osteology

Systematic Review

Comparative Outcomes of Minimally Invasive Versus Open Hallux Valgus Surgery: A Systematic Review and Meta-Analysis

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Abstract: Objectives: To compare the safety and efficacy of open surgery (OS) and minimally invasive surgery (MIS) techniques in the correction of symptomatic hallux valgus (HV). **Methods:** A systematic review of studies up to January 2024 was conducted, identifying all the relevant literature comparing OS and MIS for symptomatic HV. Searches were performed across major databases including MEDLINE, Cochrane and EMBASE. A total of 32 studies were included, comprising randomised control trials, prospective and retrospective cohort studies as well as grey literature. Key outcomes assessed included radiographic measures such as the hallux valgus angle (HVA), intermetatarsal angle (IMA), and distal metatarsal articular angle (DMAA), with preoperative and postoperative angles analysed to calculate the power of correction. Secondary outcomes included American Orthopaedic Foot and Ankle Society (AOFAS) scores, operative time, hospital stay duration, radiation exposure and complication rates. Both fixed-effect and random-effects models were applied based on the observed heterogeneity in the data. **Results:** Thirty-two studies with 2423 patients contributed to the summative outcome. Postoperative HVA and IMA were comparable between OS and MIS groups. However, MIS showed a significantly lower DMAA angle (MD = −0.90, CI: −1.55 to −0.25, $p = 0.01$). In radiographic correction analysis, MIS demonstrated significantly greater DMAA correction (MD = 1.09, CI: 0.43 to 1.75, $p = 0.001$). The odds of hardware removal were significantly higher with MIS (OR = 2.37, CI: 1.41 to 4.00, $p = 0.001$). Functional analysis showed that MIS achieved significantly higher postoperative AOFAS scores (MD = 2.52, CI: 0.92 to 4.13, $p = 0.002$). MIS was associated with a shorter operative (MD = −12.07 min, CI: −17.02 to −7.11, $p < 0.00001$) and a significantly shorter hospital stay (MD = −0.76, CI: −1.30 to −0.21, $p = 0.007$). MIS was linked to higher radiation exposure (MD = 51.18, CI: 28.71 to 73.65, $p < 0.00001$). **Conclusions:** There is no definitive superiority between MIS and OS for hallux valgus correction. While MIS offers benefits such as improved DMAA correction, higher functional AOFAS scores, shorter operative times and reduced hospital stays, it also carries risks like increased radiation exposure and a higher rate of hardware removal. The decision between MIS and OS should be personalised, taking into account the specific needs and circumstances of each patient. Larger studies are warranted to validate these findings as newer MIS techniques continue to emerge and evolve.

Keywords: hallux valgus; bunion; MIS; minimally invasive; percutaneous; osteotomy; meta-analysis

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1. Introduction

Hallux valgus (HV) is a prevalent foot deformity characterised by the progressive lateral deviation of the great toe and a medial prominence of the first metatarsal head [1]. This multifactorial pathology often leads to significant pain and discomfort, causing patients to shift more weight onto the lesser metatarsals. Consequently, this compensatory mechanism increases the risk of transfer metatarsalgia, hyperkeratosis and stress fractures in the lesser toes [2].

When conservative treatments fail or HV severely affects quality of life, surgical intervention is often necessary. Traditionally, open surgery (OS) has been the gold standard method for correcting HV. OS offers the advantage of direct visualisation and precise correction of the deformity, which can be particularly beneficial in complex cases. It allows for the comprehensive correction of both the bony and soft tissue components of the deformity, contributing to long-term stability and reliable outcomes [3–5].

In contrast, minimally invasive surgery (MIS), specifically defined as minimally invasive percutaneous surgical techniques with internal fixation for correcting hallux valgus, has emerged as an alternative approach. These percutaneous techniques involve procedures performed through small skin punctures without large incisions, with control achieved through fluoroscopic guidance. By minimising soft tissue disruption, percutaneous techniques offer potential benefits such as shorter operation times, reduced hospital stays, faster recovery, less postoperative pain, and smaller scars [6–8].

The evolution of MIS techniques began with first-generation methods reported by Isham et al., which did not utilise internal fixation after osteotomy [9,10]. This was succeeded by second-generation techniques involving an axial Kirschner (K)-wire fixation following distal transverse osteotomy of the first metatarsal to provide greater stability [11,12]. The third generation introduced screw fixation after a distal chevron osteotomy to achieve metatarsal head translation, aiming to replicate the outcomes of an open osteotomy [10,13,14]. The most recent fourth-generation techniques employ double bi-cortical rigid screw fixation after an extra-articular transverse osteotomy to facilitate the translation of the metatarsal head across the coronal, sagittal and rotational planes [15].

Despite the potential advantages of MIS, there remains ongoing debate regarding its comparative effectiveness with OS. While MIS may offer reduced soft tissue damage and quicker recovery, open surgery remains a robust option with the ability to address complex deformities directly. This article aims to systematically review the literature on this topic and compare radiographic and clinical outcomes between OS and MIS techniques.

2. Material and Methods

A systematic review and meta-analysis were conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [16].

2.1. Eligibility Criteria

This meta-analysis included randomised controlled trials (RCTs), prospective cohort studies, retrospective cohort studies and grey literature written in English that compared MIS with OS for symptomatic hallux valgus. For inclusion, MIS procedures had to include percutaneous techniques. Only studies reporting at least one outcome related to radiographic measures, complications or patient satisfaction were considered. Studies were excluded if they focused on biomechanical research without clinical outcomes, lacked relevant outcome measures, concentrated on learning curves or skill acquisition or were cadaveric in nature.

2.2. Primary Outcomes

The primary outcomes assessed included radiographic measurements and complication rates. Studies were required to report both preoperative and postoperative angles, including the Hallux Valgus Angle (HVA), the Intermetatarsal Angle (IMA), and the Distal Metatarsal Articular Angle (DMAA), to calculate correction. Additionally, outcomes such as the rates of revision surgeries, hardware removals, recurrences and incidences of infections, chronic pain and osteoarthritis were evaluated. These measures were selected to comprehensively assess the effectiveness and safety of MIS versus OS for hallux valgus.

2.3. Secondary Outcomes

Secondary outcomes included operation duration in minutes, hospital stay in days, radiation exposure in seconds, postoperative Visual Analog Scale (VAS) score and American Orthopaedic Foot and Ankle Society (AOFAS) score. The AOFAS score evaluates pain, function and alignment through a combination of clinician-reported and patient-reported components [3]. The VAS score is a patient-reported measurement of pain intensity [3]. These measures provided a comprehensive view of patient satisfaction and overall surgical impact.

