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ORIGINAL RESEARCH

Effect of Cyclotorsion Compensation in Small Incision Lenticule Extraction Surgery for the Correction of Myopic Astigmatism: A Systematic Review and Meta-Analysis

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ABSTRACT

Introduction: Small incision lenticule extraction (SMILE) has made notable advancements in addressing myopic astigmatism. Nevertheless, the potential impact of cyclotorsion on surgical outcomes cannot be overlooked. This study aims to assess the effectiveness of cyclotorsion compensation technology in SMILE surgery for the correction of myopic astigmatism, examining its influence on postoperative visual quality.

Methods: A systematic review and meta-analysis were conducted. A comprehensive literature search was performed using databases, including PubMed, Web of Science, EMBASE, Cochrane Library, EBSCO, Scopus, CNKI, VIP, and Wan Fang. Studies meeting the criteria were selected and included. Data were independently extracted by three authors. Clinical outcome parameters were analyzed using Review Manager version 5.3.

Results: This meta-analysis included ten studies. The results showed that, compared with the control group (cyclotorsion compensation was not performed in SMILE), the following indicators in the cyclotorsion compensation group were: residual astigmatism (RA) [weighted mean difference (MD) = 0.73, 95% confidence interval (CI) + 0.26 to + 1.19, $P = 0.002$], spherical equivalent (SE) (MD = 1.99, 95% CI + 0.77 to + 3.21, $P = 0.001$), coma (MD = −0.06, 95% CI −0.08 to −0.04, $P < 0.00001$), higher-order aberrations (HOAs) (MD = −0.04, 95% CI −0.06 to −0.02, $P < 0.0001$), follow-up 6-month angle of error (AE) (MD = −2.67, 95% CI −3.71 to −1.63, $P < 0.00001$), and follow-up 6-month uncorrected distance visual acuity (UDVA) (MD = −0.05, 95% CI −0.08 to −0.01, $P = 0.005$), and the differences in results were statistically significant. However, the differences among correction index, index of success (IOS), targeted induced astigmatism (TIA),

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magnitude of error (ME), and spherical aberration (SA) were not statistically significant.
Conclusion: Cyclotorsion compensation proves to be effective and predictable for correcting myopic astigmatism. The cyclotorsion compensation group demonstrated advantages over the control group in terms of postoperative residual astigmatism, and it induced fewer coma aberrations. Whether cyclotorsion compensation can lead to better visual quality remains to be seen, and further research on correcting myopic astigmatism through cyclotorsion compensation is warranted.

Keywords: Cyclotorsion compensation; Small incision lenticule extraction surgery; Astigmatism

Key Summary Points

Why carry out the study?

Cyclotorsion compensation during small incision lenticule extraction (SMILE) surgery might serve as an effective means for correcting myopia and astigmatism, but it remains controversial.

In this study, we conducted a systematic review and meta-analysis to evaluate the impact of cyclotorsion compensation on the outcomes of myopia and astigmatism in SMILE surgery.

The purpose of this study is to enhance our understanding of cyclotorsion compensation and to comprehend its significance in the correction of astigmatism.

What was learned from the study?

Our systematic review and meta-analysis found that cyclotorsion compensation has an advantage in reducing residual astigmatism (RA) and is capable of inducing fewer coma aberrations.

This study can serve as an important resource for a better understanding of myopia, astigmatism, and SMILE surgery treatment strategies.

INTRODUCTION

Astigmatism, arising from irregular corneal or lens shapes, significantly affects the visual health of the global population. With recent advancements in refractive surgery technology, it has become a pivotal option for addressing astigmatism [1]. Since its inaugural report in 2011, small incision lenticule extraction (SMILE) utilizing the VisuMax femtosecond laser (Carl Zeiss Meditec, Germany) has transformed into a well-established surgical procedure for correcting myopia [2–4]. SMILE represents a paradigm shift in keratorefractive procedures, transitioning from traditional flap-based corneal dissection to flapless extraction using femtosecond lasers to create in-matrix lenses. In terms of safety, effectiveness, and predictability, SMILE is on par with femtosecond laser-assisted in situ keratomileusis (FS-LASIK) [5]. Compared to LASIK, SMILE boasts several advantages. It results in quicker recovery from dry eye symptoms, improved control of spherical aberration, and reduced induction of corneal aberrations [6]. These benefits stem from minimally invasive incisions that better preserve anterior corneal innervation and structural integrity [7, 8]. Consequently, SMILE has gained increasing popularity as one of the mainstream refractive surgeries [9].

Nevertheless, SMILE is not without its drawbacks. For instance, VisuMax lacks twist control, and the success of the treatment is heavily reliant on the skill of the ophthalmologists. This factor has sparked skepticism regarding SMILE's capability to effectively correct moderate or high myopic astigmatism, standing out as one of its major limitations [10]. SMILE exhibits lower efficacy in correcting astigmatism compared to LASIK [11–13]. Cyclotorsion misalignment can be triggered by various factors such as head and body movement during the laser procedure, ocular torsion from the vestibular system, and unmasking of cyclophoria. Even monocular fixation can result in significant cyclotorsion. When ocular cyclotorsion exceeds 2° and remains uncorrected, it can adversely affect astigmatism correction and lead to the induction of significant aberrations

[14]. Studies have indicated that manually compensating for static cyclotorsion, guided by preoperative limbal markings can result in improved astigmatism correction outcomes [15].

As small incision microlens extraction (SMILE) gains global recognition in refractive surgery, the surgical technique has undergone progressive refinement to simplify procedures and minimize complications. Additionally, there is an expanding body of research dedicated to exploring the application of cyclotorsion compensation for the correction of myopic astigmatism during SMILE surgery.

This study seeks to perform a systematic review and meta-analysis of pertinent international clinical studies. The primary objective is to comprehensively evaluate the effectiveness of cyclotorsion compensation technology in correcting various degrees of astigmatism through SMILE surgery and to assess its impact on postoperative visual quality.

METHODS

This study was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The PRISMA 2020 checklist can be found in the updated guideline [16].

Search Strategy

We conducted a comprehensive review of published studies and executed a systematic search for research on cyclotorsion compensation for astigmatism during SMILE surgery. Two independent reviewers carried out searches across various electronic databases, including PubMed, Web of Science, EMBASE, Cochrane Library, EBSCO, Scopus, CNKI, VIP, and Wan Fang. Our search terms encompassed small incision lenticule extraction (SMILE), myopic astigmatism (short- and near-sighted astigmatism), cyclotorsion compensation, and limbal marking. The search was not restricted by language or country, and the deadline for considering articles was December 1, 2023, spanning from the inception of the respective databases. Titles and abstracts underwent independent screening by two reviewers, and relevant studies were evaluated against predefined inclusion criteria. Any disparities were resolved through discussion between the two reviewers, ultimately reaching a consensus on the results and their interpretation. Taking PubMed as an example, its specific retrieval strategy is shown in Supplementary Material 1.

