Modern total ankle arthroplasty *versus* ankle arthrodesis: A systematic review and meta-analysis

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Abstract

The controversy in surgical management of end-stage tibiotalar arthritis with Total Ankle Arthroplasty (TAA) versus Ankle Arthrodesis (AA) has grown in parallel with the evolution of both procedures. No randomized controlled trials exist due to the vast differences in surgical goals, patient expectations, and complication profiles between the two procedures. This makes high quality systematic reviews necessary to compare outcomes between these two treatment options. The aim of this study was to provide a systematic review with meta-analysis of publications reporting outcomes, complications, and revision data following third-generation TAA and/or modern AA published in the past decade. Thirty-five articles met eligibility criteria, which included 4312 TAA and 1091 AA procedures. This review reports data from a mean follow-up of 4.9 years in the TAA cohort and 4.0 years in the AA cohort. There was no significant difference in overall complication rate following TAA compared to AA (23.6% and 25.7% respectively, P-value 0.31). Similarly, there was no significant difference in revision rate following TAA compared to AA (7.2% and 6.3% respectively, P-value 0.65). Successful treatment of end-stage tibiotalar arthritis requires an understanding of a patients' goals and expectations, coupled with appropriate patient selection for the chosen procedure. The decision to proceed with TAA or AA should be made on a case-by-case basis following an informed discussion with the patient regarding the different goals and complication profiles for each procedure.

Introduction

The controversy in surgical management of end-stage tibiotalar arthritis with Total Ankle Arthroplasty (TAA) versus Ankle Arthrodesis (AA) has grown over the past few decades, in parallel with the evolution of both procedures. Surgical goals, patient expectations, and complication profiles are vastly different between these two procedures, making randomized controlled trials difficult to execute. This lack of high-quality data has resulted in debate over which procedure should be the gold standard treatment for a patient with end-stage tibiotalar arthritis.

Ankle arthrodesis has previously been accepted as the gold standard treatment over the past few decades. Results following AA are predictable, with reliable pain relief once fusion is achieved, and good to excellent intermediate-term outcomes.[1-6] However, critics of AA cite high complication rates, alterations in foot and ankle biomechanics, and variability in long-term results.[7-10] There is concern that elimination of a major motion segment through fusion places unnatural stress on adjacent joints, accelerating adjacent joint degeneration.[8,9] Furthermore, arthrodesis has been shown to negatively affect functional status at long-term follow-up.[11] For these, and other reasons, authors have pushed for the evolution of treatment with joint-sparing procedures, specifically TAA.

First-generation TAA implants were plagued with unacceptably high complication rates and poor long-term survivorship, resulting in significant resistance to accept this treatment option.[12] Since the introduction of the first-generation TAA implants, surgical techniques and implant design has significantly evolved. Studies reporting results following treatment with modern third-generation TAA designs show improved survivorship over older generation implants, and more favorable functional outcomes compared to patients treated with AA.[13-19] Despite these encouraging early findings, long-term outcome data following treatment with a third-generation TAA are lacking.

There has been significant evolution of both procedures over the past few decades. Greater attention to soft tissue management during AA, including the popularization to arthroscopic fusion techniques, have led to lower complication rates, higher fusion rates, and more predictable outcomes following arthrodesis.[1,4,20] Likewise, current third-generation TAA designs and refined surgical techniques have improved outcomes, and lowered complication rates following TAA.[15,16,21] To date, there are no randomized controlled trials comparing outcomes following TAA to AA. Due to the vast difference between these two treatment options, a randomized controlled trial comparing the two is unlikely. As both procedures continue to evolve, systematic reviews will prove necessary to help guide decision making when treating patients with end-stage tibiotalar arthritis. Current systematic reviews include outdated TAA implants and AA techniques, limiting analysis of the current state of both procedures. In this study we report data from a systematic review and meta-analysis comparing outcomes following TAA and AA with modern surgical techniques and implant designs from studies published in the past decade.

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Materials and Methods

The PRISMA guidelines were followed to conduct this systematic review and meta-analysis.

Table 1. Demographics.