2.4. Literature Search Strategy

Two authors (AHK and MT) independently conducted comprehensive searches across multiple databases, including AMED, Cochrane, EMBASE, Google Scholar, MEDLINE and Scopus. The search strategy, developed using both text words and Medical Subject Headings (MeSH) terms, utilised Boolean operators “AND” and “OR” to construct a comprehensive search string. This strategy included terms such as “Hallux valgus”, “Bunion”, and “bunionectomy” combined with “Minimally invasive”, “MIS”, “minimally invasive chevron and akin”, “MICA”, “percutaneous”, “percutaneous chevron akin”, “PECA”, “PDO”, “percutaneous distal osteotomy”, “Isham”, “Bosch”, “Bösch”, “SERI”, and “Simple, Effective, Rapid, Inexpensive”, as well as “Open osteotomy”, “Open akin”, “open chevron”, “open scarf”, “open surgery”, and “open osteotomy”. The search was conducted without language or publication date restrictions to encompass both historical and contemporary studies. Databases were searched from their inception up to 25 January 2024, when the final search was completed.

2.5. Selection of Studies

Titles and abstracts of articles identified through the literature searches were independently evaluated by two authors, AHK and MT. Full texts of the pertinent reports were then retrieved for further review. Articles that satisfied the eligibility criteria were selected for inclusion in the meta-analysis. Any disagreements regarding study selection were resolved through discussion between the authors.

2.6. Data Extraction and Management

An electronic data extraction spreadsheet was created and pilot-tested on a sample of randomly selected articles, with adjustments made as needed. The spreadsheet included fields for study-related information such as primary author, year of publication, country, study type and details on the surgical approach for both minimally invasive and open surgeries. It also recorded cohort size, follow-up length and both primary and secondary outcome data. Two authors cooperatively collected and documented the data. Any discrepancies were resolved through discussion among the authors to ensure consistency and accuracy.

2.7. Data Synthesis

Data analysis was conducted by two authors using Review Manager 5.3 software (The Cochrane Collaboration, London, UK) [17–19]. For outcomes with heterogeneity levels below 50%, a fixed-effect model was applied, while a random-effects model was used for outcomes with higher heterogeneity. The results were presented in forest plots with 95% confidence intervals (CIs), and statistical significance was set at $p < 0.05$. For dichotomous outcomes, odds ratios (ORs) were calculated, while mean differences (MDs) were used for continuous data.

Statistical analysis was performed to evaluate the corrective power of outcome measures pre- and postintervention in each study. For this, the mean, standard deviation and sample size from two independent samples within the same intervention group were used to compute mean differences and standard errors. The standard deviation of the mean difference was derived by multiplying the standard error by the square root of the sample size [17].

2.8. Assessment of Heterogeneity

Heterogeneity among the studies was assessed using Cochran's Q test (χ^2). The degree of inconsistency was quantified using the I^2 statistic, which was interpreted as follows: 0% to 25% indicating low heterogeneity, 25% to 75% indicating moderate heterogeneity, and 75% to 100% indicating high heterogeneity.

2.9. Quality Assessment

The quality of all non-randomised studies was evaluated using the ROBINS-I tool, which assesses bias across domains such as confounding, participant selection and outcome measurement. For randomised controlled trials, the RoB 2 tool, a revised Cochrane risk-of-bias tool, was used to analyse potential biases in randomisation, deviations from intended interventions and outcome reporting.

2.10. Publication Bias

This was assessed using a funnel plot and use of a statistical test as suggested by Egger et al. [20]

3. Results

3.1. Literature Search Results

Our search strategy retrieved 617 studies, and after thoroughly screening the retrieved articles, the authors identified 32 studies that met the eligibility criteria (Figure 1).

3.2. Baseline Characteristics

A total of 33 studies were included, combining a total of 2423 patients, with 1209 in MIS and 1214 in the open surgery group. A table of baseline patient characteristics can be seen below (Table 1).

Table 1. Baseline characteristics of included studies.

Author	Year	Country	Study Design	MIS Technique	Feet Number		
					Total	MIS	OS
Balesar et al. [19]	2024	Netherlands	Prospective	MICA	68	42	26
Kim et al. [21]	2024	South Korea	Retrospective	Modified MICA	65	32	33
Nicolas et al. [22] *	2023	UK	RCT	MIS	31	17	14
Toepfer et al. [23] **	2023	Switzerland	Matched Pair	MICA	112	56	56
Hwang et al. [24]	2023	Korea	Retrospective	SERI	60	30	30
Tang et al. [25] ***	2023	China	Retrospective	MIS-Chevron	60	28	32
Tay et al. [26]	2022	Singapore	Matched Cohort	MICA	60	30	30
Li et al. [27]	2022	China	Retrospective	MIS	36	16	20
Patnaik et al. [4]	2022	UK	Retrospective	MIS-Chevron	54	27	27
Dragosloveanu et al. [28]	2022	Romania	RCT	Percutaneous Chevron	50	24	26
Xu et al. [29]	2022	China	Retrospective	MIS-Chevron Screw	54	31	23
Vieria et al. [30]	2022	Switzerland	Retrospective	MI Lapidus	91	47	44
Siddiqui et al. [31]	2021	USA	Retrospective	MIDMO	61	31	30
Guo et al. [32]	2021	China	Retrospective	POO	112	48	64
Torrent et al. [33]	2021	Spain	RCT	MI Scarf Osteotomy	58	30	28
Palmanovich et al. [34]	2020	Israel	RCT	SERI	36	21	15
Kaufmann et al. [35]	2020	Austria	RCT	MI Chevron	39	19	20
Schilde et al. [36]	2020	Germany	Retrospective	MI Akin	210	124	86
Lim et al. [37]	2020	Singapore	Prospective	MIS	104	52	52
Schulze et al. [38]	2019	Germany	Retrospective	Kramer	174	72	102
Choi et al. [39]	2019	South Korea	Retrospective	MIS	55	25	30
Frigg et al. [40]	2019	Switzerland	Prospective	MICA	98	48	50
Boksh et al. [41]	2018	UK	Prospective	Mini-scarf	37	16	21
Lai et al. [42]	2017	Singapore	Retrospective	PECA	87	29	58
Lee et al. [43]	2017	Australia	RCT	PECA	50	25	25
Brogan et al. [44]	2016	UK	Retrospective	MI distal chevron	65	41	24
Othman et al. [45]	2016	Egypt	RCT	Bosch	58	33	25
Poggio et al. [46]	2015	Spain	Retrospective	Kramer	202	69	133
Giannini et al. [47]	2013	Italy	RCT	SERI	40	20	20
Radwan et al. [11]	2012	Egypt	RCT	PDO	64	31	33
Maffulli et al. [12]	2009	Italy	Matched Cohort	Bosch	72	36	36
Roth et al. [48]	1996	Austria	Retrospective	Bosch	124	88	36

MI: minimally invasive, MICA: minimally invasive chevron akin, MIDMO: minimally invasive distal metatarsal osteotomy, MIS: minimally invasive surgery, PDO: percutaneous distal-metatarsal osteotomy, PECA: percutaneous chevron and akin, POO: percutaneous oblique osteotomy, RCT: randomised control trial, SERI: simple, effective, rapid, and inexpensive, UK: United Kingdom. * abstract only, ** poster only, *** preprint.

