Clinical Effect of Isolated Lateral Closing Wedge Distal Femoral Osteotomy Compared to Medial Opening Wedge High Tibial Osteotomy for the Correction of Varus Malalignment

A Propensity Score–Matched Analysis

Marco-Christopher Rupp,[*†] MD, Felix Lindner,[†] cand. MD, Philipp W. Winkler,[†] MD, Lukas N. Muench,[†] MD, Julian Mehl,[†] MD, Andreas B. Imhoff,[†] MD, Sebastian Siebenlist,[†] MD, and Matthias J. Feucht,[‡§] MD

Investigation performed at Department of Orthopaedic Sports Medicine, School of Medicine, Technical University of Munich, Munich, Germany

Background: Recent evidence questions the role of medial opening wedge high tibial osteotomy (mowHTO) in the correction of femoral-based varus malalignment because of the potential creation of an oblique knee joint line. However, the clinical effectiveness of alternatively performing an isolated lateral closing wedge distal femoral osteotomy (lcwDFO), in which the mechanical unloading effect in knee flexion may be limited, is yet to be confirmed.

Purpose/Hypothesis: The purpose of this article was to compare clinical outcomes between patients undergoing varus correction via isolated lcwDFO or mowHTO, performed according to the location of the deformity, in a cohort matched for confounding variables. It was hypothesized that results from undergoing isolated lcwDFO for symptomatic varus malalignment would not significantly differ from the results after mowHTO.

Study Design: Cohort study; Level of evidence, 3.

Methods: Consecutive patients who underwent isolated mowHTO or lcwDFO according to a tibial- or femoral-based symptomatic varus deformity between January 2010 and October 2019 were enrolled. Confounding factors, including age at surgery, sex, body mass index, preoperative femorotibial axis, and postoperative follow-up, were matched using propensity score matching. The International Knee Documentation Committee (IKDC) Subjective Knee Form, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Lysholm score, Tegner Activity Scale, and visual analog scale (VAS) for pain were collected preoperatively and at a minimum of 24 months postoperatively.

Results: Of 535 knees assessed for eligibility, 50 knees (n = 50 patients, n = 25 per group) were selected by propensity score matching. Compared with preoperatively, both the mowHTO group (IKDC, 55.1 $\pm$ 16.5 vs 71.3 $\pm$ 14.7, P = .002; WOMAC, 22.0 $\pm$ 18.0 vs 9.6 $\pm$ 10.8, $P <$ .001; Lysholm, 55.2 $\pm$ 23.1 vs 80.7 $\pm$ 16, $P <$ .001; VAS, 4.1 $\pm$ 2.4 vs 1.6 $\pm$ 1.8, $P <$ .001) and the lcwDFO group (IKDC, 49.4 $\pm$ 14.6 vs 66 $\pm$ 20.1, P = .003; WOMAC, 25.2 $\pm$ 17.0 vs 12.9 $\pm$ 17.6, P = .003; Lysholm, 46.5 $\pm$ 15.6 vs 65.4 $\pm$ 28.7, P = .011; VAS, 4.5 $\pm$ 2.2 vs 2.6 $\pm$ 2.5, P = .001) had significantly improved at follow-up (80 $\pm$ 20 vs 81 $\pm$ 43 months). There were no significant differences between the groups at baseline, at final follow-up, or in the amount of clinical improvement in any of the outcome parameters ($P >$ .05; respectively).

Conclusion: Performing both mowHTO or lcwDFO yields significant improvement in clinical outcomes if performed at the location of the deformity of varus malalignment. These findings confirm the clinical effectiveness of performing an isolated lcwDFO in femoral-based varus malalignment, which is comparable with that of mowHTO in the correction of varus malalignment.

Keywords: varus malalignment; high tibial osteotomy; distal femoral osteotomy; location of deformity; joint line obliquity

The American Journal of Sports Medicine
2023;51(2):437–445
DOI: 10.1177/03635465221142615

A solid body of evidence has demonstrated that surgical correction of the mechanical alignment correction by valgus-producing osteotomy, which unloads the medial compartment, is an effective joint-preserving treatment option in unicompartmental medial knee osteoarthritis.[2,3,6,13,27,35,36,39,45] Although traditionally an "all-in-tibia" approach to varus deformity correction via medial opening wedge high tibial osteotomy (mowHTO) has been advocated,[6,13,39,45] the dogma of an isolated tibial-based deformity has recently been reevaluated.[10,28]

Recent investigations increasingly focus on the role of knee joint line (KJL) orientation in the context of alignment-corrective osteotomy,[15,19,28,38,43] which is horizontal in the coronal plane during gait under physiologic conditions.[30] To maintain a leveled KJL postoperatively, the osteotomy should be performed at the location of the varus deformity,[30] as an oblique KJL has been associated with nonphysiologic biomechanical pressure distribution[28] and inferior clinical outcomes.[19,38,42] As the KJL may already be tilted 2.2° laterally in a femoral-based varus malalignment preoperatively, inferior outcomes are particularly evident in these patients when performing a mowHTO that further increases the lateral downsloping of the KJL.[31] A mounting body of evidence documents favorable clinical results after double-level osteotomy performed in an effort to maintain a physiologic KJL in bifocal varus deformities,[27,33,35,36] but an isolated lateral closing wedge distal femoral osteotomy (lcwDFO) is anatomically indicated in up to 8% of cases.[10,29]

To date, evidence in current literature pertaining to clinical outcomes after isolated lcwDFO is scarce, and its effectiveness in the correction of an isolated femoral-based varus malalignment is yet to be confirmed.[11,16,22,34] Furthermore, although recent data highlight the importance of sustaining a horizontal KJL, a clinical noninferiority of isolated DFO compared with isolated HTO in the setting of varus malalignment correction has not yet been demonstrated. This is especially relevant, as biomechanical investigations on the effect of DFO on tibiofemoral contact mechanics through knee flexion postulate a limited efficacy of femoral correction regarding contact area and mean contact pressure during knee flexion.[44]

Thus, the primary objective of this study was to compare the clinical outcomes after physiologic varus correction via isolated lcwDFO for a femoral-based deformity with the outcomes after mowHTO for a tibial-based deformity in a cohort matched for confounding variables. It was hypothesized that when performing the osteotomy according to the location of the deformity, the results of undergoing isolated lcwDFO for symptomatic varus osteoarthritis would not differ from the results after mowHTO.