Study	Year published	Study design	Recruitment period	Number ankles	Prosthesis / fusion technique (n)	Mean age in years (range)	Mean follow up in years (range)	Post-traumatic, %	Idiopathic, %	Inflammatory, %	Other, %
Total Ankle Arthroplasty											
Gross *et al.*	2016	Prospective	2007-2013	455	INBONE (219) / STAR (151) / Salto (85)	62.0	3.7	71.9 (327)	13.6 (62)	8.1 (37)	6.4 (29)
Demetracopoulos *et al.*	2015	Prospective	2007-2011	395	INBONE (214) / STAR (104) / Salto (77)	63.1	3.5 (2-5.4)	69.1 (273)	17.7 (70)	5.8 (23)	7.3 (29)
Lewis *et al.*	2015	Prospective	2007-2012	249	INBONE	63.2	3.3	69.5 (173)	20.5 (51)	4.0 (10)	6.0 (15)
Daniels *et al.*	2015	Prospective	2001-2005	111	STAR	61.9 +/- 11.7	7.6 +/- 2.3 (2-9.6)	54.1 (60)	14.4 (16)	19.8 (22)	11.7 (13)
Hsu *et al.*	2015	Retrospective	2008-2012	59	INBONE	57.2 +/- 11.2 (32-79)	2.9 (2-5.4)	59.3 (35)	33.9 (20)	6.8 (4)	0.0 (0)
Adams *et al.*	2014	Retrospective	2007-2010	194	INBONE	64.0 (23-88)	3.7 (2.2-5.5)	68.0 (132)	22.2 (43)	4.1 (8)	5.7 (11)
Choi *et al.*	2014	Retrospective	2004-2011	173	HINTEGRA	66.0 +/- 7.9 (43-84)	5.0 (2-9.3)	NR	NR	NR	NR
Gaudot *et al.*	2014	Retrospective	1997-2009	66	Salto	64.0 (38-79)	2.0 (0.3-5)	45.5 (30)	15.2 (10)	6.1 (4)	33.3 (22)
Deleu *et al.*	2014	Retrospective	2008-2012	50	HINTEGRA	54.9 +/- 12.2 (30-77)	3.8 (2-6)	68.0 (34)	14.0 (7)	18.0 (9)	0.0 (0)
Barg *et al.*	2013	Retrospective	2000-2010	722	HINTEGRA	61.1 +/- 12.6 (19.8 - 90)	6.3 +/- 2.9 (2-12.2)	79.1 (571)	9.6 (69)	0.0 (0)	11.4 (82)
Rodrigues-Pinto *et al.*	2013	Prospective	2005-2011	119	Salto	55.6 (24-81)	3.2 (1.5-6)	65.5 (78)	10.1 (12)	24.4 (29)	0.0 (0)
Noelle *et al.*	2013	Retrospective	2005-2010	100	STAR	63.0 (41-80)	3.0	81.0 (81)	8.0 (8)	9.0 (9)	2.0 (2)
Brunner *et al.*	2013	Prospective	1996-2000	77	STAR	56.9 +/- 13.9 (22.3-84.5)	12.4 (10.8-14.9)	70.1 (54)	29.9 (23)	0.0 (0)	0.0 (0)
Nodzo *et al.*	2013	Retrospective	2007-2011	75	Salto	60.6 (41-82)	3.6 (2-6.1)	49.3 (37)	40.0 (30)	10.7 (8)	0.0 (0)
Schweitzer *et al.*	2013	Prospective	2007-2009	67	Salto	63.0 (34-86)	2.8 (2-4.5)	76.1 (51)	16.4 (11)	6.0 (4)	1.5 (1)
Bleazey *et al.*	2013	Retrospective	2008-2011	58	INBONE	59.5 +/- 10.9	NR	48.3 (28)	43.1 (25)	8.6 (5)	0.0 (0)
Nunley *et al.*	2012	Retrospective	1998-2008	82	STAR	63.3 +/- 10.1	5.1 (2-9)	52.4 (43)	34.1 (28)	12.2 (10)	1.2 (1)
Schenk *et al.*	2011	Prospective	2001-2007	218	Salto	56.8 +/- 11.2	3.5	59.2 (129)	29.4 (64)	11.0 (24)	0.5 (1)
Bonnin *et al.*	2011	Retrospective	1997-2000	98	Salto	56.0 +/- 13.0 (26-81)	8.9 (6.8-11.1)	43.9 (43)	14.3 (14)	27.6 (27)	14.3 (14)
Mann *et al.*	2011	Prospective	1998-2000	84	STAR	61.4 (33-86)	9.1 (2.6-11)	56.0 (47)	25.0 (21)	17.9 (15)	1.2 (1)
Bai *et al.*	2010	Retrospective	2005-2007	67	HINTEGRA	56.0 (27-77)	3.2 (2.1-4.5)	55.2 (37)	44.8 (30)	0.0 (0)	0.0 (0)
Saltzman *et al.*	2009	Prospective	2000-2006	593	STAR	63.1 +/- 11.9	NR	58.2 (345)	26.5 (157)	8.6 (51)	6.7 (40)
Wood *et al.*	2008	Prospective	1993-2000	200	STAR	59.6 (18-83)	7.3 (5-13)	12.5 (25)	28.0 (56)	59.5 (119)	0.0 (0)
Total / Adjusted Mean	2008-2016	Prospective (11) Retrospective (12)	1993-2013	4312	INBONE (993) STAR (1502) Salto (805) HINTEGRA (1012)	61.4 (54.9-66)	4.9 (2-12.4)	63.6 (2633/4139)	20.0 (827/4139)	10.1 (418/4139)	6.3 (261/4139)
Ankle Arthrodesis											
Chalayon *et al.*	2015	Retrospective	2002-2013	215	Open	56.0 +/- 14.0 (18-88)	NR	74.6 (156)	0.0 (0)	0.0 (0)	27.4 (59)
Nodzo *et al.*	2014	Retrospective	2006-2011	56	Open	49.4	0.3	73.2 (41)	21.4 (12)	0.0 (0)	5.4 (3)
Gordon *et al.*	2013	Retrospective	2004-2009	82	Open	56.1 (18-75)	3.9 (0.6-8.3)	63.4 (52)	20.7 (17)	8.5 (7)	7.3 (6)
Townshend *et al.*	2013	Retrospective	NR	30	Open	54.7 +/- 11.5	NR	13.3 (4)	63.3 (19)	13.3 (4)	10.0 (3)
Hendrickx *et al.*	2011	Retrospective	1990-2005	66	Open	47.0 +/- 13.0	9.0 +/- 4.1	87.9 (58)	0.0 (0)	0.0 (0)	12.1 (8)
Zwipp *et al.*	2010	Retrospective	1994-2000	94	Open	53.0 (34-69)	5.9 (4.8-7.8)	88.3 (83)	5.3 (5)	0.0 (0)	6.4 (6)
Saltzman *et al.*	2009	Prospective	2000-2005	66	Open	57.1 +/- 12.3	NR	65.2 (43)	28.8 (19)	6.5 (4)	0.0 (0)
Nielsen *et al.*	2008	Retrospective	1994-2005	49	Open	53.0 (20-84)	NR	65.3 (32)	20.4 (10)	4.1 (2)	10.2 (5)
Muckley *et al.*	2007	Retrospective	1993-2001	137	Open	49.0 (21-79)	3.5 (1-7.5)	98.5 (135)	1.5 (2)	0.0 (0)	0.0 (0)
Jain *et al.*	2016	Retrospective	2007-2013	52	Arthroscopic	59.4 (27-80)	2.7 (0.7-6.5)	73.1 (38)	9.6 (5)	5.8 (3)	11.5 (6)
Townshend *et al.*	2013	Retrospective	NR	30	Arthroscopic	59.4 +/- 10.6	NR	76.7 (23)	13.3 (4)	3.3 (1)	6.7 (2)
Yoshimura *et al.*	2012	Retrospective	2005-2010	50	Arthroscopic	63.0 (40-81)	3.5 (1.2-6.6)	78.0 (39)	0.0 (0)	4.0 (2)	18.0 (9)
Dannawi *et al.*	2010	Retrospective	1999-2007	55	Arthroscopic	63.0 +/- 12.2 (32-84)	4.7 +/- 1.7 (1.7-7.7)	43.6 (24)	36.4 (20)	14.5 (8)	5.5 (3)
Nielsen *et al.*	2008	Retrospective	1994-2005	58	Arthroscopic	51.0 (23-80)	NR	63.8 (37)	13.8 (8)	10.3 (6)	12.1 (7)
Gougoulias *et al.*	2007	Retrospective	1998-2005	78	Arthroscopic	54.0 +/- 14.0 (18-81)	1.8 (0.5-5.7)	48.7 (38)	38.5 (30)	5.1 (4)	7.7 (6)
Total / Adjusted Mean	2016-2007	Prospective (1) Retrospective (14)	1990-2013	1118	Open (9) Arthroscopic (6)	54.4 (47-63)	4.0 (0.3-9)	71.8 (803/1118)	13.5 (151/1118)	3.7 (41/1118)	11.0 (123/1118)
Open	2015-2007	Prospective (1) Retrospective (8)	1990-2013	795	Open (9)	53.1 (47-57.1)	4.5 (0.3-9)	76.0 (604/795)	10.6 (84/795)	2.1 (17/795)	11.3 (90/795)
Arthroscopic	2016-2007	Prospective (0) Retrospective (6)	1994-2013	323	Arthroscopic (6)	57.8 (51-63)	3.0 (1.8-4.7)	61.6 (199/323)	20.7 (67/323)	7.4 (24/323)	10.2 (33/323)

