










Does stem length affect proximal humeral stress shielding? A systematic review[☆]

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ABSTRACT

Introduction: Total shoulder arthroplasty (TSA) has increased in use, with revision surgeries also increasing. One cause of revision is aseptic loosening driven by stress shielding—a condition where altered load distribution leads to proximal humeral osteolysis surrounding the humeral prosthesis. This systematic review compares stress shielding between traditional-length (TL) and short-stem (SS) humeral prostheses, hypothesizing that SS stems reduce stress shielding.

Methods: A systematic search of Cochrane, Embase, and Medline databases was conducted. Inclusion criteria targeted studies from the last 10 years reporting radiographic outcomes of TL and SS stems. Pooled radiographic measures were stratified into a 5-zone analysis of the proximal humerus for comparison. These included cortical thinning and osteopenia (CNO), condensation lines (CL), spot welds (SW), and an overall adaptive change score. An additional GLIMMIX procedure was performed to evaluate the effect that technique and stem length had on radiographic outcomes using random effects modeling.

Results: A total of 7 studies were included, and 620 patients were analyzed, with 422 receiving SS and 198 receiving TL humeral prostheses. The weighted average follow-up was 34.8 months. TL showed higher rates of CNO around the superior-lateral humeral prosthesis, and SS showed higher rates of CNO around the inferior-lateral and medial prosthesis. TL showed higher rates of SW around the superior-lateral and medial prosthesis, but SS showed higher rates of SW around the distal-lateral and medial prosthesis. No differences were found in CL for any group or for any measure under the stem. A significantly greater proportion of TL patients had low adaptive change scores, with more SS patients possessing high adaptive change scores. Technique did not show any significant effects on radiographic outcomes while stem length showed a significant effect on CNO in the distal-lateral zone (F-Value = 19.72, $p = 0.04$, OR = 0.106, 95 % CI [0.012–0.932])

Conclusion: This study demonstrated radiographic differences between short and traditional-length stems that suggest unique patterns of bone remodeling. While short stems may better preserve proximal lateral bone, the higher incidence of distal cortical changes warrants careful patient selection, and traditional-length stems may remain preferable when metaphyseal fixation or bone quality is a concern.

1. Introduction

Over 800,000 people in the United States live with a shoulder replacement, reflecting the increased prevalence of total shoulder arthroplasty (TSA) over the past decade.¹ Even though roughly 90 % of shoulder replacements survive at least 10 years, the rate of revision surgery has continued to increase, up 392 % over the past decade.² Costs

associated with revision surgery and complications have been estimated at approximately \$206 million per year.^{1,2} Indications for revision include periprosthetic fractures, infection, aseptic loosening, and instability.^{3–5} One cause of poor outcomes and potential loosening is proximal osteolysis surrounding the humeral component of the prosthesis by mechanisms such as stress shielding.⁶

Wolff's Law states that bones will strengthen when experiencing

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increased stress and weaken when experiencing decreased stress.⁷ Stress shielding, a function of Wolff's Law, is defined as the resorption of the bone around non-stressed portions of the implant. In the case of total shoulder arthroplasty, the degree of stress unloaded from the proximal humerus can be placed on the more distal aspects of the humeral component after TSA.⁸ As such, shorter stems are thought to have decreased stress shielding compared to longer stems.⁹ Additionally, short stems often provide an easier revision surgery, possess simplified implantation, and may better fit anatomically challenging patients with narrow canals. However, SS also are prone to varus/valgus misalignment, rely solely on metaphyseal fixation, and lack long-term survivorship data. There is a paucity of literature directly comparing the rates of stress shielding in traditional length (TL) and short-stemmed (SS) humeral prostheses.

Given the lack of literature, the purpose of this systematic review is to evaluate the effect that stem length has on stress shielding in TSA. A secondary endpoint is to evaluate the survivorship of TSA, stratified by short versus long stem prostheses. We hypothesize that shorter stem lengths will result in decreased radiographic evidence of stress shielding when compared to longer, more traditional length stems.

2. Methods

This review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for reporting systematic reviews.

