Systematic Review and/or Meta-analysis

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Fate of revision total ankle arthroplasty: a meta-analysis of 999 cases

Ning Sun, MD[a,†], Hua Li, MD[a,†], Xing Li, MD[a,†], Heng Li, MD[a], Liangpeng Lai, MD[a], Yong Wu, MD[a,*], Hui Du, MD, FRCS(Orth)[a,*]

Background: Revision total ankle arthroplasty (reTAA) is becoming more common. This meta-analysis aimed to evaluate its re-revision rate and factors affecting longevity.
Methods: Following Preferred Reporting Items for Systematic reviews and Meta-Analyses statement and Assessing the Methodological Quality of Systematic Reviews guideline, we searched PubMed, Embase, Web of Science, and Cochrane Library databases from 1 January 2010 to 1 October 2024. Studies reporting survivorship of reTAA were included. Study quality was assessed using the Newcastle–Ottawa Scale (NOS). The primary outcome was the re-revision rate. Pooled estimates with 95% confidence intervals (CIs) were calculated using a random-effects model. The annual re-revision rate was introduced for time-adjusted analysis. Heterogeneity was explored using meta-regression and subgroup analyses.
Results: The analysis included 22 retrospective studies (cohort studies and case series) and one prospective cohort study. The NOS scores indicated moderate to high quality. A total of 999 reTAAs with a mean follow-up of 5 years were identified. The pooled re-revision rate was 9.9% (95% CI: 5.9% to 13.9%). The annual re-revision rate was 2.6% (95% CI: 1.8% to 3.6%). Subgroup analysis indicated that stemmed tibial components were potentially associated with a lower re-revision rate (5.5%) versus unstemmed tibial components (13.2%) ($P = 0.077$). However, meta-regression model identified follow-up duration as the only significant factor influencing re-revision rates. The pooled complication rate following reTAA was 18.2%. Among those failed reTAAs, 64.9% underwent conversion to ankle fusion and 5.3% received below-knee amputation.
Conclusion: Although most included studies were low-level evidence, our meta-analysis revealed an overall re-revision rate of 9.9% at 5-year follow-up, with an annual rate of 2.6% for reTAA. Limited evidence suggested that revision systems using stemmed tibial components might reduce the risk of re-revision.

Keywords: complication, meta-analysis, re-revision rate, revision total ankle arthroplasty, salvage procedure

Introduction

Ankle osteoarthritis affects nearly 1% of the global population, with incidence rising due to aging population[1]. In the United Kingdom, approximately 29 000 patients with symptomatic ankle osteoarthritis are referred to surgeons annually[2]. This condition causes significant disability and reduces the quality of life to a degree comparable to end-stage hip arthritis[3].

HIGHLIGHTS

- This meta-analysis revealed a 9.9% re-revision rate at 5-year follow-up and 2.6% annual re-revision rate for revision total ankle arthroplasty.
- The overall complication rate was 18.2%, with 64.9% of failed cases converted to ankle fusion.
- Limited evidence suggests revision systems with stemmed tibial components may be associated with lower re-revision risk.

Advances in modern total ankle arthroplasty (TAA) have made it a promising treatment for end-stage ankle disorders[4,5]. A study using the National Inpatient Sample database in the United States showed an approximately five-fold increase in TAA procedures from 2005 to 2017[6]. However, long-term survivorship remains a challenge, with failure rates of TAA ranging from 10% to 30% at 10 years[7,8]. Treatment options for failed TAA include revision TAA (reTAA), ankle fusion, or amputation, with reTAAs preferred for preserving ankle motion.

With the increasing trend in primary TAA procedures, reTAA is becoming more common[9]. In the United Kingdom, over 3000 TAAs are expected to require management within the next two

[a]Department of Foot and Ankle Surgery, Beijing Jishuitan Hospital, Capital Medical University, Beijing, China

[†]Ning Sun, Hua Li and Xing Li contributed equally to this work.

[*]Corresponding Author. Address: Department of Foot and Ankle Surgery, Beijing Jishuitan Hospital, Capital Medical University, No 31. Xiejiekou East Street, Beijing 100035, China. Tel.: +86 186 1009 4206. E-mail: harveydu@hotmail.com (H. Du); Department of Foot and Ankle Surgery, Beijing Jishuitan Hospital, Capital Medical University, Beijing 100035, China. Tel.: +86 189 1028 3358. E-mail: yongwu11@126.com (Y. Wu).

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decades[10]. An epidemiological study reported that 1170 reTAAs were performed in the United States in 2017, with projected growth of 45.1% to 120% by 2030[6]. Revision TAA is becoming a significant economic and healthcare burden[11].

Revision TAA is a complex procedure, often involving large bone loss and soft tissue challenges. While several studies have investigated reTAA, most are small case series with limited follow-up, and their outcomes vary. Roukis *et al* reported no failures in 32 reTAAs at 2-year follow-up[12]. Similarly, Wang *et al*[13] and Martin *et al*[14] observed no failures in their respective case series of 19 and 17 reTAAs at 3-year follow-up. However, Lachman *et al* observed 21% failure (11 out of 52 reTAAs) at a mean follow-up of 3.1 years[15] A Swedish Joint Replacement Registry study reported a 5-year survival rate of 76% for reTAA[16].

Survivorship remains a key concern in arthroplasty. Given the current uncertainties in reTAA, it is important to provide a comprehensive overview of reTAA survivorship. Therefore, we conducted this meta-analysis to evaluate the fate of reTAA and explore the factors that may influence its long-term success.

Materials and methods

This meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses Statement (PROSPERO number: blinded) and Assessing the Methodological Quality of Systematic Reviews guidelines[17,18].

Search strategy

We searched the PubMed, Embase, Web of Science, and Cochrane Library databases from 1 January 2010 to 1 October 2024. The search keywords used were: (ankle) AND (arthroplasty OR replacement) AND (revision OR failure). MeSH Terms for TAA were also used. Specific search strategies were developed for each database (Supplemental Digital Content, Table S1, available at: http://links.lww.com/JS9/E19) and the references of the identified studies were screened to identify any eligible studies.

Eligibility criteria

Eligible studies were selected based on the following inclusion criteria: (1) studies reporting the survivorship of reTAA, (2) a sample size ≥10, and (3) a mean follow-up duration of >1 year. Randomized controlled trials, cohort studies, and case series were included. Re-revision was defined following Henricson *et al*'s criteria as any procedure involving metallic prosthetic component removal or exchange, conversion to ankle fusion, or amputation[19]. Studies describing reTAA procedures without metallic component removal or exchange were excluded. Non-English language reports, *in vitro* studies, case reports, conference abstracts or posters, and reviews were excluded. After removing duplicates, two authors independently reviewed the titles and abstracts of the potentially eligible studies. Full texts were then assessed by the same authors to finalize the list of included studies. In cases of disagreement, a third senior doctor was consulted to reach a consensus.