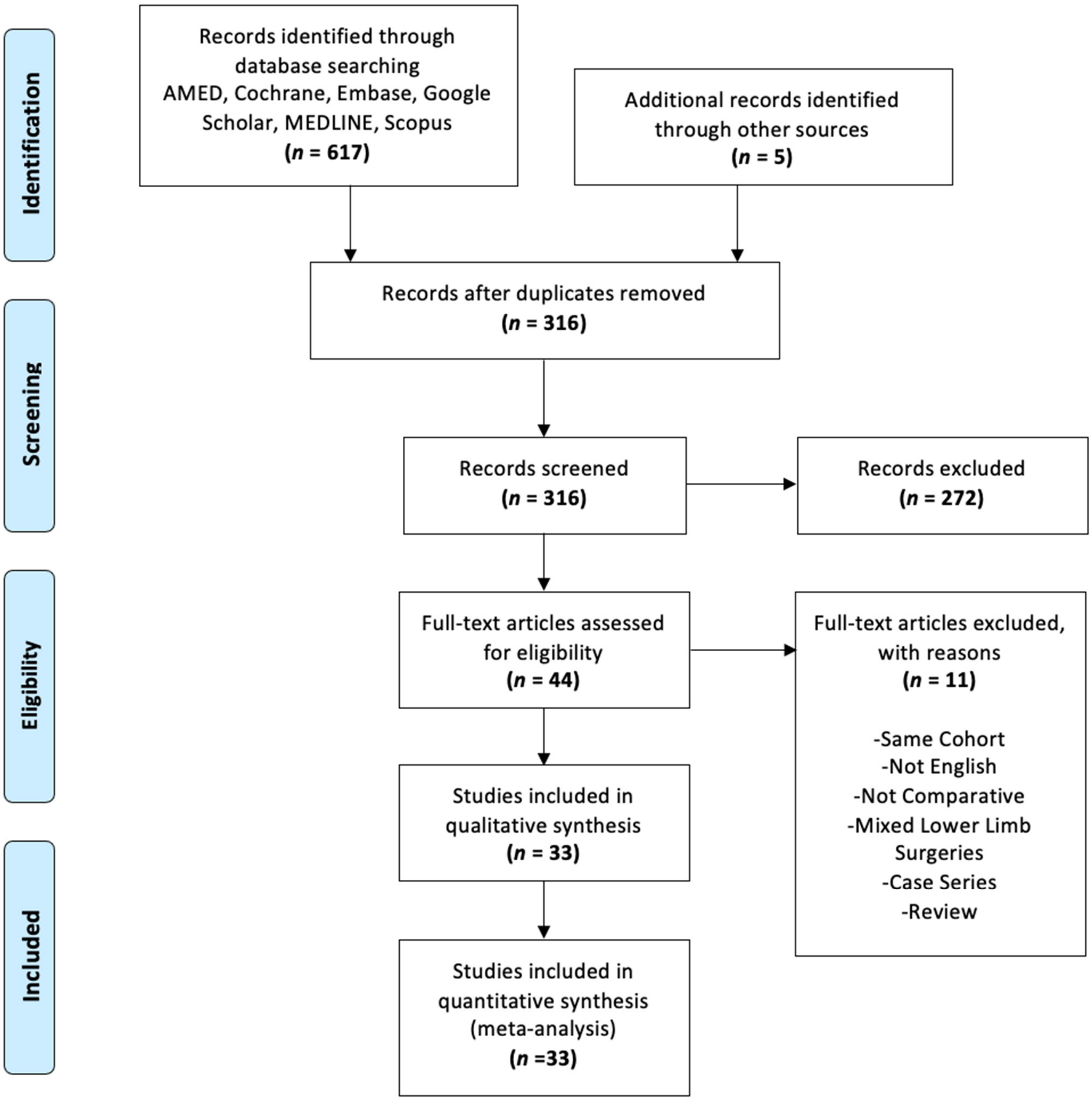

Figure 1. Prisma flow diagram. The PRISMA diagram details the search and selection processes applied during the overview. PRISMA, preferred reporting items for systematic reviews and meta-analyses.

3.3. Radiographic Outcomes

3.3.1. Postoperative HVA Angle

Postoperative HVA angle was reported in 22 studies with 1480 patients (Figure 2) [4,11,12,21,24–26,28–34,37,39,42–45,47,48]. The mean difference was −0.17 degrees (CI: −0.96 to 0.61), indicating a slight, non-significant difference between OS and MIS groups. Overall, heterogeneity was high ($I^2 = 76\%$, $p < 0.00001$). The difference in postoperative HVA angle was not statistically significant ($p = 0.66$).

3.3.2. Postoperative IMA Angle

The postoperative IMA angle was reported in 22 studies with 1630 patients (Figure 2) [4,11,12,21,24,26,28–30,34,36,37,39,42–45,47,48]. The mean difference was 0.16 degrees (CI: −0.26 to 0.59), indicating a small, non-significant difference between OS and MIS groups. Overall, heterogeneity was high (I^2 = 77%, $p < 0.00001$). The difference in postoperative IMA angle was not statistically significant ($p = 0.45$).

3.3.3. Postoperative DMAA Angle

The postoperative DMAA angle was reported in 11 studies with 654 patients (Figure 2) [12,21,25,29,30,33,34,39,44,45,47]. The MIS group had a significantly lower DMAA angle (MD = −0.90, CI: −1.55 to −0.25, $p = 0.007$). Heterogeneity was moderate (I^2 = 57%, $p = 0.010$).