2.1. Search strategy

Before beginning the literature search, a search protocol was created and published online in the PROSPERO International Prospective Register of Systematic Reviews (CRD42024586527) database. A search strategy was then implemented to query the databases of Cochrane, Embase, and Medline with no restriction on publication date. The initial literature search was conducted in August 2024. This search strategy aimed to identify studies that investigated stress shielding of the humerus after total shoulder arthroplasty. Search terms included “stress shielding”, “humeral stem”, “medial calcar osteolysis”, and “total shoulder arthroplasty” to identify the relevant articles. Inclusion criteria were: (i) primary studies published in the past 10 years, (ii) full-text available, (iii) published in English, (iv) explicit statement of stem length or classification as “traditional” or “short”, (v) evaluated radiographic outcomes such as medial calcar osteolysis, proximal humeral osteolysis, and aseptic loosening, (vi) outcomes to be included must be able to be combined into either a “short” or “traditional” length stem group for comparisons to be drawn. Exclusion criteria were: (i) did not have a minimum of 2-year follow-up data, (ii) did not utilize the 5-zone system of analyzing radiographic changes of the humerus, which were originally described by Nagels¹⁰ et al. who divided the humeral stem into zones from the geometric head of the humerus to the distal tip of the implant using an AP radiograph of the shoulder to include the superior medial/lateral half of the prosthesis (M1 and L1), the inferior medial/lateral half of the prosthesis (M2 and L2), and under the stem (US) (Fig. 1),^{10,11} (iii) cemented stems, (iv) stemless humeral prostheses, (v) did not separate stemless or cemented humeral component data from press-fit and stemmed data.

2.2. Assessment of eligibility and study selection

The initial database search yielded 378 papers matching the search terms. After removing 121 duplicate studies, 257 studies remained. Two independent reviewers (M.H. & C.R.) applied the inclusion criteria to the titles and abstracts of the studies, resulting in 167 studies being removed. Following this, a full-text review of the remaining 90 articles was conducted by the same two reviewers by applying the exclusion criteria. Any disagreements encountered during this process were

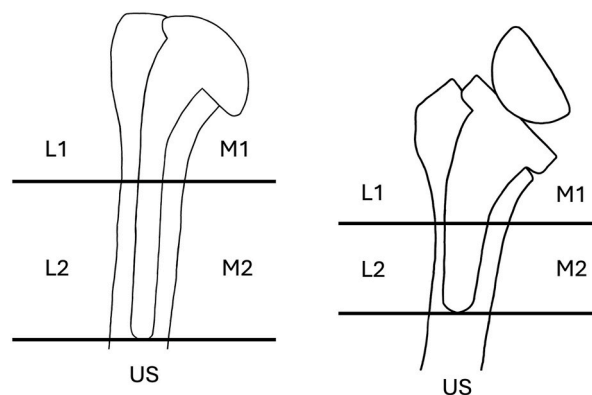


Fig. 1. Zones used for the grading of radiographic changes. L1 = Superior lateral zone, L2 = Inferior lateral zone, US=Under stem, M2 = Inferior medial zone, M1 = Superior medial zone.

resolved by a third reviewer (D.D.). Following the search process, 7 papers were identified that fit the criteria for the systematic review. A PRISMA flow chart detailing the search strategy is included in Fig. 2.

2.3. Assessment of study quality

Study quality was assessed using the Critical Appraisal Skills Programme (CASP) checklist to assess the risk of bias within each study.¹² Scores of the included studies ranged from 9 to 11, with an average score of 9.9.

2.4. Data extraction

Data extraction of the included studies was conducted by three reviewers. Extracted data included: (1) study characteristics: title, author, publication year, study design; (2) stem length classification: short <100 mm and traditional >100 mm as described by Denard et al.⁸; (3) technique used: anatomic TSA (aTSA) or reverse TSA (rTSA); (4) brand of shoulder system used; (5) study population: number of participants, sex, age, dominant arm prostheses, average follow-up interval; (6) clinical outcomes: pre- and post-operative forward flexion and external rotation, complication rate, and revision rate; (7) cortical thinning and osteopenia (CNO), spot welds (SW), and condensation lines (CL) in the 5 zones described above; and (8) adaptive change scores as defined by Denard et al.,¹³ with lower adaptive change scores indicating less bone remodeling and high adaptive change scores indicating more bone remodeling.