Search Strategy

An electronic PubMed database search was performed to identify publications reporting outcomes following TAA and/or AA published in the English language from January 1st, 2006 until July 31st, 2016. The search terms utilized include: *total ankle arthroplasty*; *ankle replacement*; *ankle arthrodesis*; and *ankle fusion*. To ensure inclusion of all relevant publications, the electronic database search was supplemented by a manual review of references in all reviews and primary full text articles identified. Two authors screened all titles, abstracts, and selected full text articles independently, with studies determined to be relevant, irrelevant, or uncertain according to study eligibility criteria. Conflicts were resolved by consensus discussion.

Selection of Articles

The review sought primary research publications reporting complication and/or re-operation rates following TAA or AA, which could be extracted from the general data. Article titles and abstracts were screened using three general criteria: i) primary research data; ii) the intervention included TAA using a third-generation implant approved for use in the United States (Implants included: HINTEGRA, STAR, Salto, INBONE) or AA achieved with internal fixation through an open or arthroscopic technique; iii) complication, re-operation, and/or revision rates were reported.

Article titles and abstracts satisfying the criteria above were selected for full text review. Full text articles were then examined and selected based on the inclusion and exclusion criteria below.

Inclusion criteria: i) primary research data; ii) published in the English language from January 1st, 2006 to July 31st, 2016; iii) report on a minimum of 50 ankles; iv) the intervention consisted of arthrodesis with internal fixation using open or arthroscopic techniques or TAA using a third-generation implant approved for use in the United States (Implants included: HINTEGRA, STAR, Salto, INBONE); v) complication, re-operation, and/or revision rates were reported.

Exclusion criteria included: i) non-generalizable patient cohorts; ii) outcomes following revision cases; iii) kinship data (for publications on the same patient population the largest series was used).

Quality Assessment

The methodology of studies included in this review was evaluated with the modified Coleman Methodology Score (CMS) as utilized in previous studies (Supplementary Table S1).[22,23] Two authors independently assessed the methodological quality of each study, and discrepancies in CMS scores were reviewed by a third author, with conflicts resolved by consensus discussion. The CMS score is between 0 and 100; with 100 indicating the study has a robust design and largely avoids biases or confounding factors (Supplementary Table S2).