Eligibility Criteria

(1) Study design: Randomized controlled trials (RCTs) or case-control studies (CCs); (2) subjects: patients with myopia and astigmatism; (3) cyclotorsion compensation performed or not performed in SMILE surgery; (4) no local or systemic eye disease.

Exclusion Criteria

(1) Case reports, letters, comments, and reviews of studies from non-comparative studies and non-human investigations; (2) duplicate published studies; (3) articles without outcomes of interest were excluded from this review.

Data Extraction

Data extraction and quality assessment were carried out independently by two researchers (XWY and YL) using standardized forms. These forms included information such as the first author, publication year, and age, among others. The primary outcome of interest was a composite poor outcome, which encompassed preoperative visual acuity (uncorrected distance visual acuity [UDVA], spherical equivalent [SE], and residual astigmatism [RA]), astigmatism parameters (targeted induced astigmatism [TIA], surgically induced astigmatism [SIA], angle of error [AE], the magnitude of error [ME], correction index, and index of success [IOS]), and higher order aberrations ([HOAs], spherical aberration [SA], coma). In instances where discrepancies arose between the two researchers, a third researcher (KMX) intervened, and consensus was achieved through discussion. The standard form is shown in Supplementary Material 2.

Risk of Bias Assessment

In clinical studies related to SMILE, achieving a complete randomized, double-blind, controlled experimental design can be challenging. The studies included in our analysis comprised both randomized controlled trials (RCTs) and controlled studies. For the included RCTs, we assessed the risk of bias following the PRISMA guidelines, utilizing the Cochrane Bias Risk tool (version 5.3, The Cochrane Collaboration, 2020, Oxford, UK) [17]. Several aspects were evaluated, including the method of random sequence generation, use of blinding methods in the study, assignment concealment, data result integrity, selective reporting of data results, and potential bias from other sources. The evaluation details are provided and explained in the respective format. In addition, we assessed the quality of the included studies using the Newcastle-Ottawa Scale (NOS), a tool commonly employed for controlled studies [18], including selection, comparability, exposure, and outcome. The scores of the included six studies are shown in Table 2, along with the judgment of each bias risk item for each included study.

Analysis Methods

Review Manager version 5.3 was used to analyze the results. Continuous variable effect values were calculated using the weighted Mean difference (MD) and the corresponding 95% confidence interval (CI). The heterogeneity among the included studies was analyzed using χ^2 test ($\alpha = 0.1$), and the heterogeneity was quantitatively determined by I^2. $I^2 > 50\%$ indicates significant heterogeneity. The random effects model or the fixed effects model is selected according to the size of the heterogeneity. Describe when the comparative analysis is not possible. Further subgroup analysis was performed for the indexes with significant heterogeneity.

Ethical Approval

This article is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

RESULTS

Literature Search

By searching the database, 756 studies that may meet the requirements were identified, and 94 studies remained after eliminating duplicates. Seventy-one studies were excluded after selecting titles and abstracts. After further consideration of the remaining 23 articles, 13 were excluded for the following reasons: 3 studies did not provide the primary data identified in this study, 6 compared SMILE to other procedures, and 4 did not report the use of intraoperative cyclotorsion compensation techniques. Finally, ten studies [19–28] were included in this meta-analysis. The flow chart of literature retrieval is shown in Fig. 1.

Features of Included Studies

Table 1 summarizes the basic characteristics of the included studies. The studies were published from 2017 to 2023. The study design included four RCTs [22, 26–28] and six CCs [19–21, 23–25]; the research was mainly focused on China, where six studies were conducted, and France, India, Turkey, and South Korea, with one study each. Seven studies were followed for 3 months and three were followed for 6 months.

Quality Assessment of Included Study

Because the SMILE is difficult to achieve complete randomized controlled studies, most of the studies are non-randomized controlled studies, and only four RCTs were included in this study. The results of RCTs' bias risk assessment are shown in Fig. 2. Among the four RCTs, none of the studies mentioned the existence of