2.5. Data analysis

Data for patients with short stem prostheses and traditional length stem prostheses were pooled together. Pooled data analysis was performed by a departmental statistician using SAS 9.4 (SAS Institute Inc) to calculate statistics such as weighted means, standard deviations, and comparative statistics between groups using chi-squared tests and simple t-tests. A series of generalized linear mixed models were also performed using the GLIMMIX procedure to assess the independent effects of stem length (short vs traditional) and surgical technique (aTSA vs rTSA) on radiographic outcomes. A binomial distribution and logit link function were specified to model the number of observed events per number of patients for each outcome. Each model included fixed effects for stem length and technique, and a random intercept for each study to account for clustering within studies and between-study heterogeneity. Models were estimated using residual pseudo-likelihood, and degrees of freedom were calculated using the containment method. For each model, we reported F-values and associated p-values from Type III tests of fixed effects to determine the strength of the relationship between

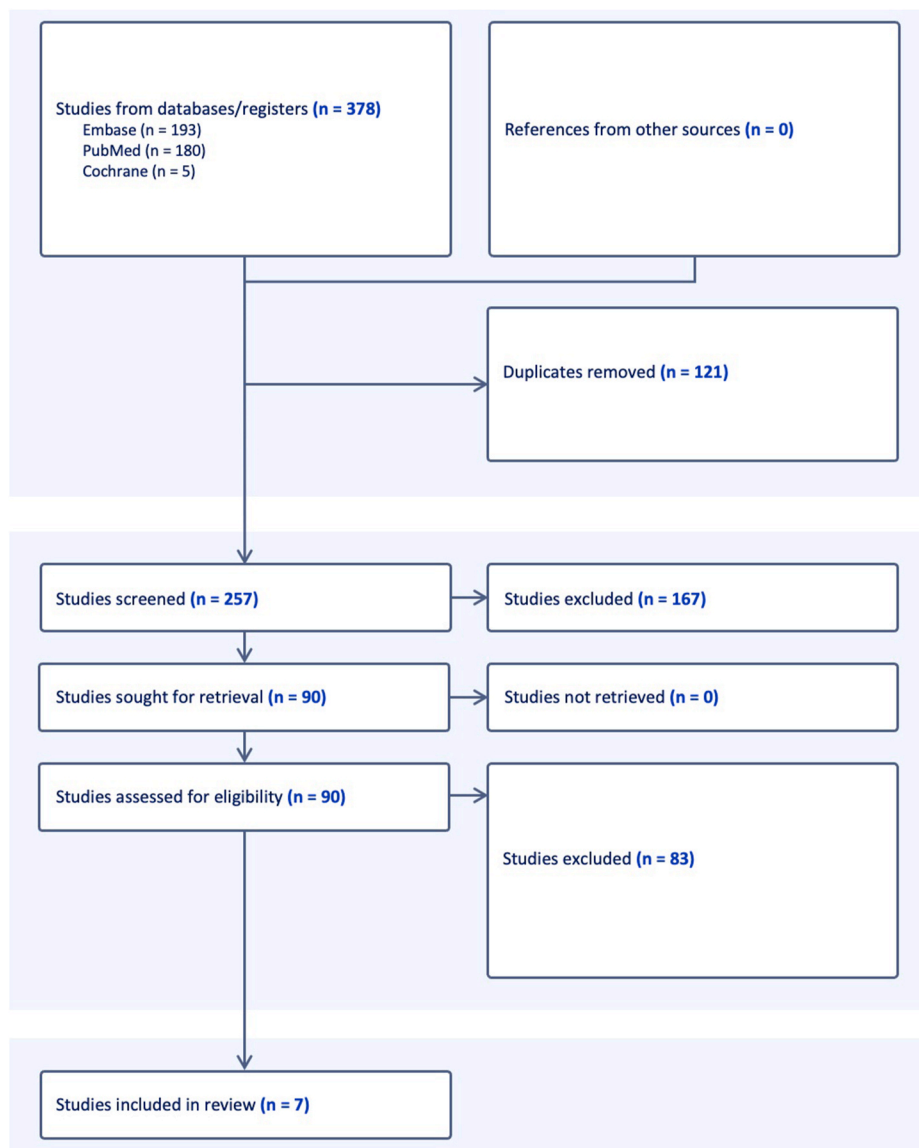


Fig. 2. Flowchart detailing the study selection process.

