the radiographic deformity (the hallux valgus angle [HVA], 1-2 intermetatarsal angle [IMA], and sesamoid position) assessed according to American Orthopaedic Foot & Ankle Society (AOFAS) guidelines as well as a visual analog scale for pain and radiographic evidence of deformity recurrence (defined as an HVA of >20° at final radiographic follow-up). P values of <0.05 were considered significant.

Results: Seven hundred and twenty-nine feet (483 patients; 456 female and 27 male; mean age, 57.9 ± 11.9 years) underwent fourth-generation metatarsal extracapsular transverse osteotomy. Radiographic data were available at a vminimum of 12 months postoperatively for 99.7% of the feet, which were followed for a mean of 2.6 ± 1.3 years (range, 1.0 to 5.7 years). There was a significant improvement ($p < 0.05$) in both the HVA (from 29.5° ± 8.5° preoperatively to 7.3° ± 6.7° at final follow-up) and the IMA (from 12.9° ± 3.3° to 4.6° ± 2.5°). All MOXFQ domains showed significant improvement ($p < 0.05$), with the MOXFQ Index improving from 36.9 ± 18.9 to 13.4 ± 15.8, Pain improving from 40.5 ± 22.0 to 17.2 ± 18.3, Walking/Standing improving from 32.3 ± 23.1 to 12.0 ± 18.2, and Social Interaction improving from 40.4 ± 20.4 to 11.0 ± 15.2. The recurrence rate was 4.5% (n = 33). The complication rate was 6.1%, which included a screw removal rate of 2.9%.

Conclusions: This study, which was the largest consecutive series of any percutaneous osteotomy technique used to correct hallux valgus deformity, demonstrated significant improvement in clinical and radiographic outcomes with a low rate of recurrence.

Level of Evidence: Therapeutic Level IV. See Instructions for Authors for a complete description of levels of evidence.

Percutaneous, or minimally invasive, surgery for hallux valgus has evolved since it was first described by De Prado and Isham[1]. Third-generation minimally invasive surgery, utilizing screw fixation of a distal metatarsal osteotomy, offers greater stability compared with first- and second-generation techniques. However, concerns over nomenclature

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and construct stability led to the development of a fourth-generation technique[1-6]. This technique utilizes 2 screws, 1 of which is bicortical, combined with an unstable osteotomy to allow 3D deformity correction including derotation of the first metatarsal. There is an increasing body of evidence that third- and fourth-generation techniques have improved clinical and radiographic outcomes for a range of deformity severities, with outcomes similar to those of open techniques[2,7-18].

One area of ongoing debate is the nature of the distal osteotomy utilized in the fourth-generation hallux valgus technique. The technique as first developed utilized a chevron osteotomy[19], but recently there has been a move to a transverse osteotomy technique[2,7,20,21]. Comparative evidence to support one technique over the other is very limited, with one biomechanical study demonstrating no significant difference in ultimate load, yield load, or stiffness between minimally invasive transverse and chevron osteotomy constructs; however, the authors did observe a trend toward increased strength in the transverse osteotomy cohort[22,23]. There is limited literature on the clinical and radiographic outcomes of transverse osteotomies for percutaneous hallux valgus correction, and many of the studies that have been published have methodological limitations such as small sample size, limited radiographic follow-up, or use of non-validated outcome measures[6]. Thus, our aim was to assess the clinical and radiographic outcomes following fourth-generation percutaneous transverse osteotomies for hallux valgus deformity.

Materials and Methods

Fourth-Generation Percutaneous Transverse Osteotomy Technique

An extracapsular transverse osteotomy is performed through a percutaneous incision at the metatarsal neck (Fig. 1). Correction of the 1-2 intermetatarsal angle (IMA), the hallux valgus angle (HVA), and metatarsal pronation is achieved through 3D reduction of the metatarsal head using a specific reduction tool. Metatarsal rotation correction is assessed intraoperatively on the basis of the round sign and sesamoid position. The osteotomy site is fixed with 2 parallel or divergent beveled cannulated screws with chamfered heads (Novastep), ensuring that the proximal screw passes through the lateral cortex of the first metatarsal shaft proximal to the osteotomy site. Medial ledge and exostosis excision is performed. A percutaneous Akin osteotomy is performed to correct any residual deformity and restore congruence of the first metatarsophalangeal joint (MTPJ). Percutaneous lateral soft-tissue release was only performed in cases with residual joint incongruity at the end of the procedure. A detailed description of the technique is provided elsewhere[2,21,24].

Patients are permitted immediate full weight-bearing following surgery. Initial recovery requires 2 weeks of foot elevation, with patients walking in a postoperative shoe. At 2 weeks postoperatively, dressings are removed, medial taping is performed to maintain alignment, and patients transition to regular athletic footwear. Active first MTPJ plantar flexion exercises begin at this time. Scar mobilization techniques commence at 3 weeks postoperatively. Physiotherapy may be