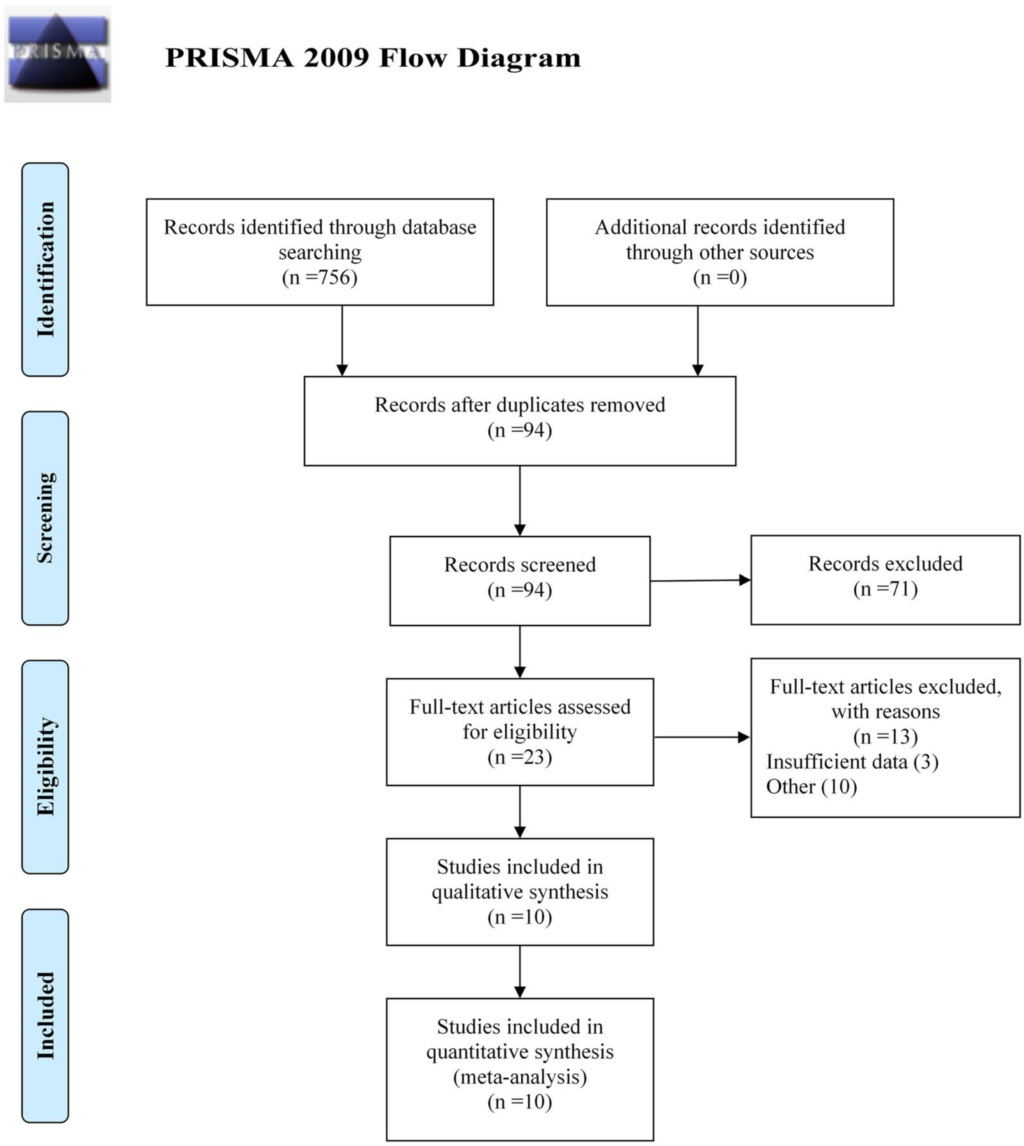

Fig. 1 Flow diagram of the study selection process

other bias, so it is unclear whether there is other bias, and the four studies did not implement allocation concealment. The definition of allocation concealment in the Cochrane glossary is a process by which, in a randomized controlled trial, the study implementers cannot know which comparison group the subjects are in. Therefore, we believe that the implementation of the blind method does not conflict with the absence of allocation concealment because the participants will know the process experienced during the operation, so there is no way to implement allocation concealment. Case-control studies were assessed using the Newscaster-Ottawa Scale (NOS) [18]. The NOS scores of these six studies were all > 7, which is a high-quality study with a low risk of bias, shown in Table 2.

Primary Outcome Measure

Meta-analysis of RA

A total of nine studies [19–25, 27, 28] evaluated the postoperative RA, including three RCTs

Table 1 Characters of included studies in the meta-analysis

First author year (Ref.)	Country	Research type	Sample size (T/C)	Age, (T/C) years	Preoperative column degree (T/C)	Follow-up (months)	Outcomes
Chen 2019	China	RCTs	54/30	20–30/23.5 ± 4.3	T: −1.72 ± 0.71 (−0.75 to −4.00) C: −1.67 ± 0.54 (−0.75 to −4.00)	6	RA, UDVA, SE, SIA, TIA, AE, ME
Köse 2020	Turkey	CCs	62/62	26.74 ± 3.6/24.83 ± 3.8	T: −1.87 ± 0.90 (−0.75 to −4.50) C: −1.97 ± 1.02 (−0.75 to−5.00)	6	RA, UDVA, SE, IOS, SIA, TIA, AE, ME, correction index
Gao 2020	China	CCs	34/24	20.2 ± 3.3/21.4 ± 5.5	T: −2.03 ± 0.41 C: −1.84 ± 0.35	3	RA, UDVA, SE, AE, Correction index
Wang 2021	China	RCTs	51/47	28.10 ± 8.25	–	3	SA, coma, HOAs
Wang 2022	China	RCTs	120/120	22 ± 4/23 ± 5	T: −1.55 ± 0.61 (−1.00 to −4.00) C: −1.57 ± 0.66 (−1.00 to −4.00)	3	RA, UDVA, SE, IOS, AE, ME, correction index
Xu 2019	China	RCTs	66/66	–	T: −1.52 ± 0.81 (−3.75 to −0.25) C: −1.57 ± 0.82 (−3.50 to −0.25)	3	RA, UDVA, SE, IOS, SIA, TIA, AE, ME, correction index
Ganesh 2017	India	CCs	81/81	27.01 ± 5.81	−1.85 ± 0.86 (−5.00 to −0.75)	3	RA, UDVA, SE,

Table 1 continued

First author year (Ref.)	Country	Research type	Sample size (T/C)	Age, (T/C) years	Preoperative column degree (T/C)	Follow-up (months)	Outcomes
Kang 2017	Korea	CCs	55/55	27.5 ± 6.2/ 27.5 ± 6.2	T: −1.09 ± 0.97 (−3.37 to 0.00) C: −0.90 ± 0.66 (−2.75 to 0.00)	3	RA, UDVA, SA, coma, HOAs
Assad 2019	France	CCs	164/164	31 ± 7	−2.01 ± 0.67 (−1.5 to −5)	3	RA, SE,
Yang 2020	China	CCs	71/71	24.37 ± 6.52/ 24.37 ± 6.52	−2.07 ± 0.69 (−1.50 to −4.75)	6	RA, SE,

T trails group; *C* control group; *RCT* randomized controlled trials; *CCs* case control studies: *RA* residual astigmatism: *UDVA* uncorrected distance visual acuity; *SE* spherical equivalent; *SIA* surgically induced astigmatism; *TIA* targeted induced astigmatism; *CI* correction index; *IOS* index of success; *AE* angle of error; *ME* magnitude of error; *SA* spherical aberration; *HOAs* higher-order aberrations

[22, 27, 28] and six CCs [19–21, 23–25]. There was significant heterogeneity among the studies ($I^2 = 99\%$, $P < 0.00001$), so the random effects model was used for analysis. The results showed that the cyclotorsion compensation group had a significant effect on the correction of RA compared with the control group, and the difference was statistically significant (MD = 0.73, 95% CI + 0.26 to + 1.19, $P = 0.002$). It is suggested that using cyclotorsion compensation based on standard SMILE can correct RA more significantly. Subgroups were divided into 3 and 6 months according to the follow-up time; after 3 months of follow-up, there was still high heterogeneity in subgroup analysis ($I^2 = 99\%$, $P < 0.00001$); the postoperative RA difference between the two groups was statistically significant (MD = 0.66, 95% CI + 0.1 to + 1.12, $P = 0.02$). However, the heterogeneity between the 6-month groups was still high ($I^2 = 99\%$, $P < 0.00001$), and there was no statistically significant difference in postoperative RA between the two groups (MD = 0.86, 95% CI −0.39 to + 2.12, $P = 0.18$), as shown in Fig. 3.

Meta-analysis of UDVA (logMAR)

Seven studies [19, 20, 22–24, 27, 28] evaluated postoperative UDVA (logMAR) uncorrected distance visual acuity, including three RCTs [22, 27, 28] and four CCs [19, 20, 23, 24]. The results showed high heterogeneity among the studies ($I^2 = 99\%$, $P < 0.00001$). Using a random effects model, the difference in UDVA between the two groups was not statistically significant (MD = −0.12, 95% CI −0.24 to −0.00, $P = 0.05$). It is suggested that using cyclotorsion compensation based on standard SMILE can significantly improve the outcome of UDVA. Subgroup analysis was performed at 3 and 6 months according to the follow-up time. After 3 months of follow-up, there was still high heterogeneity in the subgroup analysis ($I^2 = 100\%$, $P < 0.00001$), and there was no statistically significant difference in postoperative UDVA between the two groups (MD =