Data extraction

We extracted data on publication details, sample size, patient characteristics (mean age, sex ratio and body mass index [BMI]), indications for primary TAA and reTAA, time intervals between primary TAA and the index revision, follow-up duration, type of revision prostheses, re-revision cases, complications, and other relevant variables. The primary outcome of interest was the re-revision rate. To better evaluate survivorship, we introduced the annual re-revision rate, allowing for comparisons across studies with varying follow-ups and sample sizes[20]. This rate was calculated by dividing the number of re-revisions by the total observed component-years. The total component-years were calculated by multiplying the sample size by the mean follow-up duration for each study. A value of 0.01 represented an annual re-revision rate of 1%, or one re-revision event per 100 component-years of follow-up. The secondary outcomes included complications and salvage procedures after reTAA failure. Prostheses were classified by design concepts because of their variety across studies. Tibial components were categorized as "stemmed" and "unstemmed." Stemmed tibial components, such as the INBONE and INVISION systems (Wright Medical/Stryker, Kalamazoo, MI), feature a stem that extends into the tibial medullary canal for stable fixation, representing an intramedullary-referencing concept. Unstemmed tibial components, such as the HINTIGRA/Hintermann series (Newdeal, Lyon, France and DT MedTech LLC) and Salto-Talaris series (Smith & Nephew, Watford, UK), achieve stability through subchondral surface fixation or anchoring, without requiring intramedullary-referencing. Talar components were categorized as "flat-cut" and "chamfer-cut." Flat-cut talar components require planar talar dome resection, whereas chamfer-cut components preserve the natural curvature of the talar dome through anatomically shaped resection.

Assessment of quality and bias

The quality of the included studies was independently assessed by the two authors using the Newcastle–Ottawa Scale (NOS)[21]. Publication bias was estimated using funnel plots and Peters' test[22].

Statistical analysis

Statistical analysis was performed using R software (version 4.1.3), with a significance threshold set at P <0.05. Re-revision and complication rates with 95% confidence intervals (CIs) were pooled using the Freeman-Tukey double-arcsine transformation and expressed as cumulative incidence rates[23]. Annual re-revision rates were log-transformed and pooled using a Poisson-normal random-effects model via the "*rma.glmm*" function in the "*metafor*" package in R[20]. In this model, the logarithm of the total component-years was included as an offset term to normalize for different follow-up durations. Heterogeneity was estimated using the I^2 statistic and Q test. Owing to the diversity of procedures included, we preferred a random-effects model over a fixed-effects model, as we hypothesized that the effectiveness of these surgeries might vary across studies[24]. Sensitivity analysis for the primary outcome (re-revision rate) was conducted using a leave-one-out analysis. Meta-regression analysis was employed to explore the heterogeneity in the re-revision rate based on predetermined factors, including publication year, patient demographics, indications for primary and revision surgery, follow-up duration, and type of revision prostheses. In the univariate model, each predetermined factor was analyzed individually, and those with P <0.1 were extracted into the final multivariable model. Subgroup analyses were conducted based on meta-regression results, focusing on potentially significant categorical variables.

Results

Overview of search results

A total of 4561 studies were identified initially, with 2019 remaining after duplicate removal. After screening titles and abstracts, 71 publications underwent full-text assessment. Ultimately, 23 studies were included in the final analysis (Fig. 1).[10,12-16,25-41] Seventeen studies were published within the last 5 years, and two had sample sizes exceeding 100[26,35]. The analysis included 22 retrospective studies, comprising cohort studies and case series, as well as one prospective cohort study[36].

Clinical characteristics

A total of 999 reTAAs were identified. The cohort showed equal sex distribution (Male 52.2%, Female 47.8%), with an average age ranging from 52 to 68 years (weighted mean: 62.4 years). Primary or secondary ankle osteoarthritis was the predominant indication (84.2%) for initial TAA. The reasons for reTAA were documented in 22 studies, with aseptic failures (loosening, instability, subsidence and cyst formation) accounting for 93.1% of the revision indications. Regarding prostheses used during reTAA, the most commonly reported systems were the INBONE series, INVISION, HINTEGRA, and Salto-Talaris series. Ten studies used exclusively stemmed tibial components[10,13,14,25,27,29,32,36,37,40], and 13 used only flat-cut talar components.[10,12,14,25,27,29-32,36,37,39,40] The mean time interval from primary to revision TAA ranged from 1.8 to 7.8 years (weighted mean: 3.5 years). The mean follow-up duration after revision ranged from 1.3 to 15 years (weighted mean: 5.0 years) (Table 1 and Table 2).

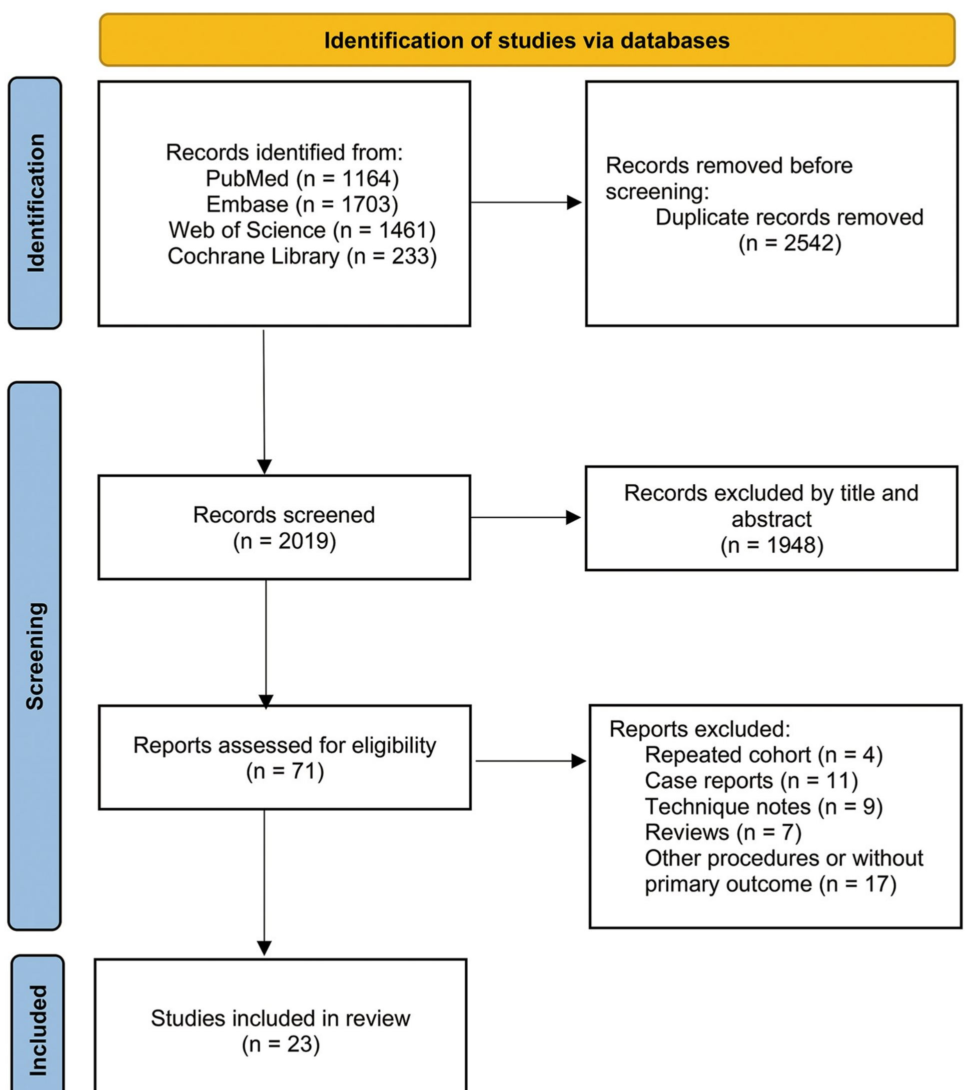

Figure 1. Preferred Reporting Items for Systematic reviews and Meta-Analyses flowchart of included studies.