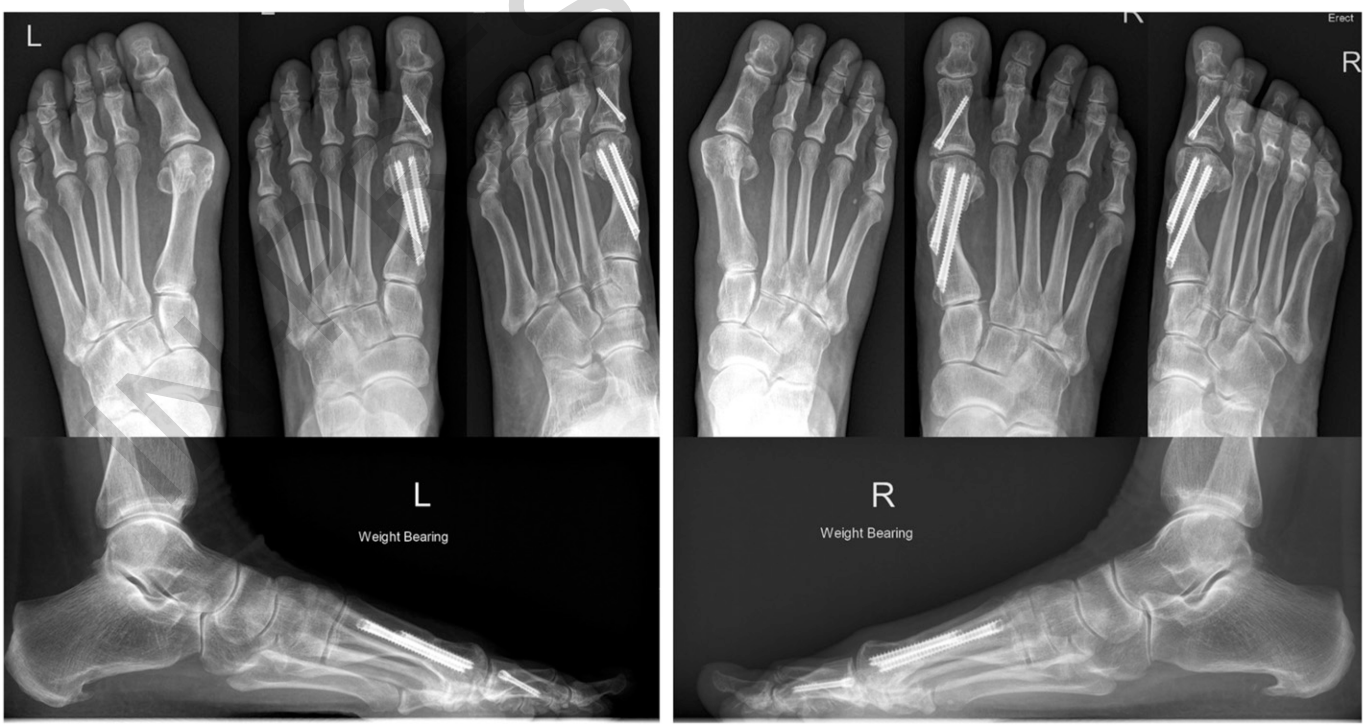

Fig. 1
Preoperative and 18-month postoperative weight-bearing radiographs (anteroposterior, oblique, and lateral) demonstrating bilateral percutaneous hallux valgus correction with the fourth-generation percutaneous transverse osteotomy technique.

prescribed at the 6-week follow-up if patients demonstrate difficulty with therapeutic exercises or scar management.

Study Design

This was a prospective observational study of a consecutive series of patients treated by a single surgeon (P.L.) in his specialist foot and ankle private practice in Sydney, Australia. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines were used to report on this study[25].

Participants

Consecutive patients who were ≥16 years old (with no upper age limit) and were undergoing primary correction of hallux valgus after the failure of nonoperative treatment were included in this study, regardless of deformity severity. Patients were not excluded if they were undergoing additional forefoot procedures, such as hammer toe correction or distal metaphyseal metatarsal osteotomy, or if they had metatarsus adductus, mild to moderate first MTPJ or tarsometatarsal joint arthritis (provided the arthritis was not the primary cause of symptoms), previous forefoot fracture, or naviculocuneiform joint arthritis. Eligibility was also not affected by smoking status or addiction issues. Exclusion criteria included previous hallux valgus surgery, advanced first-ray degenerative joint disease (characterized by either symptomatic arthritis with a positive grind test or a fixed, non-correctable HVA deformity), generalized ligamentous laxity (a Beighton score of >8), neuromuscular conditions, and bone disorders such as osteogenesis imperfecta. For patients with metatarsus adductus, treatment was modified according to its severity, with an additional distal or proximal lesser metatarsal osteotomy performed for moderate to severe cases. In patients with osteoporosis, postoperative protocols were modified to include use of stiff footwear, restricted first MTPJ plantar flexion stretches, and reduced early postoperative mobilization.

Data Collection

All data were collected prospectively and stored in an electronic registry (REDCap) by a dedicated research nurse (C.W.). Preoperative scores were not routinely collected until March 2019.