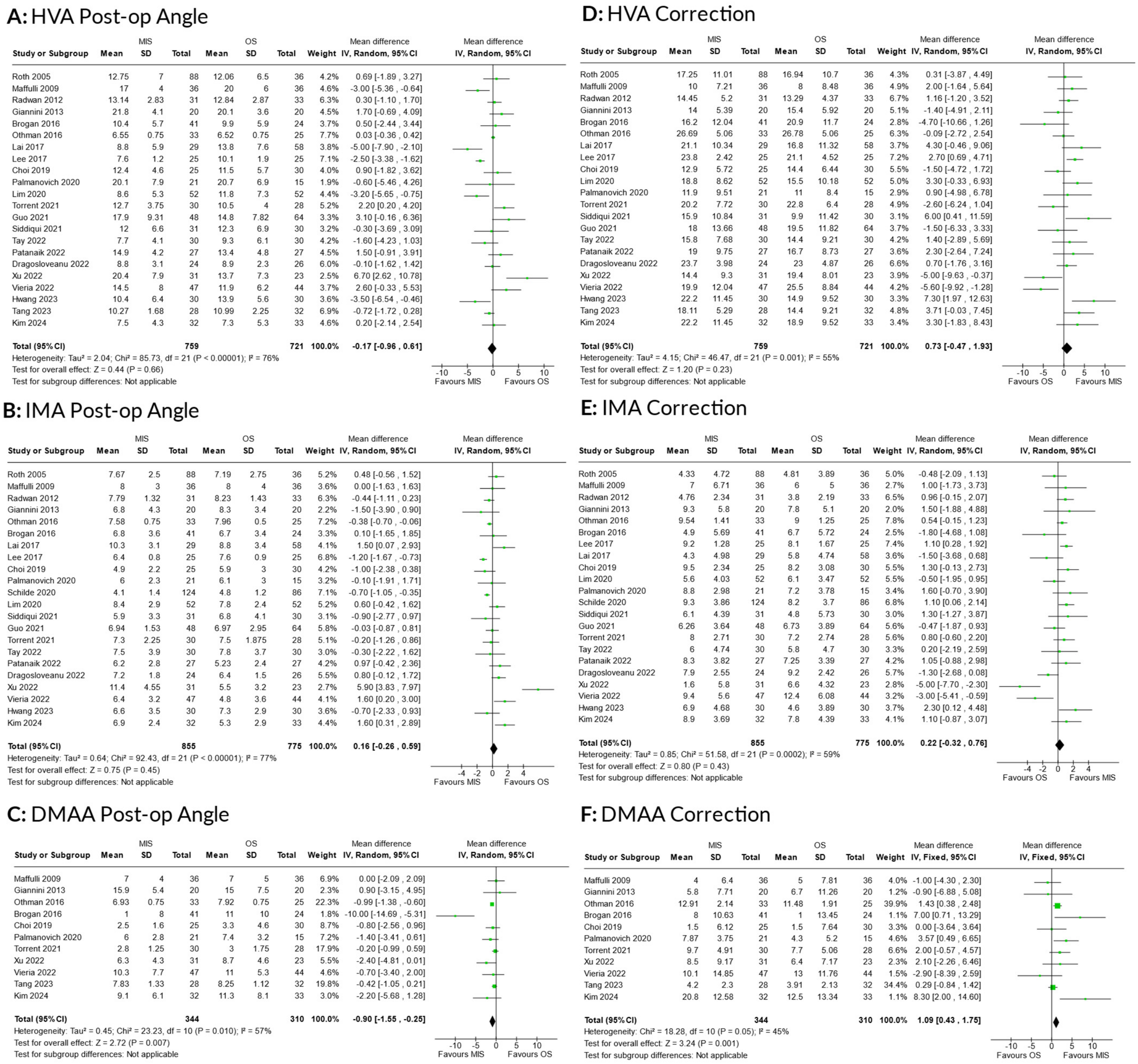

Figure 2. Forest plots of radiographic outcomes. (**A**) Postoperative HVA between MIS and open groups; (**B**) postoperative IMA; (**C**) postoperative DMAA; (**D**) HVA correction; (**E**) IMA correction and (**F**) DMAA correction. HVA, hallux valgus angle. MIS, minimally invasive surgery. IMA, intermetatarsal Angle. DMAA, distal metatarsal articular angle [4,11,12,21,24–26,28–31,33–37,39,42–45,47,48].

3.3.4. HVA Angle Correction

HVA correction was calculated from 22 studies with 1480 patients (Figure 2) [4,11,12,21,24–26,28–34,37,39,42–45,47,48]. The mean difference was 0.73 degrees (CI: −0.47 to 1.93), indicating a small, non-significant difference in corrective power between OS and MIS groups. The higher HVA correction suggests stronger corrective power, but the difference was not statistically significant (p = 0.23). Overall, heterogeneity was moderate (I^2 = 55%, p = 0.001).

3.3.5. IMA Angle Correction

IMA correction was calculated from 22 studies with 1630 patients (Figure 2) [4,11,12,21,24,26,28–31,33,34,36,37,39,42–45,47,48]. The mean difference was 0.22 degrees (CI: −0.32 to 0.76), indicating a small, non-significant difference in deformity correction between the OS and MIS groups. The higher angle suggests a greater correction of the deformity, but the difference was not statistically significant (p = 0.43). Overall, heterogeneity was moderate (I^2 = 59%, p = 0.0002).

3.3.6. DMAA Angle Correction

DMAA correction was calculated from 11 studies with 654 patients (Figure 2) [12,21,25,29,30,33,34,39,44,45,47]. MIS had significantly greater DMAA correction compared to the OS group (MD = 1.09, CI: 0.43 to 1.75, p = 0.001), indicating that MIS surgery was more effective in correcting the deformity. Overall, heterogeneity was moderate (I^2 = 45%, p = 0.05).

3.4. Analysis of Complications

3.4.1. Revision Surgery

Revision surgery rates were reported in 14 studies with 1125 patients (Figure 3) [4,12,21,25,29–34,37,39,40,46]. The analysis indicated higher odds of requiring revision surgery with MIS compared to OS (OR = 1.64, CI: 0.89 to 3.01), although this difference was not statistically significant (p = 0.11). Heterogeneity was low (I^2 = 8%, p = 0.37).

3.4.2. Recurrence

Recurrence rates were reported in 14 studies with 1046 patients (Figure 3) [21,29–31,33–35,37,39,40,44–46]. The analysis showed slightly lower odds of recurrence with MIS compared to OS (OR = 0.84, CI: 0.44 to 1.61), though the difference was not statistically significant (p = 0.60). Heterogeneity was very low (I^2 = 0%, p = 0.79).

3.4.3. Infection

Infection rates were reported in 16 studies with 1482 patients (Figure 3) [11,12,21,22,25,30,32,34,36,37,40,42,45,46,48,49]. The analysis showed no significant difference in the odds of infection between OS and MIS (OR = 1.35, CI: 0.75 to 2.42). Heterogeneity was very low (I^2 = 0%, p = 0.46), and the overall effect was not statistically significant (p = 0.32).

3.4.4. Hardware Removal

Hardware removal rates were reported in 19 studies with 1357 patients (Figure 3) [4,12,21,22,25,28–30,32–37,40,43,44,47,49]. The analysis showed significantly greater odds of hardware removal with MIS compared to OS (OR = 2.37, CI: 1.41 to 4.00). Heterogeneity was moderate (I^2 = 50%, p = 0.006), and the overall effect was statistically significant (p = 0.001).