Assessment of quality and bias

The NOS scores indicated moderate to high quality (Supplemental Digital Content, Table S2, available at: http://links.lww.com/JS9/E19). The funnel plot did not suggest a possible publication bias (Fig. 2), which was confirmed by Peters' test (P = 0.882).

Re-revision rate

The pooled re-revision rate was 9.9% (95% CI: 5.9% to 13.9%), with relatively high heterogeneity (I^2 = 79.1%, P < 0.001) (Fig. 3). Our sensitivity analysis demonstrated that removing any single study did not significantly affect the pooled estimates (Supplemental Digital Content, Figure S1, available at: http://links.lww.com/JS9/E19). The pooled log-transformed incident rate of re-revision was −3.67 (95% CI: −4.00 to −3.33; I^2 = 55.4%, P < 0.001), corresponding to an annual re-revision rate of 2.6% (95% CI: 1.8% to 3.6%) (Fig. 4).

Univariate meta-regression analysis identified that the mean age, follow-up duration, and tibial component type had crude P <0.1. No significance was found with other factors, including sex, BMI, study characteristics, surgical indications, and talar component type (Supplemental Digital Content, Figure S2, available at: http://links.lww.com/JS9/E19). In the multivariable regression model, follow-up duration was the only factor explaining heterogeneity (Table 3) (Supplemental Digital Content, Figure S3, available at: http://links.lww.com/JS9/E19).

A subgroup analysis based on the tibial component type was performed, as it was the only potentially significant categorical variable identified in the initial meta-regression model. The re-revision rates were 5.5% (95% CI: 1.4% to 9.6%, I^2 = 52.2%) in the 10 studies using stemmed tibial components and 13.2% (95% CI: 5.8% to 20.7%, I^2 = 74.7%) in the seven studies using unstemmed tibial components. Intra-subgroup heterogeneity decreased, with borderline inter-group heterogeneity (P = 0.077) (Fig. 5). We also performed a subgroup analysis based on prosthesis brands (Supplemental Digital Content, Figure S4, available at: http://links.lww.com/JS9/E19). The annual re-revision rates for each subgroup were also calculated. The rates were 2.1% (95% CI: 1.6% to 2.7%) in the stemmed subgroup and 2.8% (95% CI: 1.6% to 4.8%) in the unstemmed subgroup (Fig. 6). The difference was not statistically significant (P = 0.2489).

Table 1

Characteristics of included studies

Authors	Publication year	Ankles	Indication for primary TAA (%)	Indication for revision TAA (%)	Revision system
Henry *et al* [25]	2024	46	43% OA, No InfA	All aseptic	INBOONE, INVISION
Hintermann *et al* [26]	2024	117	95% OA, 5% InfA (gout, lupus, hemophilia)	26% loosening, 14% subsidence (12% talar), 9% cyst formation, 7% instability, 8% infection, other	HINTEGRA
Martin *et al* [14]	2024	17	NA	47% loosening, 29% cyst formation, 12% infection, other	INVISION
Purnell *et al* [32]	2024	19	NA	68% loosening, 21% malalignment, 11% infection	INVISION
Rougereau *et al* [31]	2024	25	76% OA, 24% InfA	All aseptic: 68% loosening, 12% instability, 12% malalignment, 8% PE wear	Salto-Talaris XT
Sundet *et al* [30]	2024	30	NA	All aseptic: 33% loosening, 27% pain, 13% instability, 13% PE wear, 10% cyst formation, other	Salto-Talaris XT
Valan *et al* [29]	2024	28	NA	NA	INVISION
Wang *et al* [13]	2024	19	95% OA, 5% InfA	All aseptic: loosening or subsidence	Extended stem + total talus
Wu *et al* [27]	2024	60	78% OA, 11.7% RA	75% loosening, 8% cyst formation, 7% instability, 2% infection, other	INBONE
Jennison *et al* [35]	2023	228	93% OA, 3.1% RA, 0.9% other InfA	77% aseptic, 23% infection	INBONE, Zenith, Mobility, Box, Salto-Talaris, other
Kvarda *et al* [34]	2023	54	74% OA, 26% InfA (RA, hemophilia, gout)	All aseptic: 44% instability, 22% pain, 17% loosening, 13% cyst formation, other	Hintermann Series H2
Pfahl *et al* [33]	2023	40	NA	55% loosening, 23% malalignment, 8% infection, other	INBONE, Infinity, Salto-Talaris XT
Jamjoom *et al* [10]	2022	29	NA	All aseptic: 83% loosening, 10% PE wear, 3% malalignment, other	INBONE II
Jennison *et al* [36]	2021	23	100% OA	39% loosening, 22% cyst formation, 13% malposition, 26% infection	INBONE II, INVISION
Behrens *et al* [37]	2020	18	NA	89% aseptic, 11% infection	INBONE I, INBONE II
Egglestone *et al* [38]	2020	12	NA	NA	INBONE, HINTEGRA, Infinity
Lachman *et al* [15]	2019	52	79% OA, 21% InfA (gout)	All aseptic: 42% loosening, 35% talar subsidence, 12% talar subluxation, other	INBONE, Salto-Talaris XT, Infinity, STAR
Wagener *et al* [28]	2017	12	83% OA, 17% InfA (hemophilia, lupus)	All aseptic	HINTEGRA + custom talus
Horisberger *et al* [41]	2015	10	100% OA	All aseptic	HINTEGRA + bone augment
Kamrad *et al* [16]	2015	73	71% OA, 22% RA	51% loosening, 3% infection, other	NA
Roukis *et al* [12]	2015	32	NA	91% talar loosening, 6% infection, other	Agility, INBONE, Salto-Talaris XT
DeVries *et al* [40]	2013	14	93% OA, 7% RA	All aseptic	INBONE
Ellington *et al* [39]	2013	41	83% OA, 15% InfA	All aseptic: 63% talar subsidence, 29% loosening, other	Agility

TAA, total ankle arthroplasty; OA, osteoarthritis; InfA, inflammatory arthritis; RA, rheumatoid arthritis; PE, polyethylene; NA, not available.