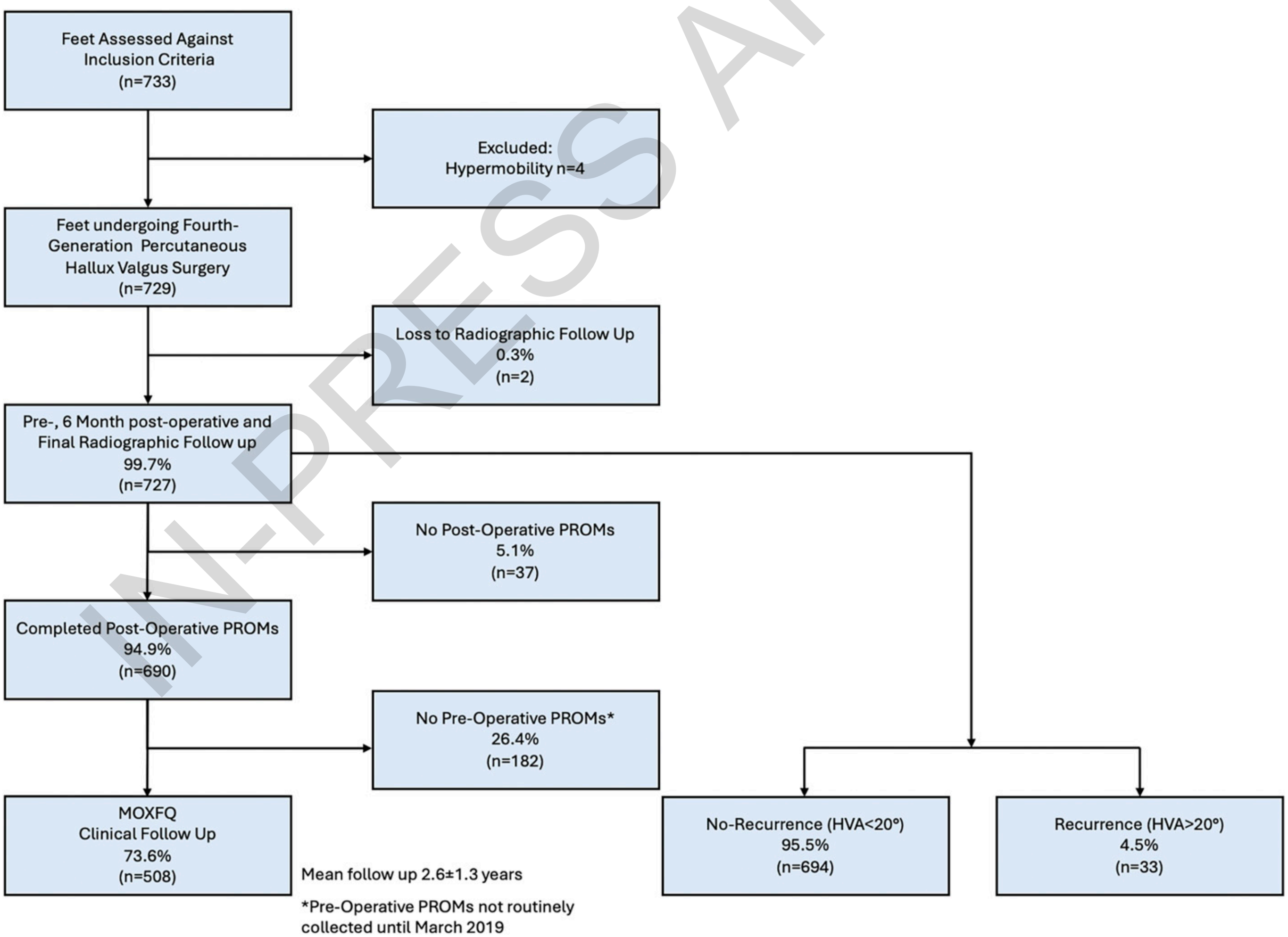

Fig. 2
A flowchart demonstrating patient participation in this study.

TABLE I Preoperative and Mean 2.6-Year Postoperative PROMs Following Fourth-Generation Minimally Invasive Hallux Valgus Surgery*

	Preop.			Postop.			
PROM	Mean ± SD	Median (IQR)	95% CI	Mean ± SD	Median (IQR)	95% CI	P Value
MOXFQ							
Pain	40.5 ± 22.0	40.0 (30.0)	38.6 to 42.4	17.2 ± 18.3	10.0 (25.0)	15.6 to 18.8	<0.001
Walking/Standing	32.3 ± 23.1	32.1 (33.0)	30.3 to 34.3	12.0 ± 18.2	3.6 (17.9)	10.4 to 13.6	<0.001
Social Interaction	40.4 ± 20.4	37.5 (31.2)	38.6 to 42.2	11.0 ± 15.2	0.0 (18.8)	9.7 to 12.3	<0.001
Index	36.9 ± 18.9	35.9 (29.7)	35.3 to 38.5	13.4 ± 15.8	7.8 (15.6)	12.0 to 14.7	<0.001
EQ-5D-5L Index	0.767 ± 0.131	0.768 (0.127)	0.754 to 0.779	0.868 ± 0.134	0.837 (0.205)	0.856 to 0.881	<0.001
EQ-VAS	76.6 ± 16.3	79.0 (19.5)	75.0 to 78.1	86.6 ± 11.9	90.0 (15.0)	85.5 to 87.8	<0.001
VAS-Pain	27.0 ± 23.4	21.0 (41.0)	24.8 to 29.2	7.5 ± 14.4	1.0 (7.8)	6.1 to 8.8	<0.001

*PROM = patient-reported outcome measure; MOXFQ = Manchester-Oxford Foot Questionnaire, scale from 0 to 100, 0 = best possible score; EQ-5D-5L Index = EuroQol 5-dimension 5-level Index, scale from −0.594 to 1, 1 = full health; EQ-VAS = EQ visual analog scale, scale from 0 to 100, 100 = best possible score; VAS-Pain = visual analog scale for pain, scale from 0 to 100, 0 = best possible score; SD = standard deviation; IQR = interquartile range; CI = confidence interval.

Patients completed questionnaires in clinic or were contacted via email and telephone to complete scores through the REDCap platform.

Outcome Measures and Study End Point

The primary outcome measure was a validated clinical patient-reported outcome measure (PROM), the Manchester-Oxford Foot Questionnaire (MOXFQ), which was specifically validated for assessment of hallux valgus[26-28]. Secondary outcome measures included radiographic measures of deformity correction; other validated clinical PROMs, including the EuroQol 5-dimension 5-level (EQ-5D-5L) Index, the EQ-5D-5L visual analog scale (EQ-VAS), and a VAS for pain (VAS-Pain); and complication data. The IMA and HVA were measured according to the American Orthopaedic Foot & Ankle Society (AOFAS) technique and categorized with regard to deformity severity[29,30] preoperatively, 6 months following surgery, and at final follow-up. The round sign and lateral sesamoid coverage were classified according to methods described by Okuda et al.[31] and Agrawal et al.[32]. The proximal IMA was measured using the method described by Lewis et al.[14]. Complication data were routinely collected prospectively for all patients until discharge and categorized using a modified Clavien-Dindo complication classification[33].