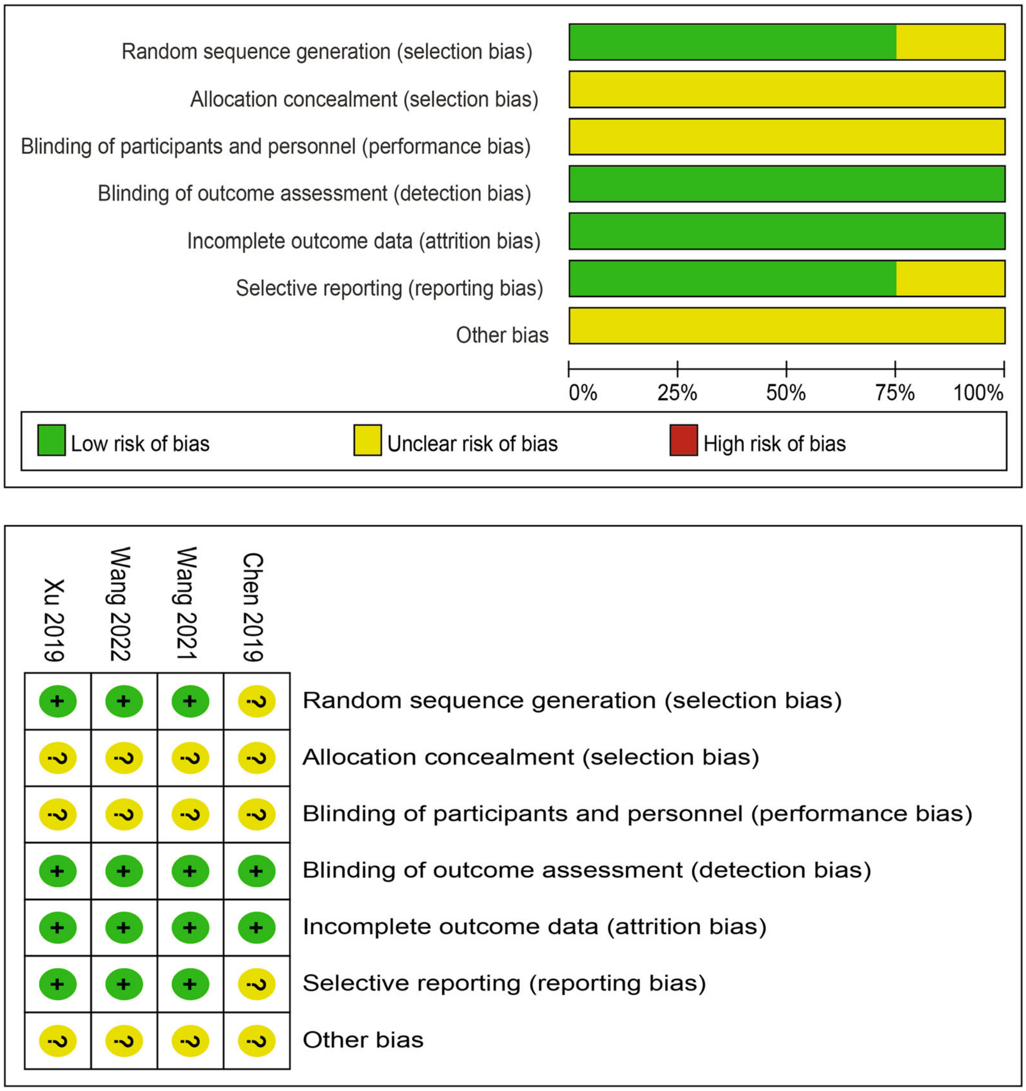

Fig. 2 Risk of bias graph of RCT studies. *RCT* randomized controlled trials

−0.15, 95% CI −0.30 to 0.00, $P = 0.06$). After 6 months of follow-up, inter-group heterogeneity disappeared ($I^2 = 0\%$, $P = 0.59$), and the postoperative UDVA difference between the two groups was statistically significant (MD = −0.05, 95% CI −0.08 to −0.01, $P = 0.005$), as shown in Fig. 4.

Meta-analysis of SE

Among the ten studies included, a total of eight studies [19, 21–25, 27, 28] evaluated postoperative SE outcomes, including three RCTs [22, 27, 28] and seven CCs [19, 21, 23–25]. There was significant heterogeneity among studies ($I^2 = 100\%$, $P < 0.00001$). Therefore, the random effects model was used for analysis. The results showed that there was a statistically significant difference in SE between the two groups (MD = 1.99, 95% CI + 0.77 to + 3.21, $P = 0.001$), suggesting that SMILE was more effective in improving SE after surgery. Subgroup analysis was performed at 3 and 6 months according to the follow-up time. There was still high heterogeneity in the 3-month subgroup analysis during follow-up ($I^2 = 100\%$, $P < 0.00001$), and the postoperative SE difference between the two groups was statistically significant (MD = 2.03, 95% CI + 0.75

Table 2 Results of quality assessment using the Newcastle-Ottawa Scale

Author	Selection	Comparability	Outcome	Score
Köse, 2020	3	2	3	8
Gao 2020	3.5	2	3	8.5
Ganesh 2017	3.5	2	3	8.5
Kang 2017	3	2	3	8
Assad 2019	3	2	3	8
Yang 2020	3.5	2	3	8.5

to + 3.30. $P = 0.002$). After 6 months of follow-up, the heterogeneity between the two groups was still significant ($I^2 = 100\%$, $P < 0.00001$), and there was no statistically significant difference in postoperative SE between the two groups (MD = 1.93, 95% CI −1.49 to + 5.34, $P = 0.27$), as shown in Fig. 5.

Outcome of Vector Analysis

Meta-analysis of Correction Index

Of the ten studies included, four [23, 24, 27, 28] assessed correction index outcomes, including two RCTs [27, 28] and two CCs [23, 24]. There was significant heterogeneity among the studies ($I^2 = 71\%$, $P = 0.02$), so the random effects model was used for analysis. The results showed that there was no statistically significant difference in correction index between the two groups (MD = 0.03, 95% CI −0.03 to + 0.08, $P = 0.35$), suggesting that the use of cyclotorsion compensation in addition to standard SMILE had no significant effect on improving the correction index, as shown in Fig. 6.

Meta-analysis of IOS

Of the ten studies included, three [23, 27, 28] evaluated IOS outcomes, including two RCTs [27, 28] and one CC [23]. Heterogeneity among studies was obvious ($I^2 = 16\%$, $P < 0.27$), so a fixed-effect model was used for analysis. The results showed that there was no statistically significant difference in IOS between the two groups (MD = −0.05, 95% CI −0.1 to + 0.01, $P = 0.10$), suggesting that the use of cyclotorsion compensation-based standard SMILE had