Table 2

Detailed information of included studies

Authors	Mean age (y)	BMI (kg/m²)	Sex ratio (% female)	Time interval form TAA to revision (y)	Follow-up duration (y)	Re-revision cases	NOS
Henry *et al* [25]	60.6	29.6	39%	NA	3.5	7	6
Hintermann *et al* [26]	58.9	26.6	48%	4.3	15.0	34	8
Martin *et al* [14]	67.9	NA	18%	NA	3.4	0	6
Purnell *et al* [32]	62	NA	47%	2.8	3.5	0	6
Rougereau *et al* [31]	55.8	26.4	72%	7.0	5.1	1	6
Sundet *et al* [30]	60.2	25.7	50%	NA	5.0	3	6
Valan *et al* [29]	67.1	30.8	64%	6.4	1.3	3	5
Wang *et al* [13]	60.6	30.1	NA	4.2	3.2	0	6
Wu *et al* [27]	64.9	30.7	48%	6.1	3.1	6	6
Jennison *et al* [35]	66	30.9	42%	2.3	2.6	29	7
Kvarda *et al* [34]	63	28	43%	NA	3.2	4	7
Pfahl *et al* [33]	62	NA	40%	7.2	5.2	1	6
Jamjoom *et al* [10]	68	NA	34%	7.3	3.3	2	7
Jennison *et al* [36]	64.7	NA	57%	NA	2.0	0	8
Behrens *et al* [37]	57.6	31	61%	4.0	6.7	4	6
Egglestone *et al* [38]	68	NA	NA	2.3	3.0	1	5
Lachman *et al* [15]	63.5	30.4	52%	5.5	3.1	11	6
Wagener *et al* [28]	53	NA	42%	7.8	6.9	1	6
Horisberger *et al* [41]	52	NA	60%	6.0	4.0	2	6
Kamrad *et al* [16]	55	NA	60%	1.8	8.0	24	6
Roukis *et al* [12]	64.6	NA	34%	6.6	2.1	0	6
DeVries *et al* [40]	65.2	NA	43%	7.8	2.4	2	6
Ellington *et al* [39]	60	29.4	71%	4.3	4.1	7	6

y, year; BMI, body mass index; TAA, total ankle arthroplasty; NOS, Newcastle–Ottawa scale; NA, not available.

Complications and salvage procedures

Complications were reported in 20 studies, with a pooled rate of 18.2% (95% CI: 13.4% to 24.2%; $I^2 = 56.8\%$, $P < 0.001$) (Fig. 7). The pooled rate for aseptic complications was 14.0% (95% CI: 9.8% to 19.5%; $I^2 = 46.2\%$, $P = 0.0127$) (Fig. 8). Thirteen studies reported salvage procedures following reTAA failure. Of the 94 documented failures, 64.9% underwent ankle fusion and 5.3% below-knee amputation (Table 4). Two studies evaluated the outcomes of re-revision arthroplasty following reTAA failure. Kamrad *et al* reported that three failed reTAAs underwent re-revision arthroplasty, with two failing again[16]. In the study by Lachman *et al*, five failed reTAAs underwent re-revision, with no subsequent failures[15].

Discussion

This is the largest meta-analysis of 999 pooled reTAAs. Our analysis represented that approximately one-tenth of the reTAAs failed at an average follow-up of 5 years. This is the first meta-analysis to estimate an annual re-revision rate of 2.6% for reTAA. Additionally, we investigated potential factors influencing reTAA survivorship.

Overview of indications for revision

In this combined cohort, most revisions were because of aseptic failure, primarily due to loosening and instability. This finding was consistent with previous reports. Richter *et al* evaluated

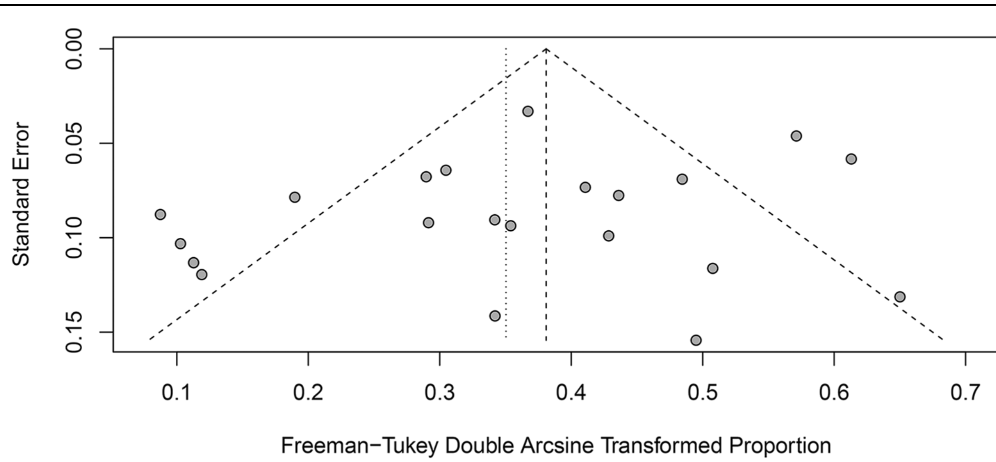

Figure 2. Funnel plot of the primary outcome (re-revision rate).

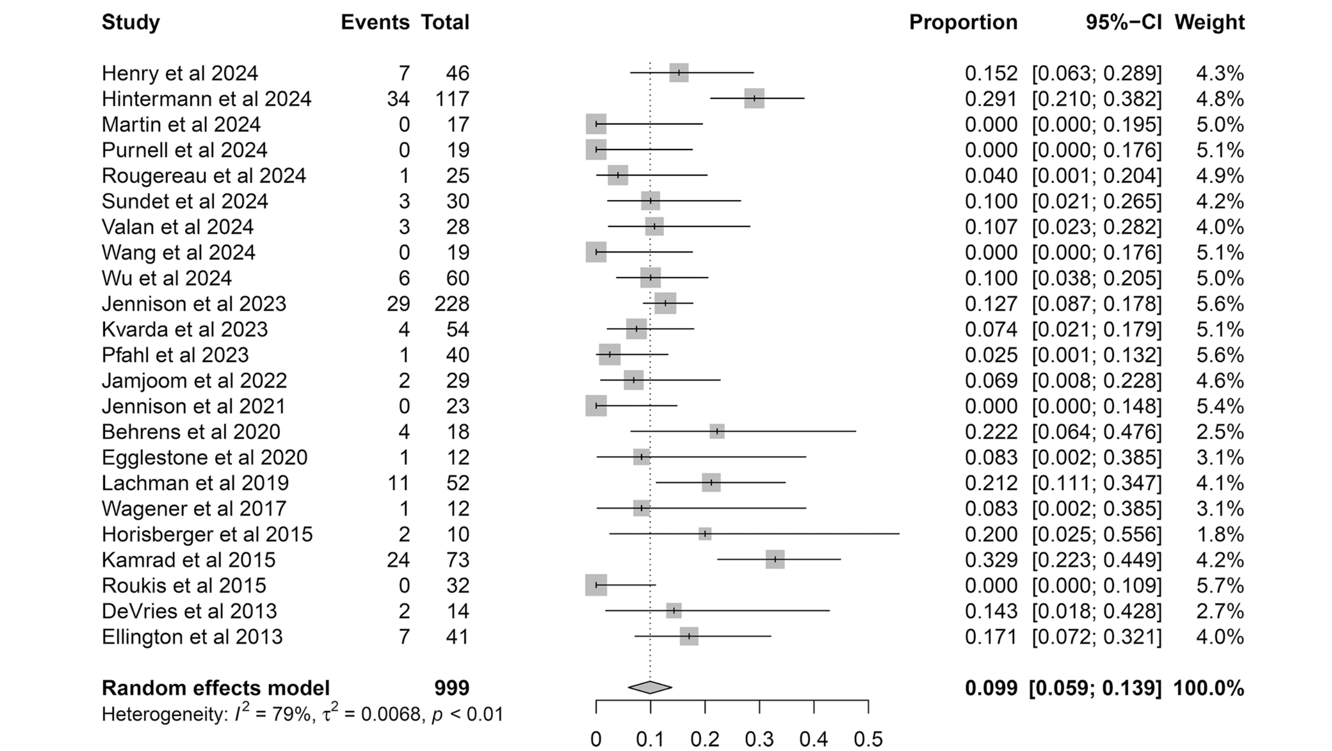

Figure 3. Forest plot of primary outcome (re-revision rate).