Bias

The use of prospectively collected data on consecutive patients reduced selection bias. All outcome data were collected and

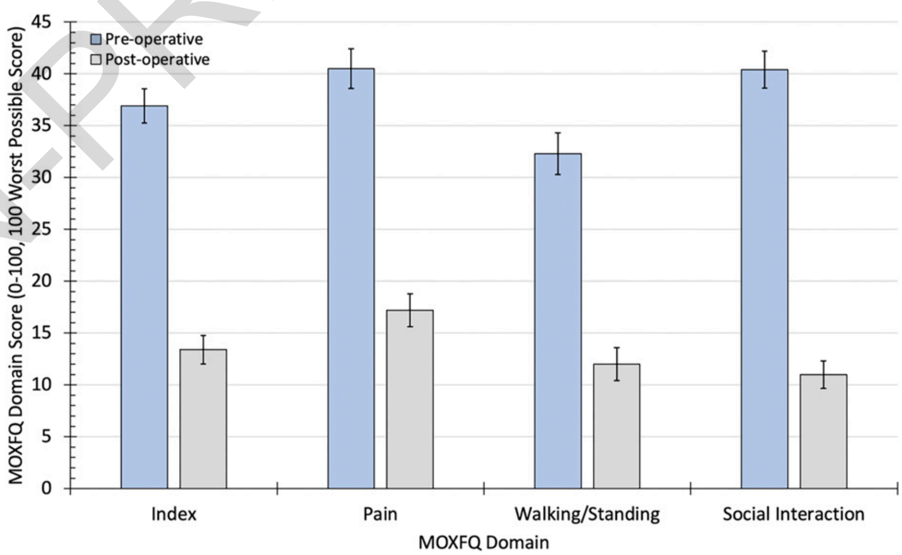

Fig. 3

Mean preoperative and 2.6-year postoperative MOXFQ domain scores for patients treated with fourth-generation percutaneous transverse osteotomy for hallux valgus deformity correction. Error bars indicate 95% confidence intervals.

TABLE II Preoperative and Final Follow-up Deformity Correction Assessed on Weight-Bearing Radiographs Following Fourth-Generation Minimally Invasive Hallux Valgus Surgery*

Parameter	Preop.	Final Follow-up	P Value (Preop. Vs. Final Follow-up)
IMA, mean ± SD *(deg)*	12.9 ± 3.3	4.6 ± 2.5	<0.001
HVA, mean ± SD *(deg)*	29.5 ± 8.5	7.3 ± 6.7	<0.001
Lateral sesamoid position *(% of feet)*			<0.001
Covered	0.7	11.7	
Mildly uncovered	21.5	49.1	
Moderately uncovered	36.4	28.5	
Uncovered	41.5	10.7	
Round sign *(% of feet)*			0.53
Angular	22.2	40.3	
Intermediate	31.3	31.1	
Round	46.6	28.6	
Overall deformity† *(% of feet)*			<0.001
Normal	0.6	87.1	
Mild	10.5	8.3	
Moderate	75.9	4.7	
Severe	13.1	0.0	

*IMA = 1-2 intermetatarsal angle, HVA = hallux valgus angle. †Mild deformity = HVA 15° to 19° and/or IMA 9° to 13°, moderate deformity = HVA 20° to 39° and/or IMA 14° to 19°, severe deformity = HVA ≥ 40° and/or IMA ≥ 20°.

analyzed independent of the operating surgeon, who was blinded to the clinical outcomes collected for this study.

Statistical Analysis Including Calculation of Sample Size

A power analysis was performed, and the sample-size calculations were based on an independently established minimal clinically important difference (MCID) in the MOXFQ Index following hallux valgus surgery. A large effect size (1.47) was noted in a previous study of fourth-generation hallux valgus surgery, which meant that only 10 feet would be needed to detect a similar effect size[2,34]. We chose a much more conservative effect size of 0.5 to be considered clinically important. This meant that a sample size of 60 feet was estimated to give a power of 0.9 with an α risk of 1%. The paired t test for parametric data and the Wilcoxon signed rank test for nonparametric data were used. Preoperative clinical data were tested for normality using the Shapiro-Wilk test, which indicated that the data had a normal distribution. Significance was defined as $p < 0.05$. Subgroup analysis specifically investigating the role of sesamoid position and its impact on recurrence was performed by stratifying patients into 2 groups.

A logistic regression model was employed to predict the recurrence of hallux valgus deformity based on several preoperative variables. The predictors included age, follow-up duration, radiographic measurements of deformity (HVA, IMA), and categorical variables such as gender and baseline round sign, which were appropriately one-hot encoded. The logistic regression model was fitted using maximum likelihood estimation (MLE), and was evaluated to assess the impact of each predictor on the likelihood of recurrence. All analyses were performed with the Python SciPy package[35].