Data Extraction

The study demographic, complication, re-operation, failure, and revision data were extracted from the selected full text articles. For continuous data, preferably the mean, range, and standard deviation were extracted. If not presented in the study, the mean and range were calculated whenever possible. Protocol-defined data from each eligible study were extracted and confirmed by two independent authors, and differences were resolved prior to data entry. Demographic data for included studies can be seen in Table 1 (demographics meta-analysis results can be seen in Table 2).

Complication, non-revision re-operation, and revision data were extracted from each study (Tables 3-6). There was significant heterogeneity between studies with respect to reporting this data. In cases where data was not explicitly stated within an article, attempts were made to calculate these rates using data reported within the study. The studies included in this review were inconsistent when reporting the complications of interest. When a data point of interest was not explicitly stated or could not be confirmed within the text, it was designated in the tables as Not Reported (NR).

Intra-operative and post-operative fractures were combined for our analysis, and reported as a single overall fracture rate. Failure rate was defined as a TAA requiring revision of implants, conversion to fusion, or below knee amputation or an AA resulting in non-union or requiring revision fusion or below knee amputation regardless of whether or not a patient decided to pursue further surgical intervention. Revision of TAA was defined as removal of the tibial and/or talar component with subsequent placement of an antibiotic spacer, revision of metal components, conversion to arthrodesis, or amputation. Revision AA was defined as return to the operating room for revision fusion or conversion to amputation.

Statistical Analysis

Data from each study was pooled for analysis. Cumulative study totals and adjusted means were reported for demographic, complication, and revision data. Adjusted means were calculated for mean follow-up and mean age by summing each study mean multiplied by the number of ankles in their study and dividing the sum by the total number of ankles in all studies reporting the variable of interest to obtain an appropriately weighted mean. Cumulative adjusted complication and revision rates were calculated by taking the number of specific complications divided by the sum of all cases for only those studies reporting the outcome of interest.

We then performed a meta-analysis using a random-effects meta-regression model for all data. Mean age and mean follow-up were two quantitative outcomes reported by each study, however many did not report corresponding standard errors. For statistical meta-analysis to be possible, missing standard deviations were imputed with the maximum reported standard deviation. Effect sizes were measured using log transformed means for quantitative outcomes (mean age and mean follow-up), and logit transformed proportions for categorical outcomes (diagnosis, complication, and

Table 2. Demographics meta-analysis results.

Variable	TAA *vs.* Combined AA p-value	TAA *vs.* Open AA p-value	TAA *vs.* Arthroscopic AA p-value	Open AA *vs.* Arthroscopic AA p-value
Mean age in years	<0.01*	<0.01*	0.26	0.02*
Mean follow up in years	0.30	0.78	0.04*	0.39
Diagnosis				
Post-traumatic	0.15	0.18	0.58	0.36
Idiopathic	0.13	0.16	0.56	0.40
Inflammatory	0.06	0.02*	0.48	0.06
Other	<0.01*	0.04*	< 0.01*	0.48

* Indicates statistically significant difference (P-value < 0.05).

Table 3. Complications and failure rates.