1074 primary TAAs and found instability (34%) and aseptic loosening (28%) as the leading causes of revision[42]. Similarly, Syed *et al* identified aseptic loosening (29.2%) as the most frequent indication for revision in joint registry data[43]. Vale *et al*'s systematic review on primary TAA complications also emphasized aseptic loosening as the primary issue[44]. These findings provide valuable insights for revision strategies.

Re-revision rate

Revision ankle arthroplasty is particularly challenging because of the limited availability of revision systems compared to revision hip or knee arthroplasties. Our overall re-revision rate of reTAA was notably higher than the failure rates reported for revision hip or knee arthroplasties, despite the lack of direct comparative studies. Dagneaux *et al* reported a 13-year re-revision rate of 5% in 925 revision hip arthroplasties[45]. Small *et al* reported a survival rate exceeding 95% in 1172 revision knee arthroplasties at 6.5 years[46]. These findings highlighted the complexity of ankle arthroplasty. Two systematic reviews examined the re-revision rate of reTAA. Jamjoom *et al* summarized 12 studies and reported a median re-revision rate of 16% at a median follow-up of 4 years[47]. Jennison *et al*'s review of 15 studies estimated a re-revision rate of 14.4%[48]. Our results aligned with these findings. Over 70% of the included studies had follow-up periods under 5 years, emphasizing the importance of the short- to mid-term period following reTAA, which might refer to the first few years once implant osseointegration is

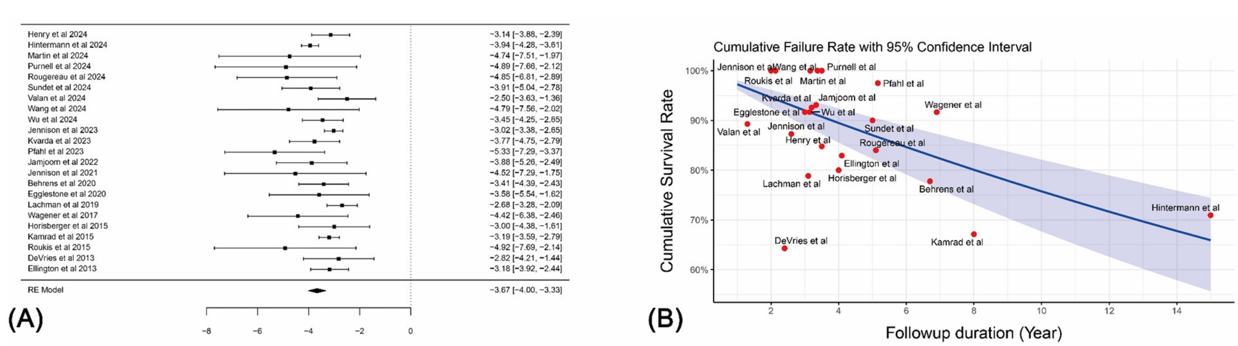

Figure 4. (A) The forest plot for log-log transformed annual revision rates. (B) Predicted survivorship of revision total ankle arthroplasty with annual re-revision rate of 2.7%. Shaded area showed 95% confidence interval; red points indicated re-revision rates from individual studies.

Table 3

Results of meta-regression model

Parameters	Number of included studies	Crude coefficient (95% CIs)	Crude *P*	Adjusted coefficient (95% CIs)	Adjusted *P*
NOS	23	0.0124 (−0.0424, 0.0671)	0.6579	-	-
Publication year	23	−0.0067 (−0.0183, 0.0031)	0.1629	-	-
Mean age	23	−0.0090 (−0.0180, 0)	0.0506	0.0016 (−0.0086, 0.0118)	0.7607
Sex ratio (female)	21	0.2636 (−0.0511, 0.5784)	0.1006	-	-
BMI	12	−0.0009 (−0.0279, 0.0261)	0.9476	-	-
Rate of OA in primary TAA	14	−0.1325 (−0.5243, 0.2594)	0.5076	-	-
Rate of septic revision	21	−0.2576 (−0.8063, 0.2911)	0.3575	-	-
Follow-up duration	23	0.0200 (0.0089, 0.0311)	0.0004	0.0181 (0.0063, 0.0298)	0.0026
Time intervals between primary TAA and index revision	18	−0.0180 (−0.0421, 0.0060)	0.1425	-	-
Tibial type (Stemmed)	17	−0.0705 (−0.1516, 0.0106)	0.0883	−0.0218 (−0.1106, 0.0670)	0.6306
Talar type (Flat-cut)	16	−0.0451 (−0.1359, 0.0456)	0.3294	-	-

CIs, confidence intervals; NOS, Newcastle–Ottawa scale; BMI, body mass index; OA, osteoarthritis; TAA, total ankle arthroplasty.

complete[25]. Additionally, most studies (22 of 23) were retrospective. The lack of standardized follow-up protocols might suggest that some failures or complications were missed or detected later, which might underestimate the related results. The only prospective study had more rigorous protocols but was limited by its small impact on pooled results (Supplemental Digital Content, Figure S1, available at: http://links.lww.com/JS9/E19)[36]. Sensitivity analysis excluding this prospective study yielded results similar to the primary analysis. Future multi-center prospective studies with standardized protocols and larger sample sizes are needed.