TABLE III Complications Following Fourth-Generation Minimally Invasive Surgery Categorized Using a Modified Clavien-Dindo Complication Classification

Grade	Complication	No.	%
1A	None	0	0.0
1B	Superficial infection treated with antibiotics	20	2.7
2A	Nonunion	1	0.1
	Broken screw (asymptomatic)	2	0.3
2B	None	0	0.0
3A	Prominent screws removed in operating theater	21	2.9
	Deep infection	1	0.1

Ethical Approval

Local institutional review board approval was obtained. Informed consent was obtained from all participants. This study was registered on ClinicalTrials.gov (NCT06625229)[36].

Results

Patient Demographics

Between November 2017 and January 2023, 483 consecutive patients (456 female and 27 male [data set did not contain data on patients' ethnicity]) met the criteria for inclusion and

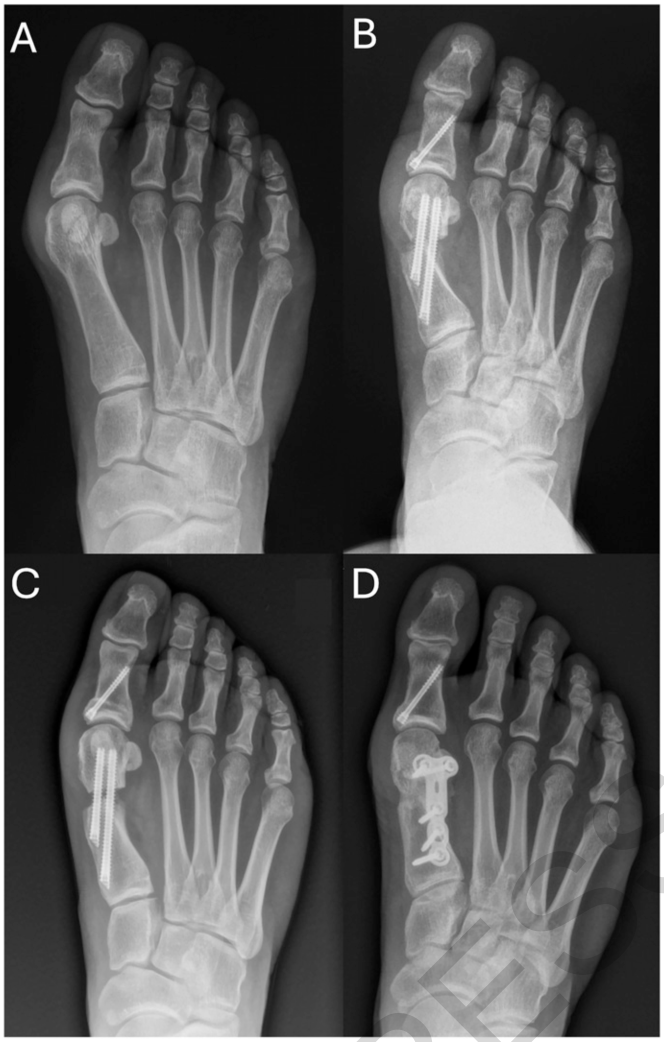

Fig. 4
Preoperative (**Fig. 4-A**), 6-week postoperative (**Fig. 4-B**), 9-month postoperative (**Fig. 4-C**), and 24-month postoperative (**Fig. 4-D**) radiographs showing nonunion and subsequent revision in the right foot.

underwent fourth-generation percutaneous metatarsal extracapsular transverse osteotomy for hallux valgus correction. There were a total of 729 feet (373 left; 356 right), and the mean age (and standard deviation) was 57.9 ± 11.9 years (range, 16.0 to 84.4 years). Figure 2 demonstrates the participant flowchart for clinical and radiographic analysis. The mean radiographic and clinical follow-up was 2.6 ± 1.3 years (range, 1.0 to 5.7 years), with 448 (61.4%) of the feet being followed for >24 months. The recurrence rate (defined as an HVA of >20° at final radiographic follow-up) was 4.5% (n = 33). An isolated metatarsal extracapsular transverse osteotomy was done in 67.9% of the feet, whereas the remaining 32.1% of the feet had additional procedures performed as part of the surgical treatment.

PROMs

Postoperative MOXFQ PROMs (primary outcome) were available for 690 feet (94.7%); however, due to the fact that we did not routinely start collecting preoperative PROMs until March 2019, both preoperative and postoperative MOXFQ PROMs were available for only 508 (73.6%) of the 690 feet (310 patients [290 female; 20 male]). There was a significant improvement ($p < 0.001$) that was greater than the MCID in each of the MOXFQ domains[27]. There was also a significant improvement in the EQ-5D-5L Index, EQ-VAS, and VAS-Pain score ($p < 0.001$). A summary of the PROMs is provided in Table I and Figure 3.

Radiographic Outcomes

Preoperative, 6-month, and final follow-up radiographic data regarding deformity correction were collected for 99.7% (727) of the 729 feet (Table II). There was no significant change in the IMA between 6 months (4.6° ± 2.5°) and the final follow-up (4.6° ± 2.5°) ($p = 0.99$). There was a statistically significant, but not clinically relevant, change in the HVA between 6 months (6.3° ± 5.6°) and final follow-up (7.3° ± 6.7°) ($p < 0.01$). The mean IMA correction (preoperative to final follow-up) was −8.4° ± 3.0° (range, −20.4° to 2.4°), while the mean HVA correction was −22.2° ± 7.4° (range, −53.4° to −4.1°). The mean proximal IMA increased from 12.9° ± 3.3° preoperatively to 17.7° ± 4.0° at final follow-up ($p < 0.01$).

Complications

Complications and their prevalences are shown in Table III. The overall rate of all grades of complications combined was 6.2%. The all-cause screw removal rate was 2.9% (n = 21 feet). There were no reported cases of lateral wall fracture, first metatarsal head osteonecrosis, symptomatic dorsal or plantar malunion, deep vein thrombosis, or pulmonary embolism at any point during follow-up. Patients did not routinely receive prophylaxis against venous thromboembolism (VTE) unless they had pre-existing risk factors for VTE.