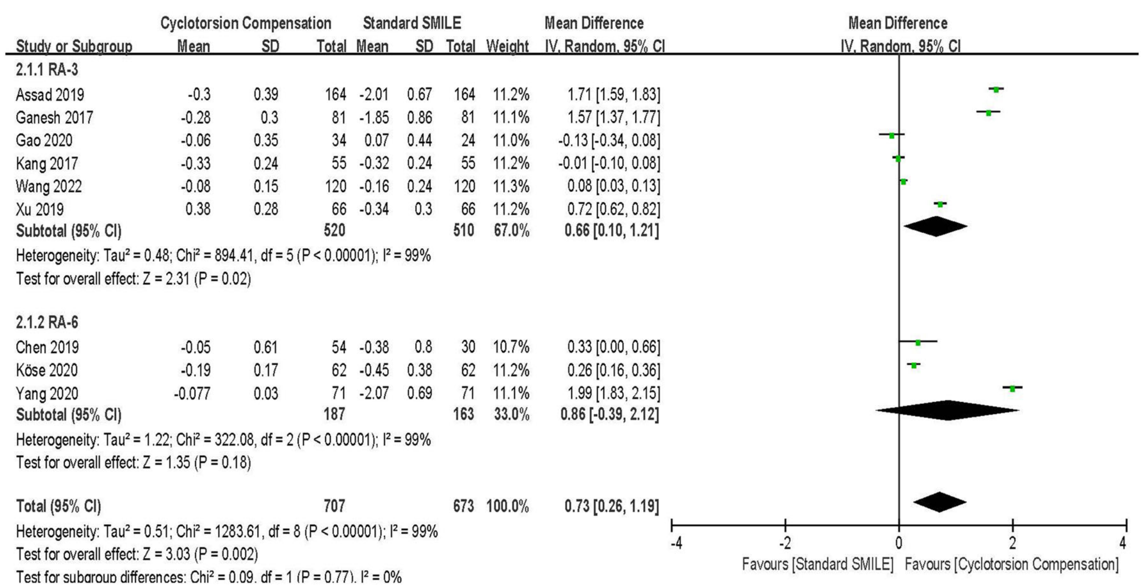

Fig. 3 Forest plot of the comparison results of postoperative residual astigmatism. *CI* confidence interval; *RA* residual astigmatism *SD* standard deviation; *SMILE* small incision lenticule extraction

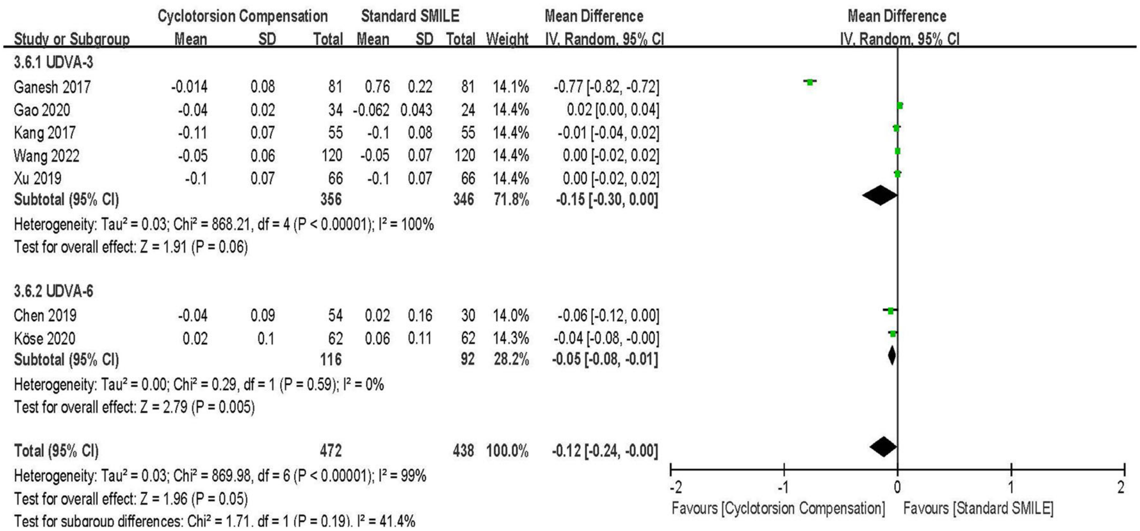

Fig. 4 Forest plot of the comparison results of postoperative UDVA. *CI* confidence interval; *SD* standard deviation; *SMILE* small incision lenticule extraction; *UDVA* uncorrected distance visual acuity

no significant effect on improving IOS. As shown in Fig. 7.

Meta-analysis of SIA

Of ten studies included, three [22, 23, 28] evaluated outcomes of SIA, including two RCTs [22, 28] and one CC [23]. There was significant heterogeneity among the studies ($I^2 = 64\%$, $P = 0.06$), so the random effects model was used for analysis. The results showed that there was no statistically significant difference in SIA between the two groups (MD = 0.13, 95% CI −0.13 to + 0.38, $P = 0.33$), suggesting that the use of cyclotorsion compensation in addition to standard SMILE had no significant effect on improving SIA, as shown in Fig. 8.

Meta-analysis of TIA

Of the ten studies included, three [22, 23, 28] evaluated TIA outcomes, including two RCTs [22, 28] and one CC [23]. There was no heterogeneity among the studies ($I^2 = 0\%$, $P = 0.79$), so the fixed-effect model was used for analysis. The results showed that there was no statistically significant difference in postoperative TIA between the two groups (MD = –0.03, 95% CI –0.18 to + 0.13, $P = 0.74$), suggesting that the use of cyclotorsion compensation in addition to standard SMILE had no significant effect on improving TIA, as shown in Fig. 9.

Meta-analysis of AE

Five studies [22–24, 27, 28] evaluated the outcomes of AE. The heterogeneity of each study was high ($I^2 = 63\%$, $P = 0.03$), so the random effects model was used. The results were as follows: compared with the control group, the effect of cyclotorsion compensation on AE was significantly different (MD = −1.24, 95% CI −1.77 to −0.71, $P < 0.00001$), suggesting that using cyclotorsion compensation in SMILE could improve the outcome of AE. Subgroup analysis was performed at 3 months and 6 months according to the follow-up time. The heterogeneity of analysis in the 3-month subgroup disappeared during follow-up ($I^2 = 0\%$, $P = 0.68$), and there was a statistically significant difference in AE between the two groups (MD = −0.74,95% CI −1.36 to −0.12, $P = 0.02$). At follow-up, the heterogeneity between the 6-month groups disappeared ($I^2 = 0\%$, $P = 0.61$), and the difference in AE between the two groups was statistically significant (MD = −2.67, 95% CI −3.71 to −1.63, $P < 0.00001$), as shown in Fig. 10.

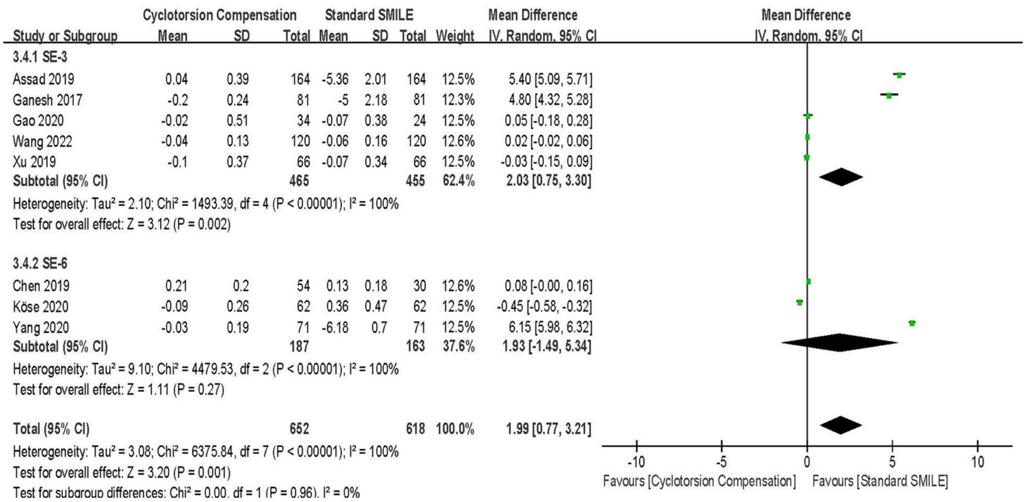

Fig. 5 Forest plot of the comparison results of postoperative SE. *CI* confidence interval; *SD* standard deviation; *SE* spherical equivalent; *SMILE* small incision lenticule extraction