Annual re-revision rate

Considering the varying follow-up periods across studies, we employed the metric of annual re-revision rate to standardize the failure rate of reTAA, thereby providing a more accurate assessment of re-revision risk. To our knowledge, only one meta-analysis regarding ankle arthroplasty has used this metric. Van der Plaat *et al* included 57 studies and reported an annual revision rate of 2.2% for primary TAA[49]. While our findings indicated that the annual re-revision rate for reTAA was higher than the annual revision rate for primary TAA, the relatively small difference between the two rates warranted attention. Several

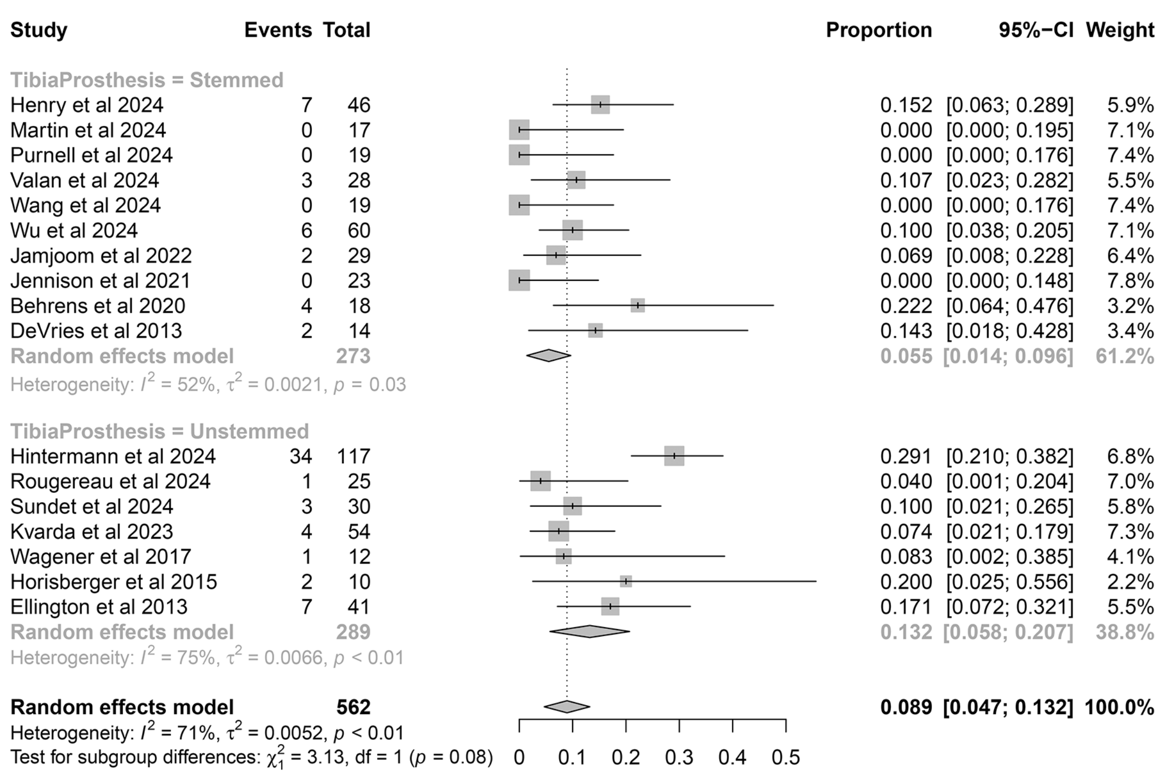

Figure 5. Subgroup analysis of re-revision rate based on tibial prosthesis.

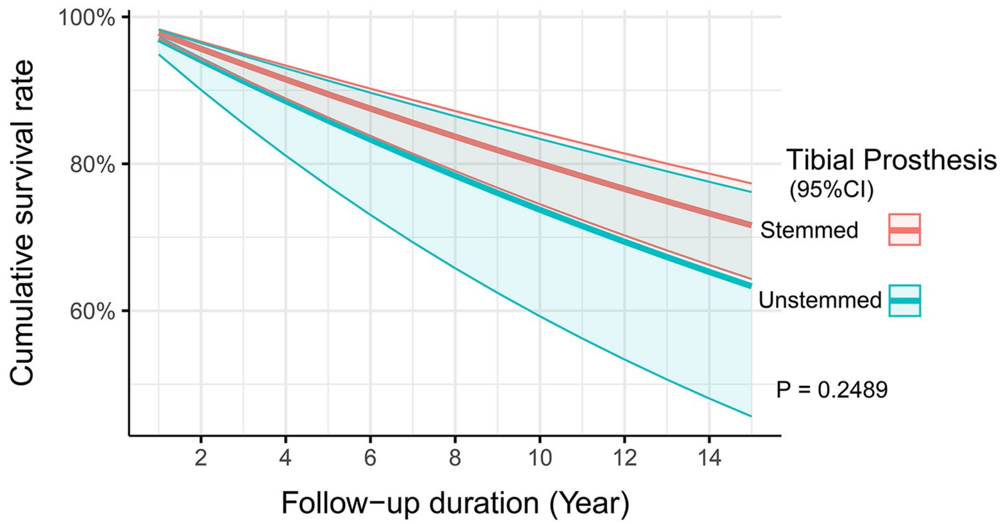

Figure 6. Predicted survivorship based on annual re-revision rates comparing stemmed (red) and unstemmed (green) tibial fixation in revision total ankle arthroplasty. Shaded areas indicated 95% confidence intervals.

factors may explain this finding. First, the increased use of modern revision-specific prostheses and advancements in surgical techniques may have reduced the failure rates of revision procedures. Second, van der Plaat *et al*'s study employed a linear model, assuming an even distribution of failures across all years[49], which might be biased given the non-linear failure patterns in arthroplasty. In contrast, we employed a Poisson model with a time-adjusted estimation.

Exploring heterogeneity: potential risk factors for re-revision

We observed high heterogeneity in re-revision rates (I^2 = 79.1%) and employed subgroup analysis and meta-regression to explore the potential sources of heterogeneity. Subgroup analysis indicated that unstemmed tibial components had a two-fold higher re-revision rate than stemmed components (5.5% vs. 13.2%, P = 0.077). While intra-subgroup heterogeneity was reduced, it

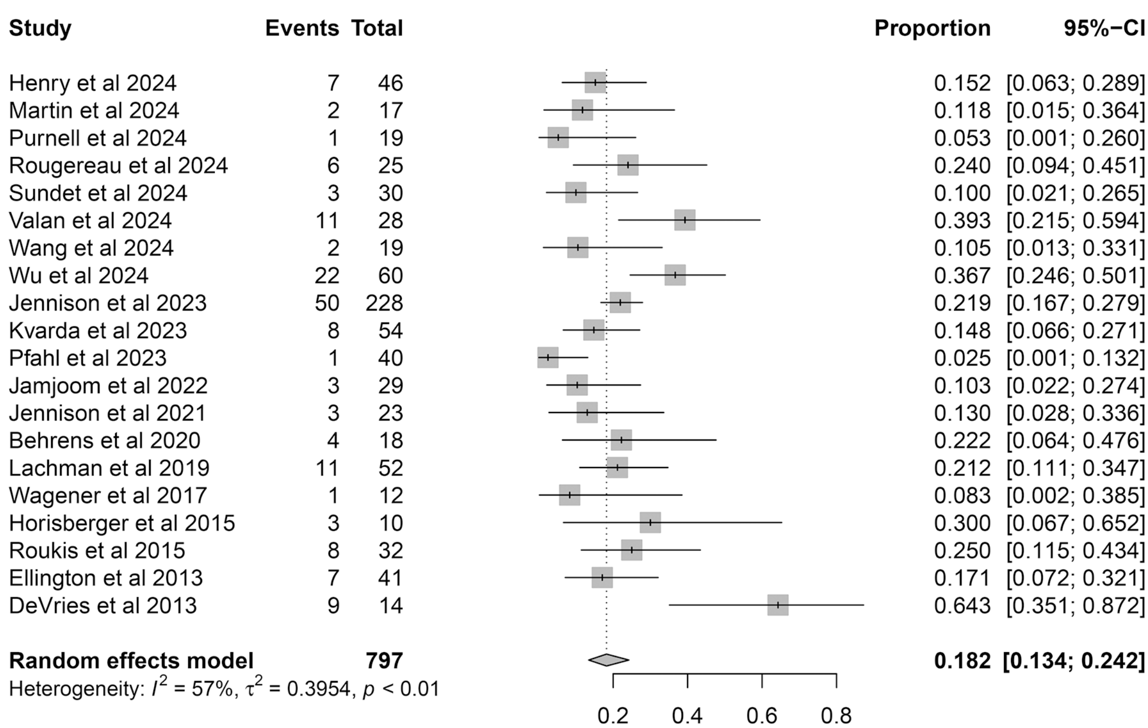

Figure 7. Forest plot of complications.