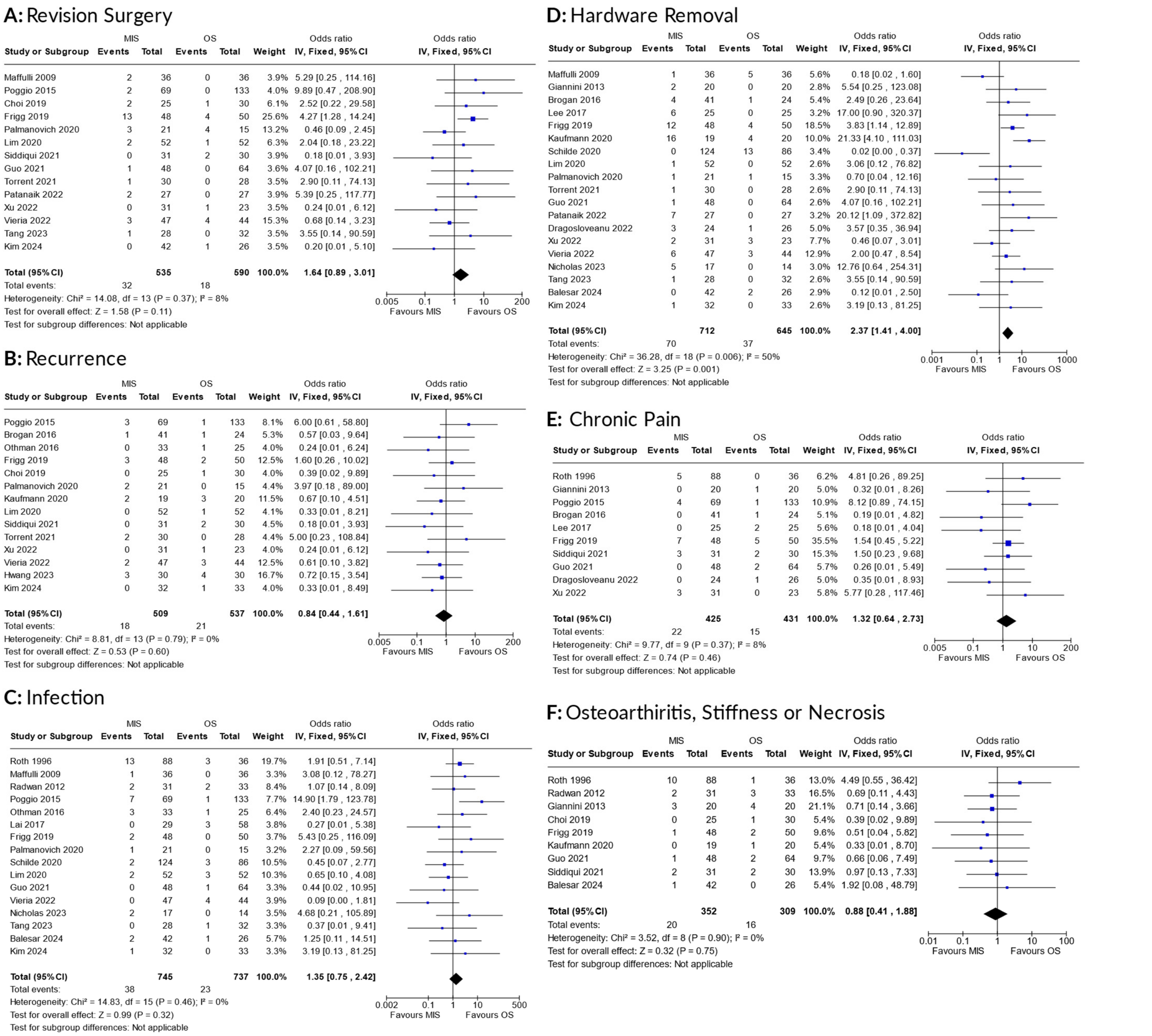

Figure 3. Forest plots of complications. (**A**) Odds of revision surgery between MIS and open groups; (**B**) recurrence; (**C**) infection; (**D**) hardware removal; (**E**) chronic pain and (**F**) osteoarthritis, stiffness or necrosis. MIS, minimally invasive surgery. [4,11,12,21,22,25,28–37,39,40,42–49].

3.4.5. Chronic Pain

Chronic pain was reported in 10 studies with 856 patients (Figure 3) [28,29,31,32,40,43,44,46–48]. The analysis showed no significant difference in the odds of chronic pain between OS and MIS (OR = 1.32, CI: 0.64 to 2.73). Heterogeneity was low (I^2 = 8%, p = 0.37), and the overall effect was not statistically significant (p = 0.46).

3.4.6. Osteoarthritis, Stiffness and Necrosis

Osteoarthritis, stiffness, or necrosis rates were reported in nine studies with 661 patients (Figure 3) [11,31,32,35,39,40,47–49]. The analysis showed no significant difference in the odds of these complications between OS and MIS (OR = 0.88, CI: 0.41 to 1.88). Heterogeneity was very low ($I^2 = 0\%$, $p = 0.90$), and the overall effect was not statistically significant ($p = 0.75$).

3.5. Postoperative Outcomes and Surgical Metrics

3.5.1. Operative Time (In Minutes)

Operative time was reported in nine studies with 738 patients (Figure 4) [11,12,21,33,37–39,42,45]. The analysis showed that MIS surgery had significantly shorter operative times compared to OS (MD = −12.07 min, CI: −17.02 to −7.11, $p < 0.00001$). Heterogeneity was very high ($I^2 = 94\%$, $p < 0.00001$), reflecting substantial variability among the studies.