METHODS

This was an institutional review board (258/20S)–approved retrospective outcome study of prospectively collected data. Review of our institutional data bank was performed to identify patients meeting the following inclusion criteria: patients with a minimum age of 18 years who underwent isolated mowHTO or isolated lcwDFO for symptomatic varus malalignment between January 2010 and October 2019 with a minimum of 24 months of postoperative follow-up. Patients who were not able to be contacted because of nonresidential status or death during follow-up were excluded. In addition, patients undergoing double-level osteotomy, concomitant reconstructive procedures such as cartilage transplantation, meniscal repair or ligament reconstruction of the ipsilateral knee, revision osteotomy, or conversion to arthroplasty were excluded from the comparative clinical outcome analysis. The decision to exclude these patients was made to precisely evaluate the isolated effect of mowHTO or lcwDFO on the clinical outcomes without confounding the data with concomitant or subsequent procedures. Informed consent was obtained from each patient.

Indication

Patients with varus malalignment and symptomatic medial compartment osteoarthritis who reported clinical improvement by 6 weeks of preoperative valgus bracing for unloading of the medial compartment were indicated for osteotomy.[26] Medial compartment osteoarthritis was defined as Kellgren-Lawrence grade 1 to 3 or medial (osteo)chondral lesions. Contraindications for osteotomy included grade 3 or 4 chondral lesions in the lateral compartment according to the International Cartilage Regeneration & Joint Preservation Society, symptomatic patellofemoral osteoarthritis or cartilage defects, presence of inflammatory arthropathy, lack of extension >15° and flexion <100°, chondrocalcinosis, chronic regional pain syndrome, or active infection.

Preoperative deformity analysis and preoperative planning were performed using 1-leg standing anterior-posterior hip-knee-ankle radiographs. The osteotomy was simulated employing the planning method according to Miniaci et al[25] using the mediCAD (mediCAD Hectec GmbH) software (Figure 1). Planning aimed for an overcorrection of the new weightbearing line crossing the center of

*Address correspondence to Marco-Christopher Rupp, MD, Department of Orthopaedic Sports Medicine, Technical University of Munich, Ismaninger Str. 22, Munich, 81675, Germany (email: marco.rupp@tum.de).

†Department of Orthopaedic Sports Medicine, School of Medicine, Technical University of Munich, Munich, Germany.

‡Orthopaedic Clinic Paulinenhilfe, Diakonie-Hospital, Stuttgart, Germany.

§Department of Orthopaedics and Trauma Surgery, Medical Center, Faculty of Medicine, Albert-Ludwigs-University of Freiburg, Freiburg, Germany.

Submitted May 23, 2022; accepted October 12, 2022.

One or more of the authors has declared the following potential conflict of interest or source of funding: A.B.I. has received consulting fees from Arthrosurface, Medi Bayreuth, and Arthrex, and receives royalties from Arthrex Inc. and Arthrosurface. S.S. has received consulting fees from Arthrex, Medi Bayreuth, medartis AG, and KLS Martin Group. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

the tibial plateau laterally (55%-65% from medial to lateral, depending on the diagnosis according to a previously published algorithm).[9] The required correction (in millimeters) was calculated accordingly. The decision on whether to perform mowHTO or lcwDFO was made based on the location of the deformity, as determined by the modified malalignment test as described by Paley.[30] With reference values for mechanical medial proximal tibial angle (mMPTA) and mechanical lateral distal femoral angle (mLDFA) of 85° to 90°,[30] for the purpose of this study, an mMPTA <87° (with a normal mLDFA) indicated a tibial deformity, and an mLDFA >90° (with a normal mMPTA) indicated a femoral deformity. Accordingly, in a predominantly tibial deformity, a mowHTO was indicated (Figure 1, A-C), while in a predominantly femoral deformity, a lcwDFO was indicated (Figure 1, D-F). Exceeding the reference values for mMPTA and mLDFA of up to 5° during osteotomy simulation was tolerated. Of note, a double-level osteotomy was performed if the deformity could not be corrected by isolated osteotomy within the tolerated range of postoperative alignment parameters during simulation. These cases were excluded from this study. In borderline cases, a mowHTO was preferred as the gold standard.

Surgical Technique

After a diagnostic arthroscopy procedure, biplanar supracondylar lcwDFO[34] or mowHTO[14] was performed as previously described. For the biplanar mowHTO, first a bicortical frontal osteotomy was performed with an ascending or a descending osteotomy orientation, depending on the patellofemoral cartilage status.[14] Next, 2 axial K-wires were positioned in an oblique direction toward the fibular head. For lcwDFO, the biplanar osteotomy planes were marked and an ascending bicortical frontal osteotomy was performed. Next, 4 axial K-wires marking the osteotomy wedge to be excised proximally and distally were placed for an axial osteotomy. Next, respective osteotomies preserving the contralateral cortex were performed with the hinge located at a 0.5- to 1-cm distance from the medial cortex. The osteotomy gap was carefully closed (lcwDFO) or opened (mowHTO), applying valgus stress and axial compression. To control for adequate mechanical correction, the osteotomy was fixed temporarily, and alignment was assessed via intraoperative hip-knee-ankle alignment fluoroscopy with an alignment rod[8] and adjusted as needed. Consecutively, the osteotomy was secured with a locking compression plate, using either a Polyetheretherketone-Power plate (Arthrex) or a Tomo-Fix plate (DePuy Synthes).

Postoperative Rehabilitation

The postoperative rehabilitation program was started on the first postoperative day. The standard protocol included manual lymphatic drainage and mobilization by continuous passive motion during the hospital stay. Full range of motion was allowed immediately after surgery. Weight-bearing was limited to 20 kg from the first postoperative day until 6 weeks postoperatively.