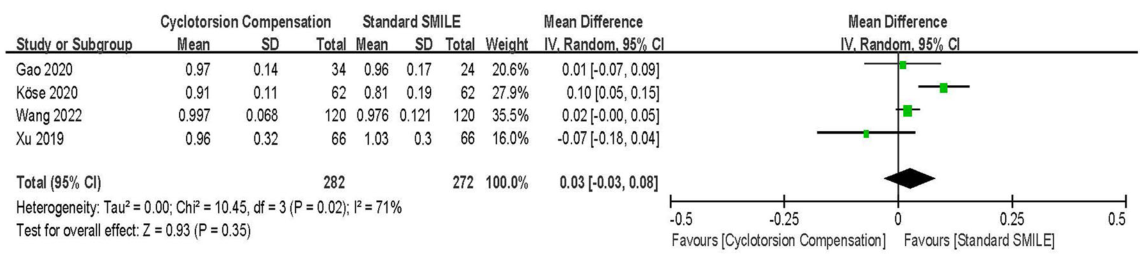

Fig. 6 Forest plot of the comparison results of postoperative correction index. *CI* confidence interval; *SD* standard deviation; *SMILE* small incision lenticule extraction

Meta-analysis of ME

Of the included studies, four [22, 23, 27, 28] studies evaluated ME outcomes, including 3 RCTs [22, 27, 28] and 1 CC [23]. Heterogeneity among studies was high ($I^2 = 87\%$, $P < 0.0001$), so a random effects model was used for analysis. The results showed that there was no significant difference in the effect of cyclotorsion compensation on ME correction compared with the control group (MD = 0.02,95% CI −0.13 to + 0.17, $P = 0.79$), suggesting that using cyclotorsion compensation based on standard SMILE had no significant effect on improving the outcome of ME, as shown in Fig. 11.

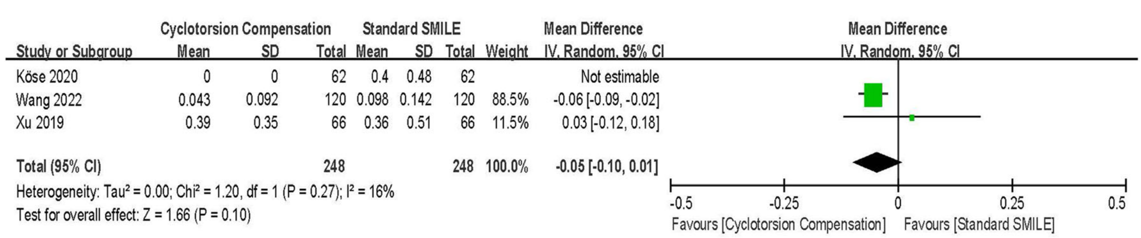

Fig. 7 Forest plot of the comparison results of postoperative IOS. *CI* confidence interval; IOS index of success; *SD* standard deviation; *SMILE* small incision lenticule extraction

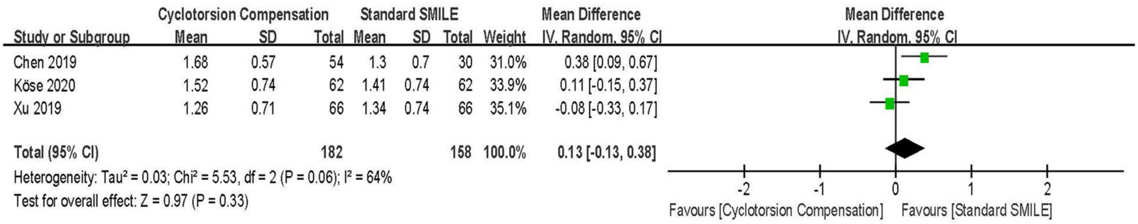

Fig. 8 Forest plot of the comparison results of postoperative SIA. *CI* confidence interval; *SIA* surgically induced astigmatism; *SD* standard deviation; *SMILE* small incision lenticule extraction

Meta-analysis of High-Order Aberrations

Meta-analysis of SA

Three studies [20, 26, 28] evaluated spherical aberration outcomes, including two RCTs [26, 28]. Heterogeneity among studies was high (I^2 = 98%, $P < 0.0001$), so a random effects model was used for analysis. The results showed that the effect of cyclotorsion compensation on SA correction was not statistically significant compared with the control group (MD = 0.04,95% CI −0.06 to + 0.13, P = 0.45), suggesting that using cyclotorsion compensation based on standard SMILE had no significant effect on improving the outcome of spherical error, as shown in Fig. 12.

Meta-analysis of Coma

Two studies [20, 26] evaluated coma outcomes. There was no heterogeneity among the studies (I^2 = 0%, P = 0.56), so the fixed-effect model was used for analysis. The results showed that the effect of cyclotorsion compensation on correcting coma was significantly different from that of the control group (MD = −0.06, 95% CI −0.08 to −0.04, $P < 0.00001$), suggesting that using cyclotorsion compensation based on standard SMILE can improve the outcome of coma, as shown in Fig. 13.

Meta-analysis of HOAs

Among the included studies, two [20, 26] assessed high-order differential outcomes. There was no heterogeneity among the studies (I^2 = 0%, P = 0.53), so the fixed-effect model was used for analysis. The results showed that the effect of cyclotorsion compensation on the correction of HOAs was significantly different from that of the control group (MD = −0.04, 95% CI −0.06 to −0.02, $P < 0.0001$), suggesting that using cyclotorsion compensation based on standard SMILE had a significant effect on the improvement of the outcome of HOAs, as shown in Fig. 14.