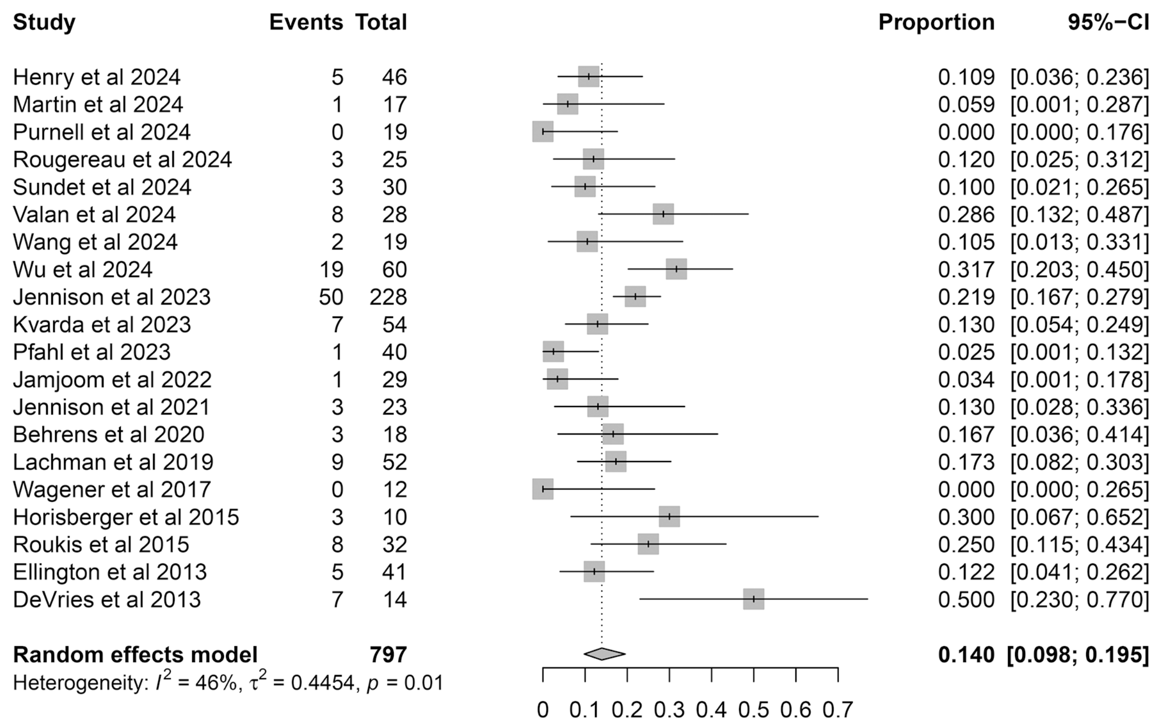

Figure 8. Forest plot of aseptic complications.

remained substantial (stemmed: I^2 = 52.2%; unstemmed: I^2 = 74.7%), suggesting that other factors may play important roles. After adjusting for follow-up duration, multivariable meta-regression analysis found that the difference in failure rates between the two tibial components became insignificant (P = 0.6306). Furthermore, a comparison of the annual re-revision rates (2.1% vs. 2.8%, P = 0.2489) supported this finding. These results indicated the importance of follow-up time when interpreting re-revision outcomes. The debate surrounding tibial component design in reTAA persists. Numerous studies have favored stemmed tibial components like INBONE in revision scenarios.[50-52] These studies suggested that extended stems could offer superior initial stability and facilitate better osseointegration. However, Behrens *et al* noticed a 38.9% incidence of tibial subsidence with stemmed components (INBONE series) at 4-year follow-up[37]. Additionally, some studies suggested that extended stems may create non-anatomic force transfer, risking ligament insufficiency and instability. In comparison, unstemmed fixation usually sacrifices less bone, increases the contact area with the subchondral solid bone, and may provide more physiological stress transfer[53]. Kvarda *et al* reported a 7.4% 2-year survival rate for reTAA using unstemmed tibial components (Hintermann series), with only 4% displaying radiographic lucency or subsidence[34]. To our knowledge, no head-to-head clinical studies have directly compared stemmed and unstemmed systems in reTAA. Although our subgroup analysis offered valuable insights with clinical implications, the indirect nature of these comparisons should be noted. With limited data, we could only infer a possible trend toward longer survivorship with stemmed tibial fixation in reTAA. We could not draw any statistically significant conclusions. Further prospective studies with direct comparisons between these two systems are required.

Assessment of bone loss severity is crucial in revision cases. Among these studies, only Hintermann *et al* introduced their classification system that provided detailed defect evaluations[26]. In their unstemmed cohort, over 25% of reTAAs fell into the most severe category (>50% of osseous surfaces loss). Other studies utilizing the INBONE series (stemmed system) cited excessive bone loss as their primary rationale for implant selection. An included study employing unstemmed systems acknowledged that severe defects required consideration of the INBONE series[12].

Talar revision is challenging due to limited bone stock and difficulty of achieving initial fixation[54]. Our meta-analysis showed no significant impact on the re-revision rates between the talar designs (flat-cut vs. chamfer-cut). Anastasio *et al* followed 132 flat-cut and 189 chamfer-cut primary TAAs over an average of 4.9 years, finding similar aseptic loosening rates (flat-cut 1.5% vs. chamfer-cut 1.6%)[55]. Henry *et al* followed 46 reTAAs for 3.5 years and found that talar failures after reTAA occurred later than tibial failures and were more likely to fail again[25]. These findings emphasize the complexity of talar reconstruction. Many factors, such as bone quality and osteolysis, could significantly influence the talar failure, which might overshadow the influence of prosthetic design itself.