There was 1 nonunion (Fig. 4), in a 38-year old woman who had undergone bilateral correction. She had good healing on 1 side, but developed a symptomatic nonunion in the other foot. She underwent open debridement of the nonunion site with autograft harvested from the calcaneus and plate fixation 9 months following the index surgery. That procedure was successful.

Recurrence

The overall rate of recurrence (defined as an HVA of >20° at final radiographic follow-up) was 4.5%. A subgroup analysis comparing patients with and without recurrence (Table IV and Fig. 5) demonstrated a significant difference between groups in terms of age, preoperative and postoperative radiographic deformity, and sesamoid position ($p < 0.05$). There was no significant difference in the preoperative or postoperative round sign ($p = 0.27$) or foot function (MOXFQ Index) between the groups ($p > 0.05$). In the recurrence group, there was no significant change in the proximal IMA between 6 months (21.3° ± 5.0°) and final follow-up (20.9° ± 4.5°) ($p = 0.396$); however, there was a significant increase in the HVA between 6 months (18.8° ± 3.7°) and final follow-up (24.2° ± 3.5°) ($p < 0.05$).

TABLE IV Subgroup Analysis of Feet with and without Recurrence at Final Radiographic Follow-up Following Fourth-Generation Minimally Invasive Hallux Valgus Surgery*

	No Recurrence (HVA < 20°)	Recurrence (HVA > 20°)	P Value (Between Groups)
No. of feet	694	33	
Gender			0.06
Male	25	4	
Female	446	25	
Age, mean ± SD *(yr)*	57.6 ± 11.9	62.5 ± 10.7	0.02
HVA, mean ± SD *(deg)*			
Preop.	28.8 ± 8.0	44.3 ± 6.5	<0.01
Final follow-up	12.8 ± 3.3	24.2 ± 3.5	<0.01
IMA, mean ± SD *(deg)*			
Preop.	6.5 ± 5.6	15.6 ± 3.7	<0.01
Final follow-up	4.4 ± 2.3	7.9 ± 3.2	<0.01
Lateral sesamoid position *(% of feet)*			<0.05
Covered			
Preop.	0.7	0.0	
Final follow-up	12.2	0.0	
Mildly uncovered			
Preop.	22.4	3.0	
Final follow-up	51.2	6.1	
Moderately uncovered			
Preop.	37.4	15.2	
Final follow-up	28.7	24.2	
Uncovered			
Preop.	39.5	81.8	
Final follow-up	7.9	69.7	
Round sign *(% of feet)*			0.27
Angular			
Preop.	22.5	15.2	
Final follow-up	41.4	15.2	
Intermediate			
Preop.	31.3	30.3	
Final follow-up	31.0	33.3	
Round			
Preop.	46.2	54.5	
Final follow-up	27.6	51.5	
MOXFQ Index, mean ± SD			
Preop.	36.8 ± 19.2	32.3 ± 17.6	0.24
Final follow-up	11.8 ± 14.0	10.7 ± 10.5	0.69

*HVA = hallux valgus angle, IMA = 1-2 intermetatarsal angle, MOXFQ = Manchester-Oxford Foot Questionnaire, SD = standard deviation.

Logistic Regression

The logistic regression analysis (Table V) showed that the 2 significant predictors of recurrence were preoperative HVA ($p < 0.001$) and male gender ($p = 0.017$). Other variables, including age, follow-up duration, preoperative IMA, sesamoid position, and the round sign, did not demonstrate significant effects on recurrence. The model's pseudo-R^2 value of 0.3833 suggests a moderate fit, with the overall model providing a reasonable explanation of the variance in recurrence outcomes. The low number of males in the cohort may explain why male gender was identified as a risk factor for recurrence.

Discussion

This study is the largest series of fourth-generation percutaneous transverse osteotomies for hallux valgus performed