Study	Number of ankles	Prosthesis / fusion technique (n)	Wound complication (n), %	Deep infection (n), %	Intra- and post-operative fracture (n), %	TAA aseptic loosening / AA nonunion (n), %	Overall complication rate (n), %	Failure rate (n), %
Total Ankle Arthroplasty								
Gross *et al.*	455	INBONE (219) / STAR (151) / Salto (85)	NR	1.5 (7)	NR	NR	14.1 (64)	3.1 (14)
Demetracopoulos *et al.*	395	INBONE (214) / STAR (104) / Salto (77)	6.6 (26)	0.8 (3)	NR	NR	NR	5.1 (20)
Lewis *et al.*	249	INBONE	8.4 (21)	1.2 (3)	3.6 (9)	4.0 (10)	NR	8.8 (22)
Daniels *et al.*	111	STAR	3.6 (4)	NR	0.9 (1)	NR	NR	11.7 (13)
Hsu *et al.*	59	INBONE	NR	0.0 (0)	3.4 (2)	NR	44.1 (26)	8.5 (5)
Adams *et al.*	194	INBONE	10.3 (20)	2.6 (5)	3.6 (7)	0.5 (1)	NR	10.8 (21)
Choi *et al.*	173	HINTEGRA	7.5 (13)	0.6 (1)	0.6 (1)	2.9 (5)	NR	3.5 (6)
Gaudot *et al.*	66	Salto	3.0 (2)	0.0 (0)	12.1 (8)	0.0 (0)	19.7 (13)	1.5 (1)
Deleu *et al.*	50	HINTEGRA	NR	4.0 (2)	NR	NR	NR	10.0 (5)
Barg *et al.*	722	HINTEGRA	NR	0.4 (3)	NR	5.8 (42)	NR	8.4 (61)
Rodrigues-Pinto *et al.*	119	Salto	3.4 (4)	1.7 (2)	5.0 (6)	0.0 (0)	14.3 (17)	1.7 (2)
Noelle *et al.*	100	STAR	6.0 (6)	4.0 (4)	2.0 (2)	6.0 (6)	NR	11.0 (11)
Brunner *et al.*	77	STAR	1.3 (1)	1.3 (1)	NR	11.7 (9)	NR	37.7 (29)
Nodzo *et al.*	75	Salto	NR	1.3 (1)	8.0 (6)	NR	NR	1.3 (1)
Schweitzer *et al.*	67	Salto	4.5 (3)	0.0 (0)	4.5 (3)	4.5 (3)	34.3 (23)	4.5 (3)
Bleazey *et al.*	58	INBONE	13.8 (8)	1.7 (1)	6.9 (4)	0.0 (0)	27.6 (16)	1.7 (1)
Nunley *et al.*	82	STAR	NR	NR	NR	NR	NR	6.1 (5)
Schenk *et al.*	218	Salto	2.3 (5)	1.4 (3)	2.3 (5)	1.8 (4)	NR	16.5 (36)
Bonnin *et al.*	98	Salto	NR	1.0 (1)	NR	1.0 (1)	NR	7.1 (7)
Mann *et al.*	84	STAR	NR	3.6 (3)	8.3 (7)	2.4 (2)	25.0 (21)	10.7 (9)
Bai *et al.*	67	HINTEGRA	11.9 (8)	1.5 (1)	11.9 (8)	0.0 (0)	47.8 (32)	1.5 (1)
*Saltzman *et al.*	593	STAR	20.9 (124)	1.2 (7)	13.5 (80)	NR	NR	4.7 (28)
Wood *et al.*	200	STAR	2.5 (5)	NR	9.5 (19)	12.5 (25)	32.5 (65)	12.0 (24)
Total / Adjusted Mean	4312	INBONE (993) STAR (1502) Salto (805) HINTEGRA (1012)	9.3 (250/2687)	1.2 (48/3919)	6.9 (168/2433)	4.3 (108/2492)	23.6 (277/1175)	7.5 (325/4312)
Ankle Arthrodesis								
Chalayon et al	215	Open	14.4 (31)	5.1 (11)	0.9 (2)	9.3 (20)	40.9 (88)	9.3 (20)
Nodzo *et al.*	56	Open	3.6 (2)	1.8 (1)	NR	12.5 (7)	NR	12.5 (7)
Gordon *et al.*	82	Open	2.4 (2)	0.0 (0)	1.2 (1)	0.0 (0)	20.7 (17)	0.0 (0)
*Townshend *et al.*	30	Open	3.3 (1)	NR	NR	3.3 (1)	NR	3.3 (1)
Hendrickx *et al.*	66	Open	0.0 (0)	1.5 (1)	0.0 (0)	6.1 (4)	10.6 (7)	9.1 (6)
Zwipp *et al.*	94	Open	5.3 (5)	0.0 (0)	0.0 (0)	1.1 (1)	9.6 (9)	2.1 (2)
*Saltzman *et al.*	66	Open	6.1 (4)	1.5 (1)	3.0 (2)	NR	NR	10.6 (7)
*Nielsen *et al.*	49	Open	NR	4.1 (2)	NR	16.3 (8)	NR	16.3 (8)
Muckley *et al.*	110	Open	10.0 (11)	7.3 (8)	0.9 (1)	14.5 (16)	19.1 (21)	14.5 (16)
Jain *et al.*	52	Arthroscopic	0.0 (0)	0.0 (0)	0.0 (0)	7.7 (4)	30.8 (16)	7.7 (4)
*Townshend *et al.*	30	Arthroscopic	3.3 (1)	NR	NR	3.3 (1)	NR	3.3 (1)
Yoshimura *et al.*	50	Arthroscopic	NR	0.0 (0)	NR	8.0 (4)	NR	8.0 (4)
Dannawi *et al.*	55	Arthroscopic	5.5 (3)	0.0 (0)	0.0 (0)	9.1 (5)	23.6 (13)	9.1 (5)
*Nielsen *et al.*	58	Arthroscopic	NR	1.7 (1)	NR	5.2 (3)	NR	5.2 (3)
Gougoulias *et al.*	78	Arthroscopic	1.3 (1)	0.0 (0)	0.0 (0)	2.6 (2)	28.2 (22)	2.6 (2)
Total / Adjusted Mean	1091	Open (9) Arthroscopic (6)	6.5 (61/934)	2.4 (25/1031)	0.7 (6/818)	7.4 (76/1025)	25.7 (193/752)	7.9 (86/1091)
Open	768	Open (9)	7.8 (56/719)	3.3 (24/738)	0.9 (6/633)	8.1 (57/702)	25.0 (142/567)	8.7 (67/768)
Arthroscopic	323	Arthroscopic (6)	2.3 (5/215)	0.3 (1/293)	0.0 (0/185)	5.9 (19/323)	27.6 (51/185)	5.9 (19/323)

re-operation rates). For each outcome, a random-effects meta-regression model was independently fitted to each subset of studies defined by type of surgical intervention (TAA, AA, open AA, arthroscopic AA). A Wald-type test was then performed to test whether the estimates from any two of the subset models are significantly different from each other. All statistical analysis was performed using R version 3.3.2 (The R Foundation for Statistical Computing, https://www.r-project.org/).

Results

Article Selection

The initial search yielded 325 abstracts, of which 136 full text articles were retrieved for further review. Thirty-five articles met all eligibility criteria for inclusion in this study.[1-6,14-16,20,21,24-47] Of the included studies, 23 reported on TAA and 15 on AA (6 arthroscopic AA, 9 open AA).