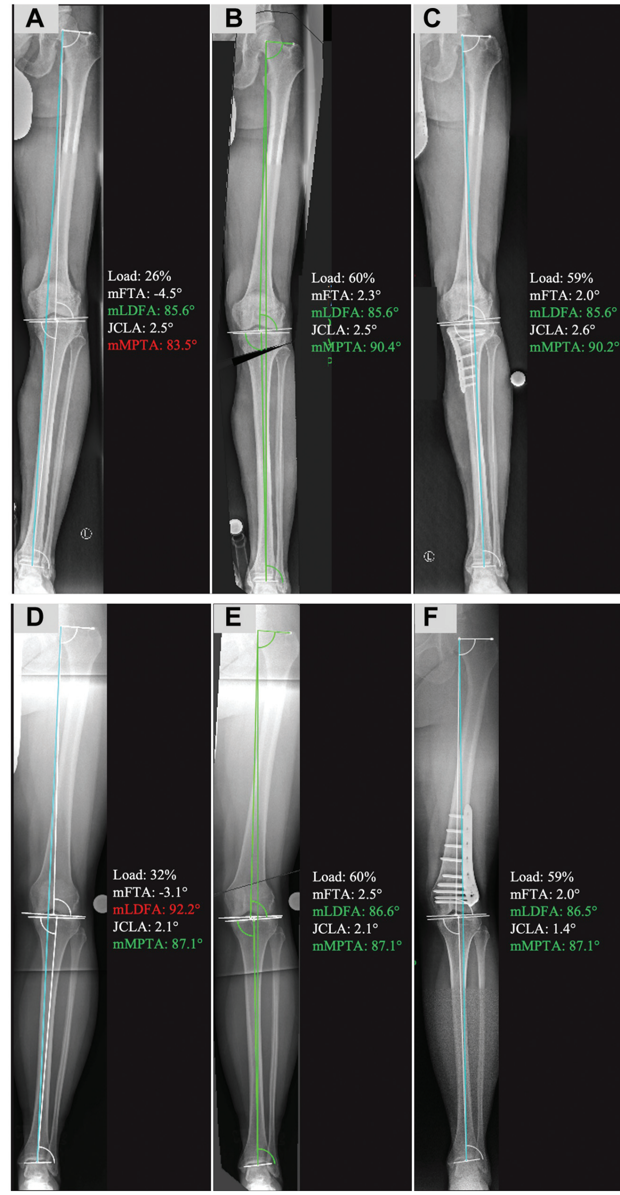

Figure 1. The selection of osteotomy level based on deformity location. (A) Deformity analysis of a left leg revealed a tibial-based varus deformity of −4.5° with a normal mechanical lateral distal femoral angle (mLDFA) and a pathologic mechanical medial proximal tibial angle (mMPTA). (B) During osteotomy, an isolated medial opening wedge high tibial osteotomy (mowHTO) sustains a leveled joint line (KJL). (C) In this case, physiologic varus malalignment correction has been performed via mowHTO. (D) Deformity analysis revealed femoral-based varus deformity of 3.1° in a right leg with a normal mMPTA and a pathologic mLDFA. (E) During osteotomy, an isolated lateral closing wedge distal femoral osteotomy (lcwDFO) sustains a leveled KJL. (F) In this case, physiologic varus malalignment correction has been performed via lcwDFO. Osteosynthesis in both cases was performed with a Tomo-Fix implant (DePuy Synthes). JCLA, joint line convergence angle.

Clinical Evaluation

Outcome measures included the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC),[4] the Lysholm score,[23] the International Knee Documentation Committee (IKDC) Subjective Knee Form,[18] the Tegner Activity Scale,[40] and the visual analog scale (VAS) for pain. These scores were collected preoperatively and at a minimum of 24 months postoperatively. As the minimal clinically important difference (MCID) for WOMAC[20] and IKDC[32] has been established for mowHTO but not for lcwDFO in the setting of varus malalignment correction, the percentage of patients who attained the MCID threshold were only reported descriptively.

Propensity Score Matching

Patients were allocated to 2 groups depending on their respective type of osteotomy: the mowHTO group or lcwDFO group. To compare the isolated effect of the type of osteotomy relatively independent from confounders, baseline variables were equalized between the 2 groups via propensity score matching, a tool for causal inference in nonrandomized studies allowing for adjustment of covariates. For the matching, the following clinically relevant potentially confounding covariates were chosen as previously proposed in the setting of alignment-correcting osteotomies[19,31]: age at surgery, sex, body mass index (BMI), preoperative mechanical femorotibial axis, and time interval since surgery.

Statistical Analysis

Sample size was determined in an a priori power analysis performed with G*Power (HHU Düsseldorf).[7] To achieve a statistical power of 0.8 to detect the MCID of the WOMAC score of 16.1 points,[20] with an SD of 15 points between the 2 groups at a calculated effect size of 1.1, a total sample size of 15 patients per group was required. Propensity scores were calculated via multiple logistic regression analysis to match the groups for the following covariates: age at surgery, sex, BMI, preoperative mechanical femorotibial axis, and follow-up. A caliper width of 0.2 was set, in accordance with previous studies.[19,31] Nearest neighbor matching according to the propensity scores (greedy algorithm) was performed with a 1-to-1 match ratio. After matching, the respective covariates were compared between the 2 groups to exclude remaining significant differences. Categorical variables are reported as count and percentage. Continuous variables are reported as mean ± SD. The distribution in continuous variables was assessed via the Shapiro-Wilk test. Continuous variables between groups were compared using the independent Student test (parametric) or the Mann-Whitney *U* test (nonparametric). The paired *t* test (parametric) or the Wilcoxon test (nonparametric) for 2 related samples was used to compare pre- and postoperative values of each outcome parameter. The 95% CIs were calculated. Categorical variables were compared performing the binary Fisher exact test or the chi-square test, as statistically indicated. The level of significance was set at $P < .05$. All statistical analysis was performed using SPSS software Version 26.0 (SPSS, Inc).

RESULTS

Between January 2010 and October 2019, a review of the institutional database identified 535 knees (516 patients) that underwent a primary single-level osteotomy for symptomatic varus malalignment and had a minimum follow-up of 24 months. After application of inclusion and exclusion criteria, 50 patients (50 knees, 25 per group) were selected using propensity score matching; the selection process is illustrated in Figure 2.