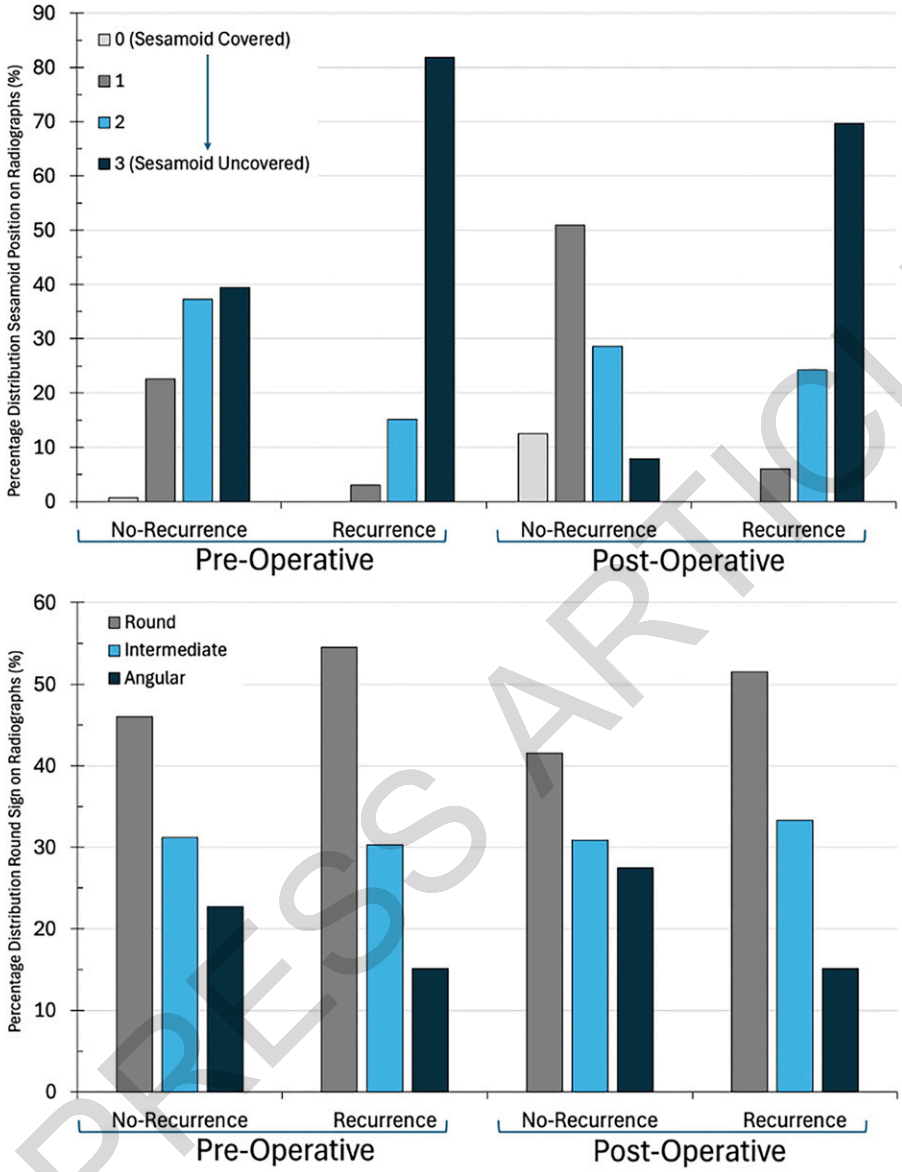

Fig. 5

Prevalences of sesamoid coverage (top) and round sign (bottom) in 2 groups of patients defined by whether or not they had recurrent hallux valgus deformity (defined as an HVA of >20°) at final radiographic follow-up.

by a surgeon experienced in minimally invasive surgery. Using validated outcome measures, it demonstrated that the procedure is safe and effective for hallux valgus deformity correction. A number of recent studies on the outcomes of fourth-generation percutaneous hallux valgus techniques (Table VI) reported similar improvements in radiographic deformity measures as well as improvement in foot function[2,7,13,18,37].

Although there was some loss to follow-up in the PROMs analysis, our study found significant improvements in foot function across all domains of the MOXFQ. These findings are similar to those in studies of both third and fourth-generation techniques as well as systematic reviews comparing open and percutaneous approaches[9,12,18,38].

We found a low recurrence rate of 4.5%, with recurrences being associated with greater preoperative deformity and incomplete correction of sesamoids. There was a higher proportion of malreduced sesamoids in the recurrence group, although the only significant factors that independently predicted recurrence were male gender and preoperative HVA. We believe that recurrence after fourth-generation minimally invasive hallux valgus surgery is more commonly due to an increase in the HVA associated with progressive stretching of the medial capsule and plantar-medial soft tissues, often associated with undercorrection at the index procedure and an ongoing pathological vector of the extensor hallucis longus (EHL) tendon, rather than being due to a progressive increase in the proximal IMA (as we found no change

TABLE V Logistic Regression Analysis of Factors Affecting Recurrence of Hallux Valgus Deformity Following Fourth-Generation Minimally Invasive Hallux Valgus Surgery*

				95% CI		
	Coefficient	Standard Error	z	Lower	Upper	P Value
(Constant)	−5.300	1.271	−4.168	−7.791	−2.808	<0.001
Age	−0.004	0.247	−0.015	−0.488	0.481	0.988
Follow-up	−0.161	0.236	−0.683	−0.624	0.301	0.495
Preop. HVA	1.936	0.288	6.721	1.372	2.501	**0.01**
Preop. IMA	−0.126	0.24	−0.523	−0.596	0.345	0.601
Male gender	1.554	0.652	2.383	0.276	2.832	**0.017**
Round sign						
Intermediate	−0.200	0.657	−0.304	−1.487	1.087	0.761
Round	−0.105	0.614	−0.171	−1.309	1.099	0.865
Sesamoid position	0.239	0.438	0.545	−0.620	1.097	0.586

*CI = confidence interval, HVA = hallux valgus angle, IMA = 1-2 intermetatarsal angle. Bold indicates significance.

in the proximal IMA from 6 months to final follow-up) (Fig. 6). A potential explanation for the undercorrection of the sesamoid position is the presence of metatarsal-sesamoid osteoarthritis and contracture leading to a decreased ability to reduce the sesamoid complex despite adequate multiplanar correction of the metatarsal head position. The limited follow-up duration in this study means that we cannot comment on the longer-term recurrence rates following transverse osteotomy compared with other osteotomy configurations.