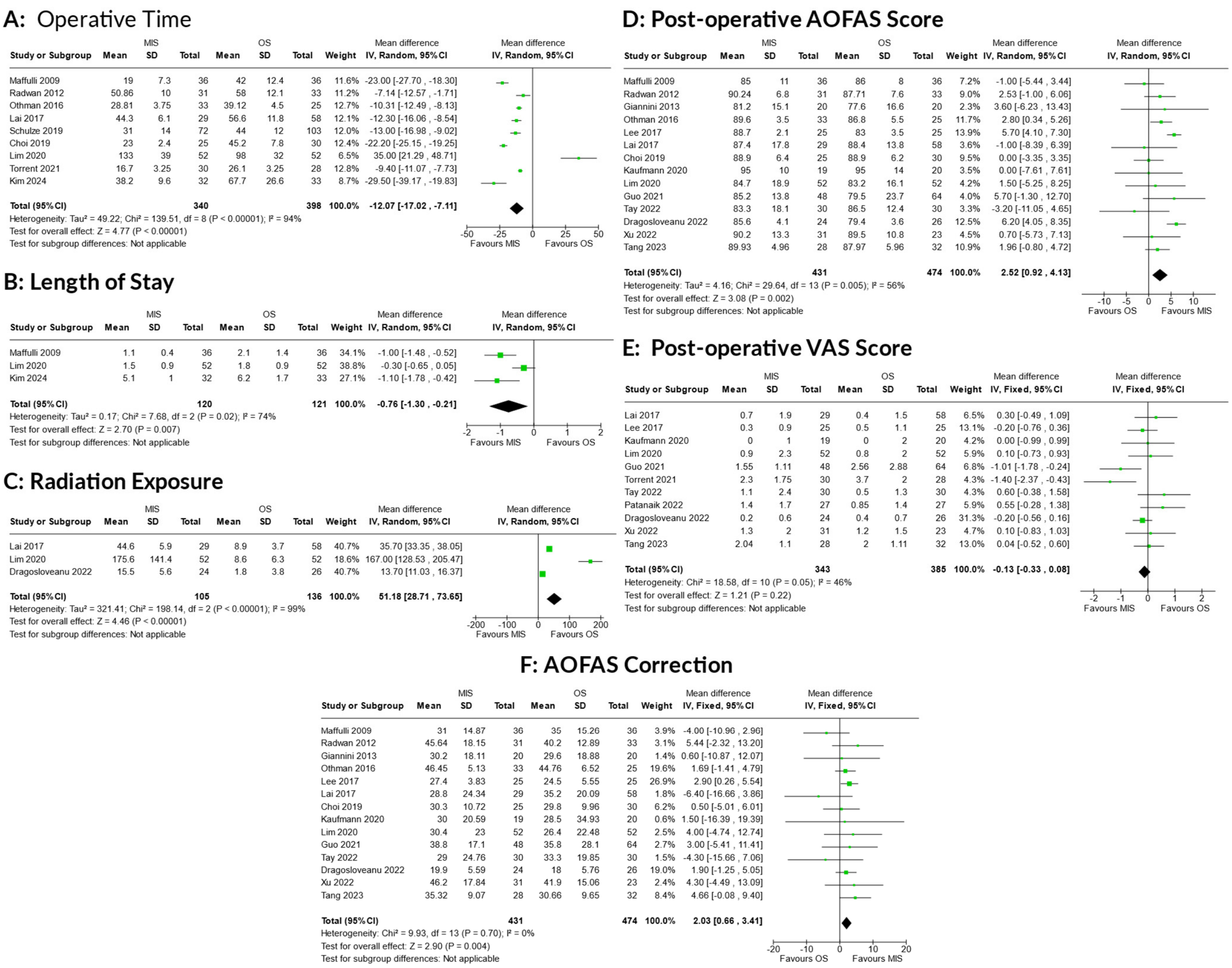

Figure 4. Forest plots of postoperative outcomes and surgical metrics. (**A**) Operative time between MIS and open groups; (**B**) length of stay; (**C**) radiation exposure; (**D**) postoperative AOFAS score; (**E**) postoperative VAS score and (**F**) AOFAS correction. MIS, minimally invasive surgery. AOFAS, American Orthopedic Foot and Ankle Society. VAS, visual analogue score [4,11,12,21,25,26,28,29,32,33,35,37–39,42,43,45,47].

3.5.2. Length of Stay (In Days)

Length of stay was reported in three studies with 241 patients (Figure 4) [12,21,37]. The analysis showed significantly shorter hospital stays with MIS compared to OS (MD = −0.76, CI: −1.30 to −0.21, $p = 0.007$). Overall, heterogeneity was moderate ($I^2 = 74\%$, $p = 0.02$).

3.5.3. Radiation Exposure (In Seconds)

Radiation exposure was reported in three studies with 241 patients (Figure 4) [28,37,42]. The analysis showed significantly higher radiation exposure with MIS compared to OS (MD = 51.18, CI: 28.71 to 73.65, $p < 0.00001$). Overall, heterogeneity was very high ($I^2 = 99\%$, $p < 0.00001$), indicating substantial variability among the studies.

3.5.4. Postoperative AOFAS Score

Postoperative AOFAS score was reported in 14 studies with 905 patients (Figure 4) [11,12,25,26,28,29,32,35,37,39,42,43,45,47]. The analysis showed significantly higher AOFAS scores with MIS compared to OS (MD = 2.52, CI: 0.92 to 4.13), indicating better functional outcomes. Overall, heterogeneity was moderate ($I^2 = 56\%$, $p = 0.005$). The difference in postoperative AOFAS score was statistically significant ($p = 0.002$).

3.5.5. Postoperative VAS Score

Postoperative VAS scores were reported in 11 studies with 728 patients (Figure 4) [4,25,26,28,29,32,33,35,37,42,43]. The analysis showed a slight reduction in pain with MIS compared to OS (MD = −0.13, CI: −0.33 to 0.08), though this difference was not statistically significant ($p = 0.22$). Heterogeneity was moderate ($I^2 = 46\%$, $p = 0.05$).

3.5.6. AOFAS Correction

The mean difference between preoperative and postoperative AOFAS scores was calculated in 14 studies with 905 patients (Figure 4) [11,12,25,26,28,29,32,35,37,39,42,43,45,47]. MIS had significantly better AOFAS correction compared to OS (MD = 2.03, CI: 0.66 to 3.41, $p = 0.004$). Overall, heterogeneity was low ($I^2 = 0\%$, $p = 0.70$).

3.6. Quality Assessment Results

The modified Cochrane Collaboration tool was used to assess the risk of bias in both randomised controlled trials (RCTs) and retrospective cohort studies. The risk of bias graphs for RCTs and non-RCTs are presented in Figure 5 and Figure 6, respectively [4,11,12,21–30,32–49].

3.7. Publication Bias

Publication bias was evaluated across the included studies using Egger's test, a linear regression method applied to the postoperative IMA angle data [20]. The results, depicted in Figure 7's funnel plot, indicated no significant evidence of publication bias ($p = 0.12$).