DISCUSSION

The effectiveness of cyclotorsion compensation for correcting astigmatism has become a debated topic in recent years [29]. Despite the numerous advantages of SMILE, addressing astigmatism through its application remains a significant challenge, particularly in the context of refractive surgery. During excimer refractive

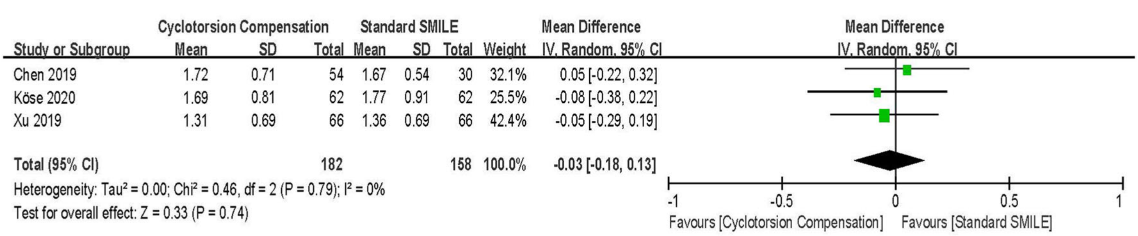

Fig. 9 Forest plot of the comparison results of postoperative TIA. *CI* confidence interval; *SD* standard deviation; *SMILE* small incision lenticule extraction; *TIA* targeted induced astigmatism

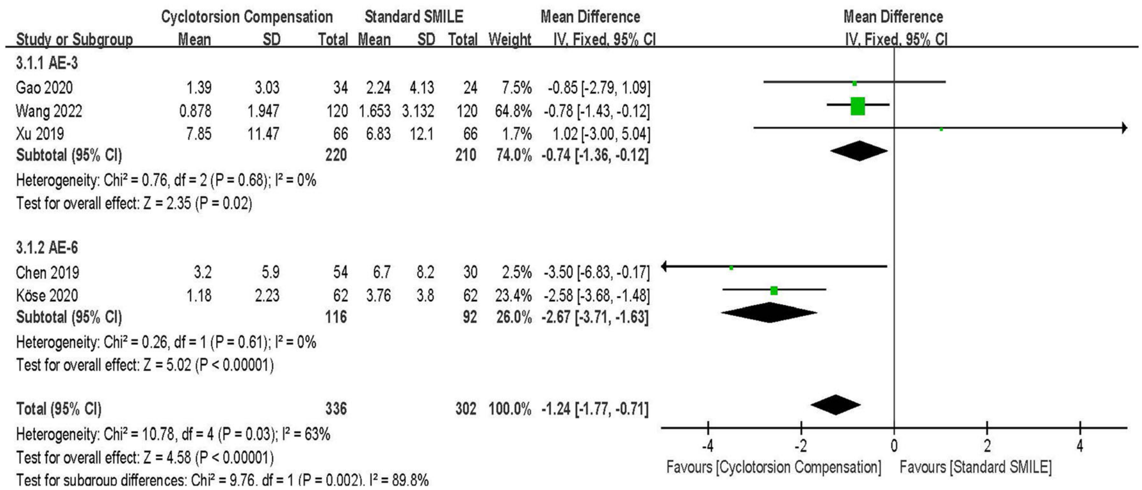

Fig. 10 Forest plot of the comparison results of postoperative AE. *AE* angle of error; *CI* confidence interval; *SD* standard deviation; *SMILE* small incision lenticule extraction

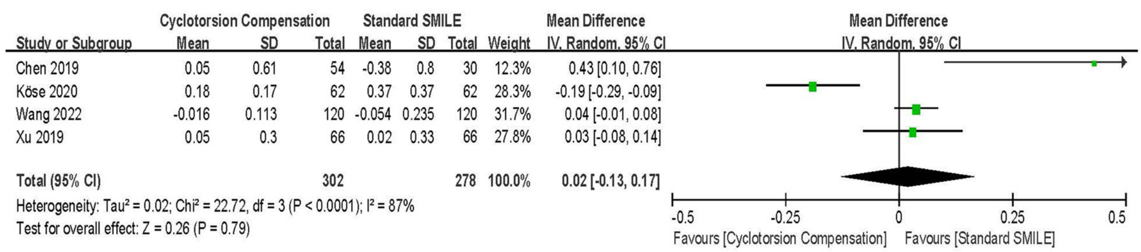

Fig. 11 Forest plot of the comparison results of postoperative ME. *CI* confidence interval; *ME* magnitude of error; *SD* standard deviation; *SMILE* small incision lenticule extraction

surgery, reports indicate that up to 38% of eyes rotate > 5° from a seated to a supine position (static cyclotorsion), and up to 68% of eyes rotate > 2° from a seated position, encompassing both static and dynamic cyclotorsion [14]. Intraoperative cyclotorsions > 2° can result in correction errors and corneal distortion, especially in cases of high astigmatism. Unlike excimer laser-based platforms, the VisuMax femtosecond laser system lacks an eyeball recognition device, posing challenges for pupil positioning and iris tracking during SMILE surgery. Manual cyclotorsion compensation has emerged as a potential solution, though surgeons remain divided on its efficacy in correcting astigmatism [30]. Cyclotorsion compensation offers certain advantages in clinical practice, as it does not require additional equipment. Another benefit of this approach is its reproducibility [31]. While some studies have demonstrated significant results in using cyclotorsion compensation to correct astigmatism, others have found no additional advantages for astigmatism correction or improvement in visual quality [32]. In this meta-analysis and systematic review, we included four randomized controlled trials and six controlled studies to investigate the impact of standard SMILE versus cyclotorsion-compensated SMILE on myopic astigmatism. Our goal is to assist clinicians in making informed decisions by comparing the effectiveness of these two options for correcting myopic astigmatism.

Little is known about whether SMILE without cyclotorsional compensation can effectively correct astigmatism, similar to FS-LASIK or transPRK [33]. To compare the effects of standard SMILE versus cyclotorsion-compensated

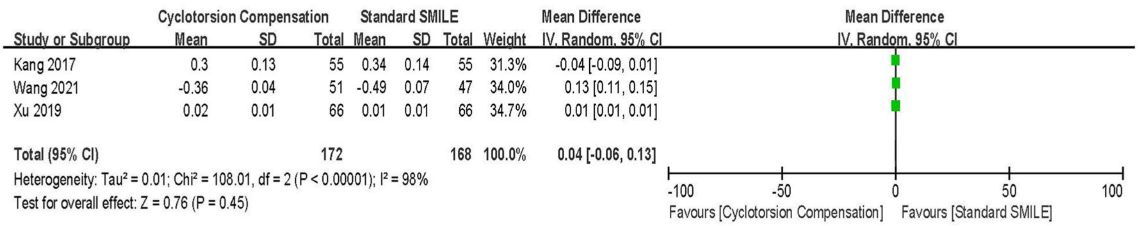

Fig. 12 Forest plot of the comparison results of postoperative SA. *CI* confidence interval; *SA* spherical aberration; *SD* standard deviation; *SMILE* small incision lenticule extraction

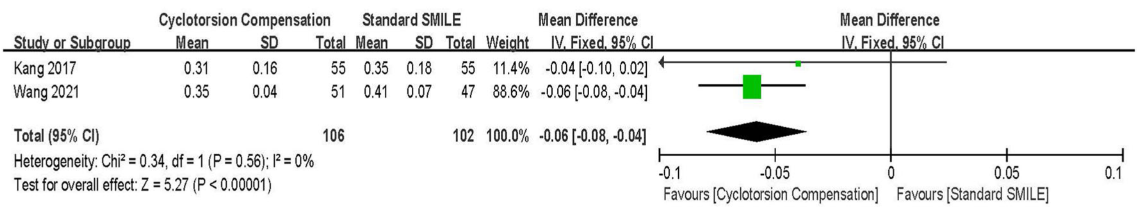

Fig. 13 Forest plot of the comparison results of postoperative coma. *CI* confidence interval; *SD* standard deviation; *SMILE* small incision lenticule extraction