After propensity score matching, the patient-specific variables such as age at surgery, sex, BMI, preoperative mechanical femorotibial axis, and follow-up did not differ significantly between the groups ($P > .05$, respectively) (Table 1) and were balanced, with a standardized mean difference of <0.2 for all parameters (Table 1). Comprehensive information on the relevant patient-specific variables before and after matching is provided in Table 1. Descriptive data on patient-specific variables, indication, and concomitant procedures are provided in Table 2.

As of a comprehensive leg alignment analysis (Table 3), the location of the deformity was predominantly tibial based in the mowHTO group, while it was predominantly femoral based in the lcwDFO group. Furthermore, the preoperative KJL orientation was tilted medially in the mowHTO group, while it was tilted laterally in the lcwDFO group ($P < .001$) (Table 3). Osteotomy was planned to restore physiologic knee alignment in both groups; detailed data on the planning of deformity correction can be found in Table 3.

At baseline, there was no statistically significant difference between groups in IKDC ($P = .251$; 95% CI, −4.1 to 15.4), WOMAC ($P = .552$; 95% CI, −14.0 to 7.6), and Lysholm scores ($P = .165$; 95% CI, −3.3 to 20.7) or Tegner Activity Scale ($P = .861$; 95% CI, −1.0 to 1.0) or VAS for pain ($P = .526$; 95% CI, −1.8 to 0.9).

In both groups, the patient-reported outcomes (PROs) significantly improved at a mean follow-up of 6.7 years for the IKDC, WOMAC, Lysholm score, and VAS for pain. The Tegner Activity Scale did not change significantly (Table 4).

When comparing the PROs at final follow-up between mowHTO and lcwDFO, there was no statistically significant difference between the groups in either the IKDC ($P = .291$; 95% CI, −4.7 to 15.3), WOMAC ($P = .953$; 95% CI, −7.0 to 3.0), Lysholm score ($P = .083$; 95% CI, −1.0 to 28.0), Tegner Activity Scale ($P = .608$; 95% CI, −0.7 to 1.2), or VAS for pain ($P = .187$; 95% CI, −2.0 to 0).

Furthermore, the pre- to postoperative change at the group level did not significantly differ between the mowHTO and lcwDFO groups for IKDC (16.6 ± 10.3 vs 18.5 ± 24.8; $P = .668$; 95% CI, −13.0 to 7.0), WOMAC (−12.0 ± 12.2 vs −11.4 ± 21.2; $P = .953$; 95% CI, −10.2 to 12.3), Lysholm (26.8 ± 16.5 vs 19.3 ± 32.0; $P = .536$; 95% CI, −11.0 to

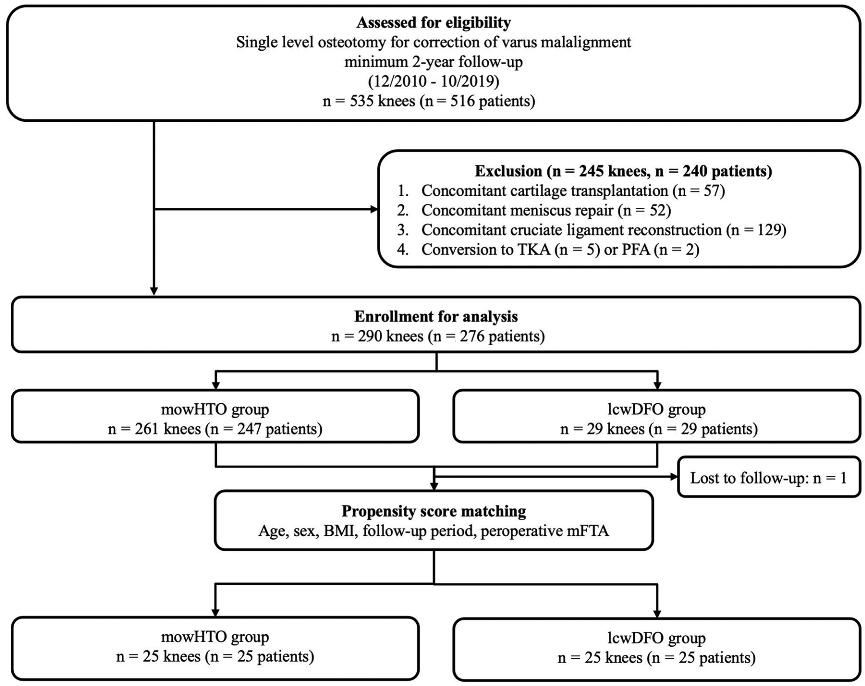

Figure 2. Flowchart visualizing the patient selection process for this study after accounting for inclusion and exclusion criteria. BMI, body mass index; lcwDFO, lateral closing wedge distal femoral osteotomy; mFTA, mechanical femorotibial angle; mowHTO, medial opening wedge high tibial osteotomy; PFA, patellofemoral arthroplasty; TKA, total knee arthroplasty.

TABLE 1

Baseline Parameters Between mowHTO and lcwDFO Groups Before and After Propensity Score Matching[a]

Variable	mowHTO	lcwDFO	Mean Difference	SMD	*P* Value
Total cases (n = 290)					
Sex					.038
Male	202 (77.4)	17 (58.6)			
Female	59 (22.6)	12 (41.4)			
Age at surgery, y	46.9 ± 11.25 (15 to 73)	47 ± 12.9 (18 to 72)	−0.10	−0.01	.968
BMI	26.7 ± 3.7 (18.4 to 43.1)	27.1 ± 3.9 (18.1 to 44.5)	−2.29	−0.58	.004
Follow-up, mo	70.01 ± 26.4 (25 to 122)	97.1 ± 39.5 (39 to 169)	−27.09	−0.93	.001
Preoperative mFTA,[b] deg	−5.5 ± 2.7 (−15.3 to −0.5)	−5.7 ± 2.4 (−1.2 to −10.5)	0.20	0.07	.681
Propensity score–matched cases (n = 50)					
Sex					.348
Male	17 (68)	15 (60)			
Female	8 (32)	10 (40)			
Age at surgery, y	47.8 ± 9 (29 to 72)	46.2 ± 10.4 (28 to 70)	1.56	0.16	.573
BMI	27.5 ± 5 (21.1 to 41.5)	28.3 ± 3.8 (18.1 to 36.1)	−0.75	−0.18	.556
Follow-up, mo	80 ± 20 (36 to 111)	81 ± 34 (30 to 154)	−1.72	−0.04	.828
Preoperative mFTA,[b] deg	−5.9 ± 2.4 (−11.8 to −2.8)	−6 ± 2.7 (−12.4 to −1.2)	−0.11	−0.04	.883

[a]Continuous variables are presented as mean ± SD (range); categorical variables are presented as n (%). BMI, body mass index; lcwDFO, lateral closing wedge distal femoral osteotomy; mFTA, mechanical femorotibial angle; mowHTO, medial opening wedge high tibial osteotomy; SMD, standardized mean difference.