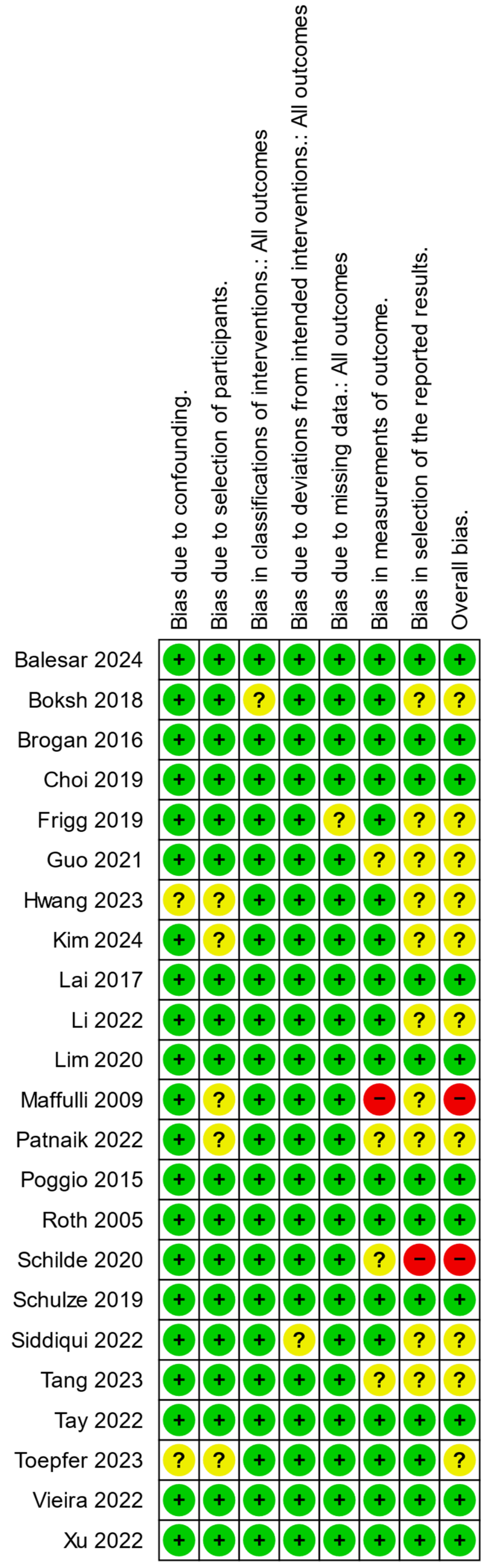

Figure 5. Quality assessment for non-randomised controlled trials (RCTs) using ROBINS-I tool. Key: +, low risk of bias; −, high risk of bias; ?, undetermined risk of bias [4,12,19,21,23–27,29–32,36–42,44,46,48].

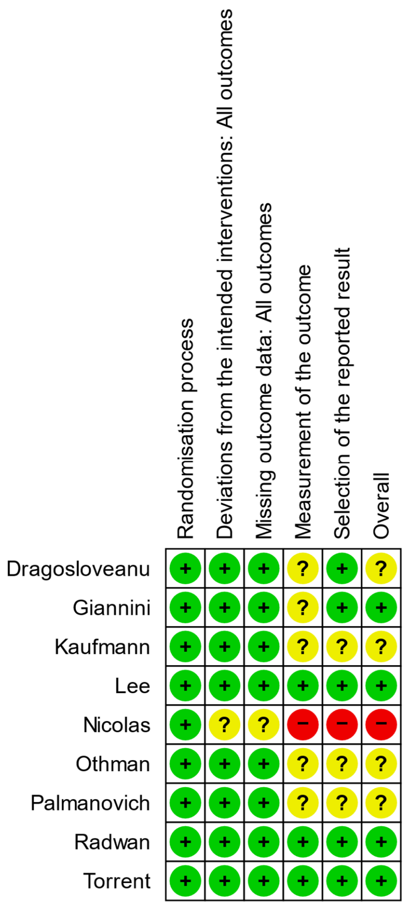

Figure 6. Quality assessment for randomised controlled trials (RCTs) using the RoB 2 tool. Key: +, low risk of bias; −, high risk of bias; ?, undetermined risk of bias [11,22,28,33–35,43,45,47].

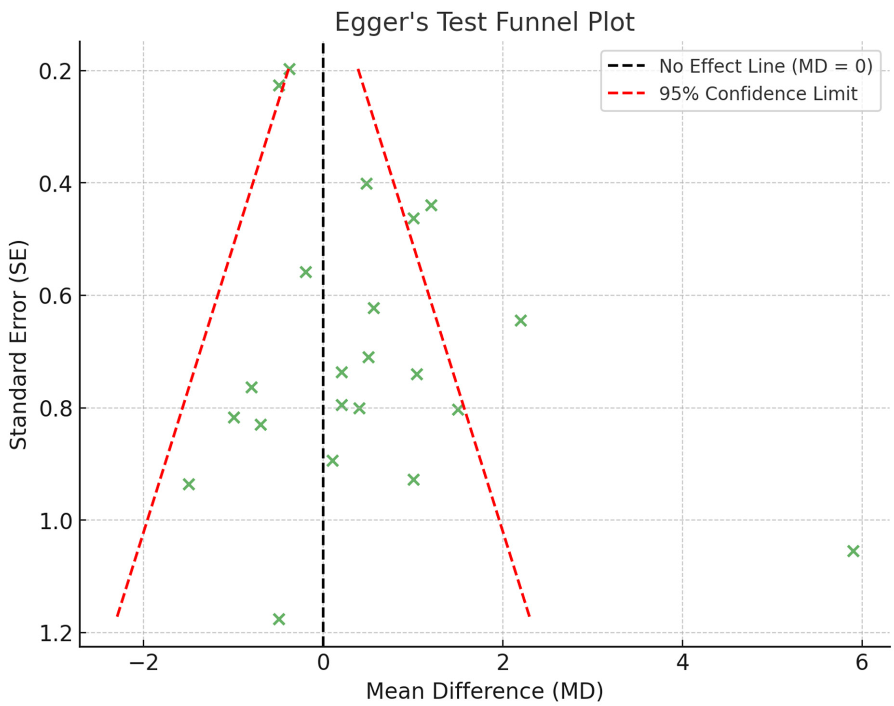

Figure 7. Egger's test funnel plot.

4. Discussion

This meta-analysis compares the outcomes of open surgery (OS) and minimally invasive surgery (MIS) for hallux valgus (HV) correction, focusing on radiographic corrections, complication rates and functional outcomes. As surgical techniques continue to evolve, the use of MIS for HV correction has gained attention due to its potential benefits in reducing tissue trauma and recovery time. The recent NICE guidance recommends minimally invasive percutaneous techniques with internal fixation as a viable option for HV correction, provided standard clinical governance and audit measures are in place. NICE concluded that MIS performs comparably to OS regarding pain and recovery, with no major safety concerns, but noted a lack of strong evidence favouring one MIS technique over another [50].

Our analysis revealed that while MIS and OS exhibit similar radiographic results for key parameters such as the HVA and IMA, MIS demonstrates notable advantages in certain areas. Specifically, MIS shows superior postoperative alignment in DMAA and better functional recovery, as evidenced by higher AOFAS scores, shorter operative times and length of stay. However, MIS is associated with higher rates of hardware removal and increased radiation exposure. Overall, these results suggest that MIS offers comparable if not slightly improved outcomes in terms of postoperative recovery and functional performance. However, considerations regarding radiation and hardware-related issues should be considered when choosing the appropriate surgical approach.

To our knowledge this meta-analysis is the most comprehensive to date, including 32 studies—surpassing the scope of previous analyses by Ji et al. (22 studies), Lu et al. (11 studies), Singh et al. (9 studies) and Alimy et al. (seven RCTs) [3,5,51,52]. In addition to the larger number of studies, our meta-analysis offers several novel contributions. We are the first to systematically calculate and analyse angle corrections across all studies, providing a more detailed evaluation of deformity correction. Previous works did not offer this level of precision. Furthermore, our study breaks down specific complications, rather than pooling them together as earlier analyses did, offering a more nuanced understanding of the risks associated with each surgical approach. Another unique aspect of our analysis is the calculation of improvement in AOFAS scores, as opposed to only reporting final scores, giving a clearer picture of functional recovery over time.