Revision TAA remains a relatively new field with limited research. In revision hip or knee arthroplasty, established risk factors for failure include younger age[56], male sex[56], overweight status[57], and inflammatory arthritis[58]. However, our meta-regression analysis and bubble plots revealed no significant correlations between these factors and re-revision rates. Similarly, Wu *et al* found no association between reTAA failure and sex, age, diagnosis

Table 4

Complications and salvage procedures

Authors	Complications	Salvage procedures
Henry *et al* [25]	7: 5 failures, 2 infections	NA
Hintermann *et al* [26]	NA	NA
Martin *et al* [14]	2: 1 infection, 1 fracture	NA
Purnell *et al* [32]	1: 1 infection wound	NA
Rougereau *et al* [31]	6: 3 infections, 1 malalignment, 1 impingement, 1 calcaneus osteotomy	NA
Sundet *et al* [30]	3: 3 failures	1 fusion, 1 re-revision arthroplasty, no amputation
Valan *et al* [29]	11: 3 failures, 3 infections, 2 wound problems, 2 nerve palsies	NA
Wang *et al* [13]	2: 1 fracture, 1 gutter debridement	NA
Wu *et al* [27]	22: 6 persistent pain, 5 nerve palsies, 3 infections, 3 fractures, 3 failures, 2 wound problems, 3 osteolysis	2 fusions, 2 re-revision arthroplasties, 1 amputation for trauma
Jennison *et al* [35]	50 aseptic complications without detailed information	19 fusions, 9 re-revision arthroplasties, 1 amputation
Kvarda *et al* [34]	8: 3 persistent pain, 1 loosening, 3 fractures, 1 wound infection	1 fusion, 3 re-revision arthroplasties, no amputation
Pfahl *et al* [33]	1: 1 failure	1 fusion, no amputation
Jamjoom *et al* [10]	3: 1 deep peroneal nerve palsy, 2 infections	NA
Jennison *et al* [36]	3: 1 intraoperative fracture, 1 acute kidney injury, 1 persistent pain	NA
Behrens *et al* [37]	4: 3 loosening, 1 infection	1 fusion, 3 re-revision arthroplasties, no amputation
Egglestone *et al* [38]	NA	NA
Lachman *et al* [15]	11: 2 infections, 9 other conditions	6 fusions, 5 re-revision arthroplasties (all in situ), no amputation
Wagener *et al* [28]	1: 1 infection	1 fusion, no amputation
Horisberger *et al* [41]	3: 2 persistent pain, 1 heterotopic ossification	2 fusions, no amputation
Kamrad *et al* [16]	NA	21 fusions, 3 re-revision arthroplasties (2 failed again), no amputation
Roukis *et al* [12]	8: 4 intraoperative fractures, 3 wound problems, 1 neurological symptom	NA
DeVries *et al* [40]	9: 2 infections	1 fusion, 1 amputation for infection
Ellington *et al* [39]	7: 5 failures, 2 infections	5 fusions, 2 amputations for infection

NA, not available.

of primary TAA, or type of revision prosthesis in their 12 failed reTAAs[59]. Nevertheless, these explorations were preliminary. Further research with larger cohorts and higher-quality designs is needed to identify the risk factors for reTAA failure.

Complications and salvage procedures

Our results revealed an 18.2% pooled complication rate, with 14% being aseptic. In reTAA failures, 64.9% received conversion to ankle fusion, while 5.3% required below-knee amputation. Wu *et al* reported similar outcomes, with 42% of failed reTAAs converted to fusion and 8% requiring amputation[59]. While ankle fusion salvages the joint, it sacrifices mobility[60]. Some researchers advocated for fusion when tibial bone defects exceeded 2 cm[52]. A previous meta-analysis reported a non-union rate for conversion to fusion as high as 13% following primary TAA failure[48], and this risk may be even higher in reTAA failure because of compromised bone and soft tissue quality[60]. Below-knee amputation is a severe outcome following reTAA failure. In this analysis, most amputations were attributed to deep infection. Additionally, we noted that after an unsuccessful reTAA, up to two-thirds of subsequent re-revision arthroplasty procedures might experience a second failure[16]. Our review is clinically relevant. Surgeons and patients should be aware of the relatively high risk of reTAA failure and poor outcomes after reTAA failure.

Limitations

There were several limitations in our meta-analysis. First, the methodology of the meta-analysis inherently contained a bias of possibly missing relevant studies. Our restriction to English-language publications may also introduce language bias, potentially excluding some relevant non-English literature. Second, although the pooled sample size seemed to be the largest and sufficient, most studies were small case series or single-arm retrospective cohorts with level IV evidence. This weakened the overall evidence level. Retrospective design might introduce inherent limitations, particularly an increased risk of selection and recall bias. Although the included studies were of acceptable quality and NOS scores did not correlate with re-revision rates, these limitations might still affect survivorship estimates. Third, we set a minimum average follow-up time of 1 year for inclusion, but there was considerable variability in follow-up durations across studies. To address this, we introduced an annual re-revision rate to standardize the outcomes. Nevertheless, this metric may still limit the external validity of our results, especially for long-term outcomes. Fourth, although we adopted Henricson *et al*'s definition of re-revision as inclusion criteria[19], the indications for revision varied across studies. Some studies revised only the single failed tibial or talar component, whereas others performed complete revision even if only one component exhibited loosening. Surgical techniques also varied. Thus, we applied a random-effects model for a more conservative estimate, despite wider CIs. Fifth, various prostheses were included. Our stratification was limited to design philosophy. Differences in implant shape, surgical approach, and bearing type (fixed vs. mobile) were not fully detailed. These variations might influence implant survivorship, which could introduce bias. Sixth, the factors selected for the meta-regression were empirically predetermined. Unpredictable but important factors may be omitted. Furthermore, not all studies reported sufficient information regarding the chosen factors. Missing data on important variables compromised the full assessment of their influence on the re-revision rate. For instance, some studies used multiple types of prostheses but did not specify which types were associated with failures. Accordingly, we restricted the crude subgroup analysis to studies that used a single prosthesis type. However, this approach results in an inevitable loss of data. Seventh, we did not analyze clinical functional scores because the included case series or single-arm cohorts generally showed pre- to postoperative improvements, offering limited insights for reTAA evaluation. We also excluded radiographic outcomes, as a few studies have suggested that radiographic measurements were subjective and failed to demonstrate significant correlation with the need for re-revision[34,61]. Nevertheless, we recommend future research with larger sample sizes and more rigorous methodologies to clarify how functional and radiographic outcomes relate to the clinical success of reTAA.

Conclusion

This meta-analysis of 999 reTAAs revealed a 5-year re-revision rate of 9.9% (2.6% annually) and an 18.2% complication rate. Following reTAA failure, 64.9% required ankle fusion. Although revision systems using stemmed tibial components showed potential for improved survivorship, evidence was limited. Our results warrant careful interpretation because most evidence came from retrospective studies. Larger cohorts and longer follow-up with higher-level evidence are needed to better understand reTAA outcomes.

Ethical approval

This is a systematic review and meta-analysis thus ethical approval is not required.

Consent

None.

Sources of funding

None.

Author contributions

All authors: conceptualization, writing – review & editing; N. S., Hua.L., and X.L.: data collection; Hua.L., Y.W., and L.L.: formal analysis; N.S., L.L., and Heng.L.: investigation; Hua.L., H.D., and Y.W.: methodology; N.S., Hua.L. and Heng.L.: software; N.S., H.D., and X.L.: visualization; N.S., Hua.L., and X.L.: writing – original draft.

Conflicts of interest disclosure

None.

Research registration unique identifying number (UIN)

This is a systematic review which has been registered in PROSPERO (CRD42024606084).

Guarantor

Yong Wu and Hui Du.

Provenance and peer review

Not commissioned, externally peer-reviewed.

Data availability statement

Dr. Hua Li had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Assistance with the study

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