[b]Negative values indicate varus malalignment.

19.0), Tegner Activity Scale (−0.3 ± 2.66 vs −0.41 ± 2.81; P = .720; 95% CI, −1.4 to 2.0), or VAS for pain (−2.5 ± 2.3 vs −2.1 ± 2.5; P = .542; 95% CI, −1.9 to 1.0).

Of the patients who were able to reach MCID mathematically, 83% of patients in the mowHTO group reached the MCID in either the IKDC (83%) or WOMAC (78%), which did not differ significantly from the lcwDFO group, in which 75% (P = .703) of the patients reached the MCID in either the IKDC (64%; P = .454) or WOMAC (75%; $P > .99$).

TABLE 2
Patient Population Characteristics[a]

Variable	mowHTO	lcwDFO	*P* Value
Laterality			.129
Right	10 (40)	15 (60)	
Left	15 (60)	10 (40)	
Smoker			.054
No	12 (48)	14 (66.7)	
Yes	7 (28)	7 (33.3)	
NA	6 (24)	0 (0)	
Indication			
Varus osteoarthritis			.999
No	3 (12)	3 (12)	
Yes	22 (88)	22 (88)	
Osteochondral lesion			.999
No	22 (88)	22 (88)	
Yes	3 (12)	3 (12)	
Posttraumatic condition			
No	25 (100)	25 (100)	
Yes	0 (0)	0 (0)	
Concomitant procedures			
Bone graft			.098
No	19 (76)	25 (100)	
Yes	6 (24)	0 (0)	
Partial meniscal resection			.463
No	19 (76)	22 (88)	
Yes	6 (24)	3 (12)	

[a]Categorical variables are presented as n (%). lcwDFO, lateral closing wedge distal femoral osteotomy; mowHTO, medial opening wedge high tibial osteotomy; NA, not available.

The incidence of complications did not significantly differ ($P = .349$) between the 2 groups, with 1 case of nonunion reported in the lcwDFO collective versus 3 cases of delayed union and 1 case of postoperative infection in the mowHTO collective.

DISCUSSION

This study provides evidence for 2 major findings. First, both mowHTO and lcwDFO yield significant improvements in clinical outcomes postoperatively at a mean of 6.7 years postoperatively when performed at the location of the varus deformity. Second, the data confirm that the clinical effectiveness of performing an isolated lcwDFO in femoral-based varus malalignment is comparable with the effectiveness of mowHTO in a matched cohort undergoing correction of varus malalignment. Based on these results, the limited efficacy of a DFO in higher degrees of knee flexion compared with HTO does not seem to have a clinically relevant effect on the postoperative outcome.

Recent biomechanical and clinical evidence on the effect of KJL questions the historical all-in-tibia approach to varus malalignment correction. When a mowHTO is performed in a predominantly femoral varus malalignment, this may result in the creation of an oblique KJL,[30] which emphasizes the paradigm that the corrective osteotomy should be performed at the location of the deformity to sustain a physiologic KJL postoperatively.[10,30] Biomechanical consequences of an oblique KJL created during mowHTO

TABLE 3
Osteotomy Simulation Parameters[a]

Variable	mowHTO	lcwDFO	*P* Value
Preoperative alignment parameters			
mFTA,[b] deg	−5.9 ± 2.4	−6.0 ± 2.7	.961
mLDFA, deg	89.9 ± 2.1	92.4 ± 1.9	**<.001**
mMPTA, deg	86.0 ± 2.1	88.6 ± 1.9	**<.001**
JLCA, deg	2.0 ± 1.6	2.3 ± 1.6	.485
KJL[c]	−0.6 ± 2.1	1.8 ± 2.9	**<.001**
Osteotomy-specific parameters			
Height of osteotomy gap, mm	8 ± 3	7 ± 3	.298
New WBL crossing the tibial plateau,[d] %	55.4 ± 2.6	54.9 ± 4.2	.401
Postoperative alignment parameters			
mFTA	1.5 ± 0.7	1.3 ± 0.9	.63
mLDFA, deg	89.9 ± 2.1	85.1 ± 2.1	**<.001**
mMPTA, deg	93.2 ± 1.6	88.6 ± 1.9	**<.001**
JLCA, deg	2.0 ± 1.6	2.3 ± 1.6	.395

[a]Pre- and postoperative alignment parameters after osteotomy simulation with MediCAD reveal significant differences in the mLDFA, mMPTA, and knee joint line orientation between tibial-based and femoral-based varus deformity: while the mMPTA is lower with greater potential for open wedge correction in tibial-based deformities that underwent mowHTO, the mLDFA is significantly higher and with greater potential for correction in femoral-based deformities that underwent lcwDFO. After simulation, physiologic alignment parameters were preserved in both groups. Continuous variables are presented as mean ± SD; categorical variables are presented as counts. Bold values denote a statistically significant difference. JLCA, joint line convergence angle; KJL, knee joint line; lcwDFO, lateral closing wedge distal femoral osteotomy; mFTA, mechanical femorotibial angle; mLDFA, mechanical lateral distal femoral angle; mMPTA, mechanical medial proximal tibial angle; mowHTO, medial opening wedge high tibial osteotomy; WBL, weightbearing line.

[b]Negative values indicate varus malalignment.

[c]Negative value indicate medial inclination.

[d]0% = medial edge of tibial plateau, 100% = lateral edge of tibial plateau.