SMILE on myopic astigmatism, we examined postoperative astigmatism and visual acuity between the two groups. Our findings indicated that in cases where forest plots displayed significant differences between RA and uncorrected distance visual acuity (UDVA), cyclotorsion compensation yielded better results. This is reflected as a repeated counterclockwise deviation from the intended axis, which may be attributed to mild torsional eye movements during suction application. This finding aligns with the outcomes observed by Yang et al. [34]. Zhao et al. also demonstrated that wavefront-guided FS-LASIK and optimized SMILE achieved comparable outcomes in terms of astigmatism correction. Several cyclotorsion alignment methods have been employed in SMILE to enhance astigmatism correction [19, 23, 35, 36]. Another noteworthy discovery was that certain parameters including correction index, IOS, ME, TIA, and SIA remained comparable after both procedures. However, the cyclotorsion-compensated SMILE group exhibited smaller AE postoperatively than the standard SMILE group, indicating the accuracy of cyclotorsion compensation in correcting astigmatism amplitude with standard SMILE. The forest plots depicted cyclotorsion compensation as negative, suggesting a tendency toward under-correction, while standard SMILE tended to over-correct. Vector parameters such as size and axis are crucial for achieving satisfactory surgical outcomes in patients with myopic astigmatism [15]. Each parameter used in this vector analysis holds clinical significance for post-refractive surgery eye treatment outcomes.

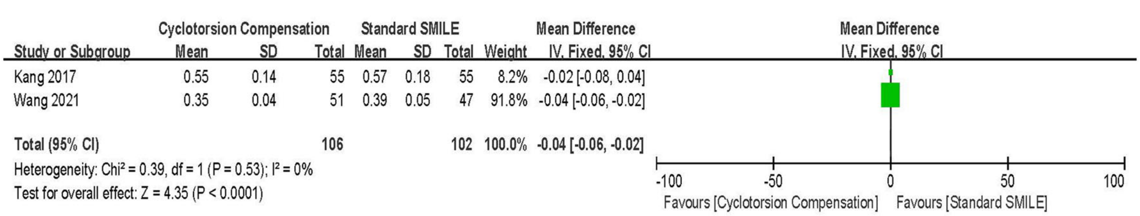

Fig. 14 Forest plot of the comparison results of postoperative HOAs. *CI* confidence interval; HOAs higher-order aberrations; *SD* standard deviation; *SMILE* small incision lenticule extraction

This method offers clinical advantages for comparing astigmatism correction across different techniques, as it incorporates multiple parameters and provides a more comprehensive evaluation than a simple numerical analysis of astigmatism refractive surgery outcomes. In our study, we implemented manual cyclotorsion compensation with limbal markers for static cyclotorsion control, along with a cross-axial alignment approach to minimize axial misalignment with SMILE, comparable to FS-LASIK or transPRK [37, 38]. We employed AE to assess the magnitude of deviation and found that cyclotorsion compensation with SMILE resulted in a smaller AE compared to the control group. This suggests that cyclotorsion compensation effectively mitigated astigmatism axis deviation caused by ocular cyclotorsion. In addition to analyzing two common parameters, the success index and correction index, our vector-based predictive analysis method allowed for quantification of under- or overcorrection of astigmatism. When the correction index is < 1, it signifies insufficient astigmatism correction, which was observed in our study, irrespective of cyclotorsion compensation use.

In our analysis, we noted variations in follow-up duration among the included studies. However, the majority of outcome measures were primarily assessed at the 3-month mark. It is important to highlight that there is no universally accepted standard for reporting results in trials involving refractive procedures [5]. Previous research has indicated that clinical efficacy and safety tend to remain stable 3 months post-surgery. Therefore, all the studies we included conducted assessments at the 3-month postoperative point, a time when the corneal shape is considered stable and corneal wounds have typically healed.

The limitations of our study are as follows: (1) The primary limitations of this study mainly stem from the small sample size and lack of diversity. Most of the included studies had small sample sizes, making subgroup analysis difficult, and the underlying causes could not be explained, potentially affecting the conclusions. (2) Additionally, due to the absence of long-term follow-up data, we were unable to assess the impact of cyclotorsion compensation techniques on the long-term efficacy of astigmatism correction. (3) Some of the included studies may carry a risk of bias, leading to potential measurement and evaluation biases. Furthermore, the technology under investigation (which has not yet received formal FDA approval) adds a layer of uncertainty.

Given the outlined limitations, future studies should aim to address these challenges comprehensively. Expanding the sample size to encompass a more diverse population and conducting long-term follow-up studies would be essential for a more robust evaluation of outcomes. Additionally, researchers should consider accounting for continuous advancements in surgical techniques and the individual differences among patients to more accurately assess the effectiveness of cyclotorsional compensation in various scenarios. Notably, cyclotorsion compensation has shown acceptable results in correcting myopic astigmatism. While there is a current consensus on the superiority of excimer laser-based techniques in astigmatism treatment, particularly for lower levels of astigmatism, outcomes for high levels of astigmatism remain unpredictable with the either surgical approach, although LASIK may offer a faster time to vision recovery. The overall effectiveness of different treatments in such cases is a subject of debate. These findings suggest that there is room for further progress in the VisuMax femtosecond laser system. The availability of automatic centering and cyclotorsion control in the VisuMax system holds the potential to significantly enhance SMILE astigmatism correction outcomes in the coming years [10].

As SMILE continues to gain widespread adoption worldwide, ongoing research in the field of refractive surgery and the pursuit of advancements in surgical technology will be key drivers in the progress of ophthalmology. Looking ahead, the future of SMILE surgery holds exciting prospects in line with technological advancements. With the rapid development of science and technology, there is a clear trajectory toward optimizing preoperative planning and enhancing intraoperative guidance. This includes the integration of cutting-edge technologies such as artificial intelligence and machine learning into SMILE surgery. The aim is to explore more advanced and precise surgical techniques that will ultimately lead to improved surgical outcomes and enhanced visual quality. We anticipate a growing body of research focused on the utilization of cyclotorsion compensation in SMILE surgery. This research aims to provide more accurate predictions and corrections for astigmatism, further elevating the standard of surgical outcomes and overall visual quality. As the field continues to evolve, the future of SMILE surgery promises to be marked by continuous innovation and advancement.

CONCLUSIONS

In correcting myopic astigmatism, cyclotorsion compensation has shown significant effectiveness and predictability. The cyclotorsion compensation group exhibited an advantage over the control group in terms of RA, and it induced fewer coma aberrations. However, the potential for cyclotorsion compensation to offer improved visual quality remains uncertain. Further research is warranted to explore the potential benefits and limitations of using cyclotorsion compensation in the correction of myopic astigmatism.

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Declarations

Conflict of Interest. Xinwei Yang, Ying Liu, Kaimin Xiao, Qiuyi Song, Yunxi Xu, Jialing Li, and Yuehua Zhou have nothing to disclose.

Ethical Approval. This study is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

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