Quality Assessment

The quality of all articles included in this study was assessed using the modified Coleman Methodology Score (CMS). Results of the modified CMS for each study can be seen in Supplementary Table S2. The mean CMS score for the TAA studies was 59.4 (Range: 39-81) compared to 41.4 (Range: 29-53) for the AA studies (p<0.01).

Demographics

Demographic data can be seen in Table 1. The included studies report on 4312 TAA and 1118 AA patients (795 open, 323 arthroscopic). Patients who underwent TAA were significantly older than the AA patients (61.4 years and 54.4 years respectively, p<0.01). There was no significant difference in mean follow-up between the TAA and AA studies (4.9 years and 4.0 years respectively, p-value 0.30). Post-traumatic arthritis was the most common diagnosis for both the TAA and AA groups. Demographics meta-analysis results can be seen in Table 2.

Complications and Failure Rates

The most common complication for patients who underwent TAA was wound complication (9.3%) followed by intra- or post-operative fracture (6.9%). Nonunion (7.4%) was the most common complication for patients who underwent AA, followed by wound complication (6.5%). See Table 3 for complication and failure rate data. Deep infection was significantly more common following open AA compared to TAA (p<0.01) and arthroscopic AA (p=0.04). Intra- and post-operative fractures were significantly more common following TAA compared to AA (p<0.01), while nonunion was significantly more common in AA patients than aseptic loosening in TAA patients (p<0.01). There was no significant difference in overall complication rate or failure rate between the two procedures. Complication and failure rate meta-analysis results can be seen in Table 4.

Re-Operation and Revision Rates

There was no significant difference in the non-revision re-operation rate following TAA compared to AA (11.3% and 9.8% respectively, p-value 0.47). Similarly, there was no significant difference in the overall revision rate following TAA compared to AA (7.2% and 6.3% respectively, p-value 0.65). There was no difference in the rate of revision to amputation between the two procedures (p-value 0.30). See Table 5 for re-operation and revision rate data, and Table 6 for meta-analysis results.

Discussion and Conclusions

TAA and AA continue to evolve as surgical treatment options for end-stage tibiotalar arthritis. With the growth and evolution of both procedures, the debate regarding the best surgical option has persisted. Randomized controlled trials are difficult to execute given the vast differences in surgical goals, patient expectations, and complication profiles between these two procedures. This lack of high quality data contributes to the ongoing debate over which procedure should be the gold standard treatment for end-stage tibiotalar arthritis, and highlights the importance of systematic reviews to provide data to help guide the discussion of surgical options for patients presenting with this pathology. Our review compares complication and revision rates between modern third-generation TAA implants and current AA techniques to more accurately reflect the current state of these treatment options.

Previous systematic reviews are limited, drawing few meaningful conclusions, and predominately focus on clinical outcomes and revision rates following TAA and AA. Haddad et al. reported a 7% revision rate following TAA compared to a 9% revision rate following AA at a mean follow-up of 5.1 years.[48] The authors conclude the intermediate outcome of TAA appears to be similar to that of AA. Jordan et al. concluded the lack of high quality literature was insufficient to determine which treatment is superior for the management of end-stage tibiotalar arthritis.[49] Van Heiningen *et al.* reported a systematic review in rheumatoid arthritis patients, finding an 11% re-operation rate following TAA compared to 12% following AA, with both interventions showing clinical improvement.[50] A limitation of previous systematic reviews is the inclusion of outdated TAA implants and AA techniques, which have evolved significantly over the past few decades.

Our data suggests there is a similar wound complication rate following TAA compared to open AA (9.3% and 7.8%

Table 4. Complications and failure rates meta-analysis data.

Variable	TAA *vs.* Combined AA p-value	TAA *vs.* Open AA p-value	TAA *vs.* Arthroscopic AA p-value	Open AA *vs.* Arthroscopic AA p-value
Wound complication	0.45	0.85	0.14	0.21
Deep infection	0.12	< 0.01*	0.58	0.04*
Intra- and post-operative fracture	< 0.01*	< 0.01*	0.02*	0.64
TAA aseptic loosening / AA nonunion	< 0.01*	< 0.01*	0.07	0.09
Overall complication rate	0.31	0.19	0.95	0.16
Failure	0.23	0.10	0.68	0.07

* Indicates statistically significant difference (P-value <0.05). * Indicates statistically significant difference (P-value <0.05).

Table 5. Re-operation and revision rates.