TABLE 4
Pre- and Postoperative Patient-Reported Outcomes

Variable	HTO Preoperatively	HTO Postoperatively	*P* Value	95% CI	DFO Preoperatively	DFO Postoperatively	*P* Value	95% CI
IKDC	55.1 ± 16.5	71.3 ± 14.7	.002	11.8 to 21.4	49.4 ± 14.6	66 ± 20.1	**.003**	6.6 to 26.9
WOMAC	22 ± 18	9.6 ± 10.8	<**.001**	−6.2 to −17.7	25.2 ± 17	12.9 ± 17.6	**.003**	−3.4 to −22.5
VAS	4.1 ± 2.4	1.6 ± 1.8	<**.001**	1.4 to 3.5	4.5 ± 2.2	2.6 ± 2.5	**.001**	3.2 to 1.1
Lysholm	55.2 ± 23.1	80.7 ± 16	<**.001**	18.8 to 34.7	46.5 ± 15.6	65.4 ± 28.7	**.011**	5.9 to 32.9
Tegner	4.1 ± 2.2	3.6 ± 1.3	0.675	0.9 to 1.5	4.1 ± 2.6	3.4 ± 1.9	.357	0.8 to 1.9

Patients of both the HTO and the lateral closing wedge DFO group significantly improved in IKDC, WOMAC, Lysholm, and VAS for pain compared with preoperatively, while Tegner activity level did not change significantly. Continuous variables are presented as mean ± SD; categorical variables are presented as counts. Bold values denote a statistically significant difference. DFO, distal femoral osteotomy; HTO, high tibial osteotomy; IKDC, International Knee Documentation Committee; VAS, visual analog scale; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

include increased tibial contact pressure,[43] increased shear stress to the articular cartilage,[28] translational knee instability,[15] tibiofemoral subluxation,[43] and progressive degeneration of the joint space.[38] Clinically, this may translate into inferior PROs[38] and lateral compartment pain.[19]

A radiographic analysis showed a prevalence of an isolated femoral varus deformity in 23% of the patients undergoing corrective osteotomy for varus malalignment.[10] The data in the present study indicate that the preoperative KJL is already tilted laterally 1.8° in patients with a predominantly femoral deformity. This confirms previous findings of a laterally downsloping KJL of 2.2° preoperatively in patients with varus malalignment that is not based on a tibial deformity.[31] Consequently, indicating a mowHTO in these patients introduces the risk of surpassing the recently postulated cutoff for the postoperative KJL of 4° after mowHTO, as the lateral tilt of the KJL increases approximately 3° to 5° after mowHTO.[1,12,31] Of relevance, postoperative KJL of >4° has been shown to be associated with inferior clinical outcomes.[38]

More specifically, outcome data by Park et al[31] document that clinical results were inferior after mowHTO in a group of patients with a nontibial deformity compared with a matched cohort of patients with a tibial deformity. Comparable with the present study, in the study by Park et al, the preoperative KJL was already tilted laterally in patients with a nontibial varus deformity compared with patients with tibial deformity, in which the preoperative KJL was tilted medially.[31] Furthermore, there is additional evidence that an overcorrection of the mMPTA of >95° by mowHTO is associated with inferior postoperative outcomes at a short-term follow-up.[1]

Recent data report favorable clinical results after double-level osteotomy performed in an effort to maintain a physiologic KJL.[27,33,35,36] However, for a patient with a mild or moderate isolated femoral located varus deformity, a double-level osteotomy is relatively invasive, with complication rates of up to 19% of cases and a reported time frame of return to sports and work of 7.7 ± 4.8 and 5.9 ± 9.4 months, respectively.[33]

As a result of this unmet clinical need for a patient population with an isolated femoral varus deformity, an lcwDFO that exclusively addresses the femoral varus malalignment and retains the KJL has been proposed.[29] However, to date, clinical outcome data after isolated lcwDFO are sparse and reports are limited to case series.[11,16,22,34] As such, the results of the present study underscore the clinical efficacy of performing an isolated lcwDFO, with postoperative clinical outcome improvements exceeding the MCID for the IKDC Subjective Knee Form[32] established for mowHTO at a group level. The level of postoperative PROs is within the range of previous studies reporting a postoperative Lysholm score of 68 points in a collective of DFOs including 14 lcwDFOs.[16] Furthermore, the degree of improvement of lcwDFO of 19.3 points in the Lysholm score is within the range of a previous case series reporting a mean improvement of 19.6 points.[11]

Of note, there is a scarcity of evidence on the clinical effectiveness and postoperative outcomes after an isolated lcwDFO compared with an isolated mowHTO when the physiologic varus malalignment correction is performed at the location of the deformity. This is especially relevant, as there exists biomechanical concern regarding the efficacy of an isolated femoral deformity correction. Biomechanical data show that a DFO effectively unloads the affected compartment near full knee extension—the position of maximal mechanical stress during the stance phase of gait[24]—as quantified by peak contact pressure, mean contact pressure, and contact area.[44] However, a biomechanical study on the effect of DFO on tibiofemoral contact mechanics through knee flexion observed a limited efficacy of femoral correction during knee flexion.[44] Nevertheless, it is not clear to date whether this is of clinical relevance for the patient population undergoing malalignment correction.

In the present study, 2 cohorts undergoing lcwDFO and mowHTO for physiologic correction of varus malalignment were compared to address this question. The cohorts were matched on potentially confounding variables to examine the isolated effect of performing the correction at the location of deformity on postoperative clinical outcomes. Although there was a significant postoperative improvement of PROs in both groups, there was no significant intergroup difference in postoperative PROs or in the extent of pre- to postoperative improvement in any of the scores. A tool to evaluate the efficacy of a novel treatment such as lcwDFO compared with the gold standard such as mowHTO would be the determination of clinical noninferiority.[41] Even though propensity score matching, a tool for causal inference, was used in this study, claiming therapeutical noninferiority is reserved for a prospective randomized study design.[41] However, of interest, the 95% CI of the intergroup difference in the PROs did not include the noninferiority margin defined by the MCID for the WOMAC score[20] or IKDC Subjective Knee Form[32] in this cohort matched for cofounding factors. According to the statistical definition of noninferiority,[41] this fact is a descriptive indicator for therapeutical noninferiority that can be investigated in prospective study designs. The lower level of postoperative PROs in the lcwDFO group, in particular the Lysholm score, although not statistically significant, may potentially be explained by the lower level of PROs at baseline in this group.