Our findings are similar to those reported in other studies investigating factors that may lead to deformity recurrence[39-43]. There may be a number of reasons why the percutaneous technique is associated with a low recurrence rate, including the fact that deformity correction is achieved through osseous and

TABLE VI Studies Reporting on Fourth-Generation Hallux Valgus Techniques Using a Transverse Osteotomy*

	No. of Feet	Mean Age *(yr)*	Follow-up *(mo)*	IMA† *(deg)*	HVA† *(deg)*	VAS-Pain† (0-10 Scale)	Clinical Outcomes†	Complication Rate *(%)*
Current study	729	57.9	31	12.9 to 4.6	29.5 to 7.3	2.7 to 0.8	MOXFQ Index decreased from 36.9 to 13.4	6.1
Lewis et al.[2], 2023	50	55.8	17	14.0 to 4.2	32.7 to 7.9	4.6 to 1.5	MOXFQ Index decreased from 53.4 to 13.1	18.0
Marciano et al.[13], 2024								
Non-fractured lateral cortex of Akin	43	48.7	12	13.2 to 3.4	27.2 to 10.7	7.5 to 0.6	FFI decreased from 53.9 to 17.9	2.0
Fractured lateral cortex of Akin	55	47.9	12	13.3 to 3.8	29.3 to 7.1	7.7 to 0.6	FFI decreased from 54.2 to 17.2	0.0
Yoon et al.[7], 2023								
Mild-moderate hallux valgus deformity	75	59.0	29	12.0 to 5.1	30.5 to 6.9	5.1 to 0.9	FAOS Pain, Symptoms, ADL, Sports, QOL improved significantly	22.7
Severe hallux valgus deformity	41	65.0	28	16.5 to 2.4	46.8 to 8.4	4.5 to 0.8	FAOS Pain, Symptoms, ADL, Sports, QOL improved significantly	17.1
Nunes et al.[37], 2024	22	44	15	13.2 to 2.7	26.8 to 4.6	6 to 1	AOFAS increased from 45 to 91	27.2

*IMA = 1-2 intermetatarsal angle, HVA = hallux valgus angle, VAS-Pain = Visual Analog Scale-Pain, MOXFQ = Manchester Oxford Foot Questionnaire, FFI = Foot Function index, FAOS = Foot and Ankle Outcome Score, ADL = activities of daily living, QOL = quality of life, AOFAS = American Orthopaedic Foot & Ankle Society score. †Preoperative to follow-up.

Fig. 6
Radiographs demonstrating recurrence of hallux valgus deformity (hypothesized to be due to stretching of medial soft tissues and progressive subluxation of the first MTPJ). From left to right: preoperative, 6 weeks postoperative, 6 months postoperative, and 30 months postoperative.

soft-tissue realignment. Assuming that osseous union is achieved, there is arguably a reduced risk of recurrence as soft-tissue failure/laxity (particularly around peri-articular structures) is less likely to impact overall alignment[21]. Another possible reason for the low recurrence rate is the preservation of soft-tissue integrity with percutaneous techniques. Reduced disruption of medial soft tissues such as capsule and ligaments reduces the potential for failure of these structures[44,45]. Similarly, minimizing joint exposure may decrease the risk of joint contractures and joint instability. In addition, avoiding a lateral release, which is a core step of open reduction but not always performed when using a percutaneous technique, may improve the stability of the first MTPJ and reduce the risk of recurrence[44,46,47]. Also, maximizing the biomechanical stability of the osteosynthesis using 2 screws with fixation in the lateral cortex may reduce the forces transmitted through the soft tissues and reduce the risk of displacement leading to malunion[5,22,48,49]. Finally, the deforming forces leading to hallux valgus are such that incomplete deformity correction at the time of surgery carries a greater risk of recurrence[46,50]. Percutaneous osteotomy techniques potentially facilitate large deformity correction through lateral displacement of the metatarsal head by >100%, reducing the risk of incomplete deformity correction and thereby possibly reducing the risk of recurrence[44].

The low rate of nonunion that we observed in our study demonstrates that percutaneous hallux valgus correction with a transverse osteotomy technique can achieve stable and reliable osseous healing even with large metatarsal head shifts. This was seen in other studies utilizing a percutaneous transverse osteotomy technique[2]. Lewis et al. found a higher, but not significantly higher, rate of symptomatic delayed union and revision for nonunion after percutaneous hallux valgus correction with a transverse osteotomy compared with a chevron osteotomy[51]. Loder et al. found no difference between transverse and chevron osteotomies in terms of radiographic deformity correction[52].

We believe that the fourth-generation technique combining 3D deformity correction, a dual-screw configuration, and lateral cortex fixation contributes to optimal osseous alignment and reduced stress/movement at the osteotomy site, thereby decreasing the risk of nonunion[2,5,9,14] and loss of position. This may also have contributed to the low screw removal rate in our study.

Strengths and Limitations

The clear strengths of this study are the use of validated outcome measures and a large sample size that is greater than that in many other studies reporting on either percutaneous or open techniques for hallux valgus correction. We deliberately adopted an inclusive approach to reflect real-world clinical practice. This pragmatic approach allows our findings to be generalizable to the typical patient population presenting with hallux valgus in clinical practice. The follow-up for this study is also longer than that in other studies reporting the outcomes of other transverse fourth-generation techniques; however, we acknowledge that 38.4% of the feet had <2 years of follow-up, limiting insight into the longer-term outcomes such as recurrence following this procedure. There are also important limitations inherent to an experienced-single-surgeon case series, including the unavailability of a comparison group and the selection bias due to the fully private nature of the lead surgeon's practice. Consequently, the results may not be generalizable to a wider population due to the potential for variability among individual surgeons in technique, experience, clinical setting, and patient selection criteria. Finally, there was moderate incompleteness of the data for the functional PROM outcomes due to the date on which preoperative PROM data started to be collected.

Conclusions

In conclusion, fourth-generation percutaneous hallux valgus correction utilizing a transverse osteotomy is safe and effective. This technique offers large deformity correction with significant improvement in foot function and a low risk of complications such as screw removal and nonunion. Further work should focus on evaluation of this technique in comparison with other surgical techniques as well as longer-term outcomes in more diverse populations, to determine if the results found here are reproducible. ■

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