Study	Number of ankles	Mean follow up in years (range)	Prosthesis / fusion technique (n)	Non-revision re-operation rate, %	Revision rate, %			
					Overall revision rate	Revision to TAA	Revision to AA	Revision to amputation
Total Ankle Arthroplasty								
Gross *et al.*	455	3.7	INBONE (219) / STAR (151) / Salto (85)	NR	3.1 (14)	NR	NR	NR
Demetracopoulos *et al.*	395	3.5 (2-5.4)	INBONE (214) / STAR (104) / Salto (77)	9.6 (38)	5.1 (20)	2.3 (9)	2.5 (10)	0.3 (1)
Lewis *et al.*	249	3.3	INBONE	14.5 (36)	8.4 (21)	4.4 (11)	3.6 (9)	0.4 (1)
Daniels *et al.*	111	7.6 +/- 2.3 (2-9.6)	STAR	20.7 (23)	11.7 (13)	3.6 (4)	7.2 (8)	0.9 (1)
Hsu *et al.*	59	2.9 (2-5.4)	INBONE	23.7 (14)	8.5 (5)	8.5 (5)	0.0 (0)	0.0 (0)
Adams *et al.*	194	3.7 (2.2-5.5)	INBONE	11.0 (21)	6.2 (12)	2.1 (4)	3.6 (7)	0.5 (1)
Choi *et al.*	173	5.0 (2-9.3)	HINTEGRA	NR	3.5 (6)	2.9 (5)	0.6 (1)	0.0 (0)
Gaudot *et al.*	66	2.0 (0.3-5)	Salto	3.0 (2)	1.5 (1)	0.0 (0)	1.5 (1)	0.0 (0)
Deleu *et al.*	50	3.8 (2-6)	HINTEGRA	18.0 (9)	10.0 (5)	4.0 (2)	6.0 (3)	0.0 (0)
Barg *et al.*	722	6.3 +/- 2.9 (2-12.2)	HINTEGRA	NR	8.4 (61)	7.5 (54)	1.0 (7)	0.0 (0)
Rodrigues-Pinto *et al.*	119	3.2 (1.5-6)	Salto	5.0 (6)	0.8 (1)	0.0 (0)	0.8 (1)	0.0 (0)
Noelle *et al.*	100	3.0	STAR	10.0 (10)	11.0 (11)	7.0 (7)	4.0 (4)	0.0 (0)
Brunner *et al.*	77	12.4 (10.8-14.9)	STAR	54.5 (42)	37.7 (29)	35.1 (27)	2.6 (2)	0.0 (0)
Nodzo *et al.*	75	3.6 (2-6.1)	Salto	16.0 (12)	1.3 (1)	1.3 (1)	0.0 (0)	0.0 (0)
Schweitzer *et al.*	67	2.8 (2-4.5)	Salto	10.4 (7)	1.5 (1)	1.5 (1)	0.0 (0)	0.0 (0)
Bleazey *et al.*	58	NR	INBONE	8.6 (5)	1.7 (1)	1.7 (1)	0.0 (0)	0.0 (0)
Nunley *et al.*	82	5.1 (2-9)	STAR	13.4 (11)	6.1 (5)	NR	NR	NR
Schenk *et al.*	218	3.5	Salto	NR	16.5 (36)	11.0 (24)	5.5 (12)	0.0 (0)
Bonnin *et al.*	98	8.9 (6.8-11.1)	Salto	17.3 (17)	7.1 (7)	1.0 (1)	6.1 (6)	0.0 (0)
Mann *et al.*	84	9.1 (2.6-11)	STAR	6.0 (5)	10.7 (9)	4.8 (4)	6.0 (5)	0.0 (0)
Bai *et al.*	67	3.2 (2.1-4.5)	HINTEGRA	7.5 (5)	1.5 (1)	1.5 (1)	0.0 (0)	0.0 (0)
Saltzman *et al.*	593	NR	STAR	6.9 (41)	4.7 (28)	NR	NR	NR
Wood *et al.*	200	7.3 (5-13)	STAR	3.0 (6)	12.0 (24)	2.0 (4)	10.0 (20)	0.0 (0)
Total / Adjusted Mean	4312	4.9 (2-12.4)	INBONE (993) STAR (1502) Salto (805) HINTEGRA (1012)	11.3 (310/2744)	7.2 (312/4312)	5.2 (165/3182)	3.0 (96/3182)	0.1 (4/3182)
Ankle Arthrodesis								
Chalayon *et al.*	215	NR	Open	11.2 (24)	7.9 (17)	0.0 (0)	7.4 (16)	0.5 (1)
Nodzo *et al.*	56	0.3	Open	NR	12.5 (7)	0.0 (0)	12.5 (7)	0.0 (0)
Gordon *et al.*	82	3.9 (0.6-8.3)	Open	14.6 (12)	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Townshend *et al.*	30	NR	Open	0.0 (0)	3.3 (1)	0.0 (0)	3.3 (1)	0.0 (0)
Hendrickx *et al.*	66	9.0 +/- 4.1	Open	0.0 (0)	9.1 (6)	0.0 (0)	9.1 (6)	0.0 (0)
Zwipp *et al.*	94	5.9 (4.8-7.8)	Open	3.2 (3)	1.1 (1)	0.0 (0)	1.1 (1)	0.0 (0)
Saltzman *et al.*	66	NR	Open	1.5 (1)	10.6 (7)	NR	NR	NR
Nielsen *et al.*	49	NR	Open	20.4 (10)	6.1 (3)	0.0 (0)	6.1 (3)	0.0 (0)
Muckley *et al.*	110	3.5 (1-7.5)	Open	NR	10.0 (11)	0.0 (0)	10.0 (11)	0.0 (0)
Jain *et al.*	52	2.7 (0.7-6.5)	Arthroscopic	3.8 (2)	7.7 (4)	0.0 (0)	7.7 (4)	0.0 (0)
Townshend *et al.*	30	NR	Arthroscopic	6.7 (2)	3.3 (1)	0.0 (0)	3.3 (1)	0.0 (0)
Yoshimura *et al.*	50	3.5 (1.2-6.6)	Arthroscopic	12.0 (6)	6.0 (3)	0.0 (0)	6.0 (3)	0.0 (0)
Dannawi *et al.*	55	4.7 +/- 1.7 (1.7-7.7)	Arthroscopic	9.1 (5)	9.1 (5)	0.0 (0)	9.1 (5)	0.0 (0)
Nielsen *et al.*	58	NR	Arthroscopic	25.9 (15)	3.4 (2)	0.0 (0)	3.4 (2)	0.0 (0)
Gougoulias *et al.*	78	1.8 (0.5-5.7)	Arthroscopic	14.1 (11)	1.3 (1)	0.0 (0)	1.3 (1)	0.0 (0)
Total / Adjusted Mean	1091	4.0 (0.3-9)	Open (9) Arthroscopic (6)	9.8 (91/925)	6.3 (69/1091)	0.0 (0/1025)	6.0 (61/1025)	0.1 (1/1025)
Open	768	4.6 (0.3-9)	Open (9)	8.3 (50/602)	6.9 (53/768)	0.0 (0/702)	6.4 (45/702)	0.1 (1/702)
Arthroscopic	323	3.0 (1.8-4.7)	Arthroscopic (6)	12.7 (41/323)	5.0 (16/323)	0.0 (0/323)	5.0 (16/323)	0.0 (0/323)