In terms of external validity of the postoperative clinical outcome, results after single-level osteotomy in the present study fall within the range of isolated mowHTO at midterm follow-up, with reported IKDC scores of 67 to 69[5,37] and Lysholm scores of 67 to 76.[5,21] Of note, the Tegner Activity Scale in this study population did not improve significantly. This finding is in accordance with previous studies that highlighted the difficulty to return to higher levels of activity after osteotomy, with rates of return to high-impact activity after mowHTO,[17] DFO,[16] and double-level osteotomy[33] ranging approximately 9%, 6%, and 23%, respectively.

In terms of clinical relevance, a mounting body of work has advocated performing an lcwDFO for the surgical correction of a predominantly femoral varus deformity.[10,29,31] As patients included in this study were corrected according to the location of the deformity, the results do not provide a definitive answer on whether an lcwDFO produces superior outcomes compared with mowHTO in a predominantly femoral varus deformity. As such, it remains to be investigated if the effect of avoiding an oblique KJL clinically outweighs the effect of creating only limited unloading effects in higher degrees of flexion via a DFO. Although mowHTO has the advantages of technical ease, greater experience with the procedure, and proven clinical outcomes, the results of this study provide clinical evidence that lcwDFO is a viable option for this patient collective.

This study has several limitations. First, even though the risk of selection bias was minimized by matching for covariates, the study inherits the associated biases of a retrospective design. Second, the external validity of the results may be limited to the noncomparative aspect of including patients in a single reference center for alignment correction. Third, because of limitations by the radiation protection guidelines at the authors' institution, a postoperative hip-knee-ankle radiograph was not routinely collected. However, the accordance of preoperative planning and intraoperative correction was verified via intraoperative fluoroscopy in all cases.

CONCLUSION

In the correction of varus malalignment, performing both lcwDFO and mowHTO yields significant improvement in clinical outcomes if performed at the location of the deformity in an effort to sustain a physiologic joint line. Comparing the outcomes in a cohort matched for confounding variables, the postoperative improvement after lcwDFO is comparable with that of mowHTO. These findings confirm the clinical effectiveness of performing an isolated lcwDFO in a femoral-based varus malalignment.

ORCID iDs

Marco-Christopher Rupp https://orcid.org/0000-0001-7899-6299
Andreas B. Imhoff https://orcid.org/0000-0001-5085-6446

REFERENCES

1. Akamatsu Y, Kumagai K, Kobayashi H, Tsuji M, Saito T. Effect of increased coronal inclination of the tibial plateau after opening-wedge high tibial osteotomy. *Arthroscopy*. 2018;34(7):2158-2169.e2152.
2. Akamatsu Y, Nejima S, Tsuji M, Kobayashi H, Muramatsu S. Joint line obliquity was maintained after double-level osteotomy, but was increased after open-wedge high tibial osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(2):688-697.
3. Babis GC, An KN, Chao EY, Rand JA, Sim FH. Double level osteotomy of the knee: a method to retain joint-line obliquity: clinical results. *J Bone Joint Surg Am*. 2002;84(8):1380-1388.
4. Bellamy N, Buchanan WW, Goldsmith CH, Campbell J, Stitt LW. Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. *J Rheumatol*. 1988;15(12):1833-1840.
5. Bode G, von Heyden J, Pestka J, et al. Prospective 5-year survival rate data following open-wedge valgus high tibial osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(7):1949-1955.
6. Cao Z, Mai X, Wang J, Feng E, Huang Y. Unicompartmental knee arthroplasty vs high tibial osteotomy for knee osteoarthritis: a systematic review and meta-analysis. *J Arthroplasty*. 2018;33(3):952-959.
7. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175-191.
8. Feucht MJ, Mehl J, Forkel P, Imhoff AB, Hinterwimmer S. Distal femoral osteotomy using a lateral opening wedge technique. *Oper Orthop Traumatol*. 2017;29(4):320-329.
9. Feucht MJ, Minzlaff P, Saier T, et al. Degree of axis correction in valgus high tibial osteotomy: proposal of an individualised approach. *Int Orthop*. 2014;38(11):2273-2280.
10. Feucht MJ, Winkler PW, Mehl J, et al. Isolated high tibial osteotomy is appropriate in less than two-thirds of varus knees if excessive overcorrection of the medial proximal tibial angle should be avoided. *Knee Surg Sports Traumatol Arthrosc*. 2020;29(10):3299-3309.
11. Fürmetz J, Patzler S, Wolf F, et al. Tibial and femoral osteotomies in varus deformities—radiological and clinical outcome. *BMC Musculoskelet Disord*. 2020;21(1):201.
12. Goshima K, Sawaguchi T, Shigemoto K, Iwai S, Fujita K, Yamamuro Y. Comparison of clinical and radiologic outcomes between normal and overcorrected medial proximal tibial angle groups after open-