When comparing radiographic outcomes, our findings revealed no significant differences between MIS and OS in key postoperative angles such as HVA and IMA. However, our analysis identified a significant advantage for MIS in the correction of the DMAA, a finding not emphasised in previous studies. The DMAA is the angle between the distal articular surface and the longitudinal axis of the first metatarsal. The superior correction of DMAA with MIS can be attributed to the transverse osteotomy technique typically employed in MIS. This offers surgeons greater control of the distal segment compared to the chevron or scarf osteotomies used in OS. This enhanced control in DMAA correction makes MIS particularly beneficial in patients with higher angle deformities, where achieving optimal realignment is crucial in prevent recurrence or revision surgeries. The correction in HVA and IMA between the two techniques were non-significant, suggesting both techniques are effective for typical HV cases. For patients with mild to moderate deformities, the choice of technique may therefore be guided by other factors such as patient preference, surgeon experience and the specific clinical scenario. However, in cases with severe deformities, MIS may offer an edge due to its superior control over DMAA, improving overall alignment and long-term outcomes.

The American Orthopaedic Foot and Ankle Society (AOFAS) score is a widely used tool for evaluating foot and ankle conditions. It integrates both patient-reported and physician-determined factors to gauge pain, function, and alignment on a scale from 0 to

100 [53]. In this analysis, MIS demonstrated significantly improved postoperative AOFAS scores, indicating patients who undergo MIS may achieve better functional recovery than those who have OS. As a non-validated measure that combines subjective patient inputs with objective clinician assessments, it is susceptible to bias and requires careful interpretation [54]. This raises the possibility of the AOFAS score exaggerating the effectiveness of techniques like MIS, potentially inflating perceived functional recovery benefits. While these limitations are crucial to acknowledge, the AOFAS score widespread implementation facilitates comparisons across various studies. Its findings, despite being potentially biased, still provide meaningful insights when understood within the scope of its limitations.

Another key advantage of MIS our analysis highlighted is its shorter operative durations and reduced hospital stays. MIS has the potential to reduce productivity loss and absenteeism costs by enabling patients to resume their daily activities and responsibilities sooner. This efficiency not only enhances patient quality of life but also mitigates the economic impact of lost wages and reduced productivity for both employees and employers. By minimising time off work due to surgery, MIS can contribute to a more sustainable workforce and lower overall healthcare costs.

In terms of complications, our analysis found no significant differences between OS and MIS in major adverse outcomes such as revision surgery, recurrence, wound infection, chronic pain, or osteoarthritis. This suggests that both techniques offer comparable safety profiles and these results are reassuring for both surgeons and patients when considering surgical options for HV correction. However, MIS was associated with a higher likelihood of hardware removal, an area of concern that warrants attention. This may be due to the use of more hardware in MIS or patient discomfort caused by its proximity to soft tissues.

The most frequent complication in our analysis was implant removal, particularly in earlier-generation techniques such as SERI and Bösch osteotomies with K-wires and third-generation minimally invasive chevron-akin osteotomies with cannulated screws. While this presents a clear challenge, recent improvements in screw morphology have reduced soft tissue irritation, potentially decreasing the need for hardware removal in future fourth-generation MIS techniques [15]. Additionally, a finite element analysis (FEA) model by Lewis et al. demonstrated that fixation with two screws, one bicortical and one intramedullary, was the optimal screw configuration in producing the lowest values for osteotomy displacement, minimum and maximum stress, and von Mises stress on both bone and screws [55]. This fourth-generation technique shows promise for improving outcomes, allowing for early weight-bearing and rehabilitation, and potentially reducing the incidence of implant removal. As these newer techniques become more widely adopted and improved screw designs are implemented, we anticipate further advancements in patient recovery and a reduction in hardware-related complications.

The learning curve is a critical factor to consider when adopting MIS for HV. Baumann et al. concluded that the learning curve for MIS in HV typically plateaus after approximately 35.5 surgeries (range 27–40) [51]. During this learning phase, surgeons experienced longer operating times and greater reliance on fluoroscopy. Despite these challenges, Baumann et al. found no significant difference in patient outcomes or complication rates between the learning phase and the plateau phase, suggesting that patient safety remains largely unaffected by the learning curve. However, they emphasised the need for further research to fully understand the impact of the learning curve on long-term outcomes. In our meta-analysis, several studies accounted for the learning curve by excluding early cases to mitigate the potential for complications. For example, two papers excluded the first 10 and first 20 cases, respectively, and one study initially abandoned MIS due to a high rate of burn wounds before resuming once the technique was perfected [34,35]. By excluding these early cases, the reported complication rates may reflect selective reporting bias, as complications during the learning curve were not included. Complications during the learning phase should not be viewed as just a byproduct, as they can have lasting effects on patients. To mitigate these risks, cadaveric training and thorough practice with MIS-specific instruments are highly recommended. This allows surgeons to develop the necessary tactile skills and lessen the learning curve's influence on patient outcomes.

This meta-analysis has several limitations that should be considered when interpreting the results. First, the inclusion of different generations of MIS techniques, some utilising K-wires and others one or two screws, contributes to high heterogeneity, complicating direct comparisons. Furthermore, the studies included in this meta-analysis span over two decades (1996–2024), a period during which there have been significant advancements in surgical techniques and peri-operative care. Newer fourth-generation MIS techniques have emerged in recent years, while older first- and second-generation techniques are likely to be phased out. This evolution complicates direct comparisons of surgical outcomes, as older techniques may no longer represent contemporary practice. Improvements in peri-operative care over the years and its variability across the globe, including better patient preparation, anaesthesia protocols and postoperative management, may have contributed to reduced operative times and shorter lengths of hospital stay, further complicating the interpretation of pooled outcomes. Advances in screw morphology and design over the past two decades also add complexity, as newer screws are designed to improve fixation and outcomes, making comparisons with older methods less reliable. Additionally, non-randomised studies and grey literature were included, which introduces potential biases inherent to retrospective designs. Variability in study duration and differing time points also affect consistency across pooled data. Furthermore, the incomplete reporting of primary and secondary outcomes in several studies limits the robustness of our findings. The AOFAS score, although widely used, is non-validated and may result in biased assessments. Moreover, some studies excluded early MIS cases to account for the learning curve, introducing selective reporting bias. Finally, the possibility of publication bias may have influenced the overall results.

5. Conclusions

In conclusion, this meta-analysis demonstrates that both OS and MIS for HV correction achieve similar radiographic outcomes, with MIS showing advantages in certain areas, such as superior DMAA correction, shorter operative times and improved functional recovery. However, MIS is associated with higher rates of hardware removal and increased radiation exposure, which must be carefully considered. While the learning curve for MIS presents challenges, adequate training can help mitigate complications. Overall, MIS offers comparable and, in some cases, improved outcomes, but requires careful patient selection and surgeon expertise.

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