Table 6. Re-operation and revision rates meta-analysis data.

Variable	TAA *vs.* Combined AA p-value	TAA *vs.* Open AA p-value	TAA *vs.* Arthroscopic AA p-value	Open AA *vs.* Arthroscopic AA p-value
Non-Revision Re-Operation Rate	0.47	0.20	0.93	0.22
Overall Revision Rate	0.65	0.44	0.62	0.25
Revision to TAA	< 0.01*	< 0.01*	0.02*	0.61
Revision to AA	< 0.01*	< 0.01*	0.06	0.37
Revision to Amputation	0.30	0.54	0.29	0.64

*Indicates statistically significant difference (P-value <0.05).

respectively, p-value 0.85). Despite not reaching statistical significance, the wound complication rate following arthroscopic AA was lower than that of TAA and open AA at 2.3%. However, there were significantly fewer deep infections following arthroscopic AA compared to open AA (0.3% and 3.3% respectively, p-value < 0.01). Arthroscopic AA is becoming popularized, due to this techniques ability to achieve fusion, while limiting the approach related morbidity and soft tissue dissection.[4,20,44,51-53] Nielsen *et al.* found similar union rates; with arthroscopic AA patients having shorter hospital stays compared to open AA patients.[4] Duan *et al.* reported a low wound complication rate of 1.5% in 68 arthroscopic ankle fusions. As fusion techniques continue to improve, the potential exists for continued improvement in fusion rates and lower complication rates than what have been seen with older techniques.

A similar evolution has been seen in TAA, with modern third-generation implants having improved survivorship over older generation designs.[13-16] Our data shows a significantly lower rate of TAA aseptic loosening compared to AA nonunion (4.3% and 7.4% respectively, P-value <0.01); however, there was no significant difference in revision rates between the two procedures (P-value =0.65). Brunner *et al.* reported on 77 TAA patients and found an 11.7% aseptic loosening rate and 37.7% revision rate at a mean follow-up of 12.4 years, which are much higher than our systematic review averages.[32] More studies on third-generation TAA implants with longer follow-up are required to compare aseptic loosening and revision rates with AA at long-term follow-up.

The current literature does not strongly favor either procedure for the treatment of end-stage tibiotalar arthritis in the general population. It is important for physicians to have knowledge of each treatments pros, cons, and complication profile to aid in counseling patients. The patient's goals, expectations, and understanding of the differences between TAA and AA are important to consider when deciding on a treatment option. Successful treatment of end-stage tibiotalar arthritis relies on appropriate patient selection, with various cases more appropriate for one treatment over the other. Ultimately, the decision to proceed with TAA or AA should be made on a case-by-case basis after an informed discussion with each patient.

There are multiple limitations of this study. The data reported is from a mean follow-up of 4.9 years in the TAA cohort and 4.0 years in the AA cohort. Longer follow-up data remains necessary to determine if aseptic loosening rates and revision rates remain competitive with AA data at longer follow-up intervals. Furthermore, the methodological quality of the studies available for this analysis was poor as evident by the Coleman Methodology Scores (Supplementary Table S2). There is significant heterogeneity in the data reported in the included studies, with variations in complications reported and differences in definitions of non-revision re-operation and implant failure between articles. This made data extracting and analysis difficult and vulnerable to bias.

The current literature lacks high quality studies with long-term follow-up comparing modern TAA to AA techniques. Existing data does not strongly support one treatment over the other for the management of end-stage tibiotalar arthritis. Our data suggests at a mean follow-up of 4.9 years in the TAA cohort and 4.0 years in the AA cohort, there is no significant difference in overall complication rate or revision rate. More data on third-generation TAA implants are necessary to compare failure and revision rates with AA at long-term follow-up. Successful treatment of end-stage tibiotalar arthritis requires an understanding of a patients goals and expectations, as well as appropriate patient selection for the chosen procedure. Ultimately, the decision to proceed with TAA or AA should be made on a case-by-case basis following an informed discussion with the patient regarding each procedure different goals and complication profiles.

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