wedge high tibial osteotomy. *Arthroscopy*. 2019;35(10):2898-2908.e2891.
13. Harris JD, McNeilan R, Siston RA, Flanigan DC. Survival and clinical outcome of isolated high tibial osteotomy and combined biological knee reconstruction. *Knee*. 2013;20(3):154-161.
14. Hinterwimmer S, Beitzel K, Paul J, et al. Control of posterior tibial slope and patellar height in open-wedge valgus high tibial osteotomy. *Am J Sports Med*. 2011;39(4):851-856.
15. Hooper JM, Walker P, Hsu TT, et al. Biomechanical implications of an oblique knee joint line. *J Knee Surg*. 2018;31(8):761-766.
16. Hoorntje A, van Ginneken BT, Kuijer PPFM, et al. Eight respectively nine out of ten patients return to sport and work after distal femoral osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(7):2345-2353.
17. Hoorntje A, Witjes S, Kuijer PPFM, et al. High rates of return to sports activities and work after osteotomies around the knee: a systematic review and meta-analysis. *Sports Med*. 2017;47(11):2219-2244.
18. Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the International Knee Documentation Committee Subjective Knee Form. *Am J Sports Med*. 2001;29(5):600-613.
19. Kim GW, Kang JK, Song EK, Seon JK. Increased joint obliquity after open-wedge high tibial osteotomy induces pain in the lateral compartment: a comparative analysis of the minimum 4-year follow-up outcomes using propensity score matching. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(10):3495-3502.
20. Kim MS, Koh IJ, Choi KY, et al. The minimal clinically important difference (MCID) for the WOMAC and factors related to achievement of the MCID after medial opening wedge high tibial osteotomy for knee osteoarthritis. *Am J Sports Med*. 2021;49(9):2406-2415.
21. Kohn L, Sauerschnig M, Iskansar S, et al. Age does not influence the clinical outcome after high tibial osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(1):146-151.
22. Liska F, Haller B, Voss A, et al. Smoking and obesity influence the risk of nonunion in lateral opening wedge, closing wedge and torsional distal femoral osteotomies. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(9):2551-2557.
23. Lysholm J, Gillquist J. Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. *Am J Sports Med*. 1982;10(3):150-154.
24. Maquet P. The biomechanics of the knee and surgical possibilities of healing osteoarthritic knee joints. *Clin Orthop Relat Res*. 1980;146:102-110.
25. Miniaci A, Ballmer FT, Ballmer PM, Jakob RP. Proximal tibial osteotomy. A new fixation device. *Clin Orthop Relat Res*. 1989;246:250-259.
26. Minzlaff P, Saier T, Brucker PU, Haller B, Imhoff A, Hinterwimmer S. Valgus bracing in symptomatic varus malalignment for testing the expectable ''unloading effect'' following valgus high tibial osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(7):1964-1970.
27. Nakayama H, Iseki T, Kanto R, et al. Physiologic knee joint alignment and orientation can be restored by the minimally invasive double level osteotomy for osteoarthritic knees with severe varus deformity. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(3):742-750.
28. Nakayama H, Schröter S, Yamamoto C, et al. Large correction in opening wedge high tibial osteotomy with resultant joint-line obliquity induces excessive shear stress on the articular cartilage. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(6):1873-1878.
29. Ollivier M, Fabre-Aubrespy M, Micicoi G, Ehlinger M, Hanak L, Kley K. Lateral femoral closing wedge osteotomy in genu varum. *Orthop Traumatol Surg Res*. 2021;107(7):102989.
30. Paley D. *Principles of Deformity Correction*. Springer; 2002.
31. Park JG, Han SB, Jang KM. Association of preoperative tibial varus deformity with joint line orientation and clinical outcome after open-wedge high tibial osteotomy for medial compartment osteoarthritis: a propensity score-matched analysis. *Am J Sports Med*. 2021;49(13):3551-3560.
32. Patel S, Haunschild E, Gilat R, et al. Defining clinically significant outcomes following high tibial osteotomy with or without concomitant procedures. *J Cartilage Joint Preservation*. 2021;1(2):100014.
33. Rupp MC, Muench LN, Ehmann YJ, et al. Improved clinical outcome and high rate of return to low impact sport and work after double level osteotomy for bifocal varus malalignment. *Arthroscopy*. 2022;38(6):1944-1953.
34. Rupp MC, Winkler PW, Lutz PM, et al. Dislocated hinge fractures are associated with malunion after lateral closing wedge distal femoral osteotomy. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(3):982-992.
35. Saragaglia D, Rouchy RC, Krayan A, Refaie R. Return to sports after valgus osteotomy of the knee joint in patients with medial unicompartmental osteoarthritis. *Int Orthop*. 2014;38(10):2109-2114.
36. Schröter S, Nakayama H, Yoshiya S, Stöckle U, Ateschrang A, Gruhn J. Development of the double level osteotomy in severe varus osteoarthritis showed good outcome by preventing oblique joint line. *Arch Orthop Trauma Surg*. 2019;139(4):519-527.
37. Schuster P, Schulz M, Mayer P, Schlumberger M, Immendoerfer M, Richter J. Open-wedge high tibial osteotomy and combined abrasion/microfracture in severe medial osteoarthritis and varus malalignment: 5-year results and arthroscopic findings after 2 years. *Arthroscopy*. 2015;31(7):1279-1288.
38. Song JH, Bin SI, Kim JM, Lee BS. What is an acceptable limit of joint-line obliquity after medial open wedge high tibial osteotomy? Analysis based on midterm results. *Am J Sports Med*. 2020;48(12):3028-3035.
39. Sun H, Zhou L, Li F, Duan J. Comparison between closing-wedge and opening-wedge high tibial osteotomy in patients with medial knee osteoarthritis: a systematic review and meta-analysis. *J Knee Surg*. 2017;30(2):158-165.
40. Swanenburg J, Koch PP, Meier N, Wirth B. Function and activity in patients with knee arthroplasty: validity and reliability of a German version of the Lysholm score and the Tegner Activity Scale. *Swiss Med Wkly*. 2014;144:W13976.
41. Thoma A, Farrokhyar F, Waltho D, Braga LH, Sprague S, Goldsmith C. Users' guide to the surgical literature: how to assess a noninferiority trial. *Can J Surg*. 2017;60(6): 426-432.
42. van Raaij TM, Takacs I, Reijman M, Verhaar JA. Varus inclination of the proximal tibia or the distal femur does not influence high tibial osteotomy outcome. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(4):390-395.
43. Wang D, Willinger L, Athwal KK, Williams A, Amis AA. Knee joint line obliquity causes tibiofemoral subluxation that alters contact areas and meniscal loading. *Am J Sports Med*. 2021;49(9):2351-2360.
44. Wylie JD, Scheiderer B, Obopilwe E, et al. The effect of lateral opening wedge distal femoral varus osteotomy on tibiofemoral contact mechanics through knee flexion. *Am J Sports Med*. 2018;46(13):3237-3244.
45. Yan J, Musahl V, Kay J, Khan M, Simunovic N, Ayeni OR. Outcome reporting following navigated high tibial osteotomy of the knee: a systematic review. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(11):3529-3555.