Table 1
Study characteristics and demographics.

Author	Year	Study Design	Technique	System Used	Stem Length	Follow-up (months)	Number of Patients			Average Age	Dominant Arm Prostheses N (%)
							Total	Male	Female		
Abduh et al.	2022	Retrospective cohort	Anatomic	Ascend™ Flex	Short	27	33	6	27	66.4 ± 10.2	15 (45 %)
			Reverse	Ascend™ Flex	Short	27	33	9	24	74.2 ± 6.7	24 (73 %)
Cole et al.	2020	Case Series	Anatomic	Univers II	Traditional	78.6	47	25	22	65.3	29 (62 %)
Denard et al.	2018	Retrospective Cohort	Anatomic	Ascend or Ascend Flex	Short	35	42	28	14	67.7	22 (63 %)
			Anatomic	Apex	Short	25	35	22	13	66.5	23 (68 %)
Denard et al.	2018	Retrospective Cohort	Anatomic	Univers II	Traditional	30.5	58	33	25	64.7	24 (41 %)
Schnetzke et al.	2016	Case Series	Anatomic	Aequalis Ascend Monolithic	Short	32	52	21	31	71.6	27 (52 %)
Raiss et al.	2019	Case Series	Anatomic	Ascend™ Flex	Short	28	77	–	–	72	–
			Reverse	Ascend™ Flex	Short	32	150	–	–	68	–
Denard et al.	2020	Retrospective Cohort	Reverse	Univers Reverse	Traditional	36.1	93	40	53	71.1	55 (59 %)

stem length, surgical technique, and radiographic outcomes.

3. Results

3.1. Study characteristics and demographics

Characteristics and demographics are summarized in Table I. A total of 620 patients were included across studies, with 422 short-stemmed prostheses and 198 traditional-length stems. The weighted average age was 68.2 years across all studies, with a weighted average age of 69.4 years in the SS group and 67.0 years in the TL group ($p = 0.17$). The weighted average follow-up interval was 34.8 months across studies, 30.2 months in the SS group, and 44.5 months in the TL group ($p = 0.34$). Dominant arm prostheses comprised 55 % of the total sample, 57 % of SS, and 55 % of TL ($p = 0.84$). There were 184 (47 %) males and 209 (53 %) females in total, with 86 (44 %) males in the SS group and 98 (49 %) males in the TL group ($p = 0.54$). Raiss et al.¹⁴ did not report the sex of participants or the number of dominant arm prostheses.

3.2. Range of motion values

Pre- and post-operative range of motion values are found in Table II.

3.3. Pre-operative

The weighted average pre-operative forward flexion (FF) in the SS and TL groups was $98.4^\circ \pm 30$ and $100.5^\circ \pm 35.1$, respectively ($p = 0.55$). The weighted average external rotation (ER) in the SS and TL groups was $15.8^\circ \pm 16$ and $28.4^\circ \pm 17.6$, respectively ($p < 0.001$).

3.4. Post-operative

The weighted average post-operative FF in the SS and TL groups was $136.0^\circ \pm 28.8$ and $135.2^\circ \pm 30.0$, respectively ($p = 0.79$). The weighted average ER in the SS and TL groups was $38.9^\circ \pm 23.5$ and $45.3^\circ \pm 18.2$, respectively ($p = 0.007$).

3.5. Pre vs post-operative

FF and ER significantly improved for both SS and TL groups when comparing average pre- and post-operative values ($p = 0.003$, $p = 0.03$). The change in FF from pre-to post-TSA in SS and TL groups was $38.0^\circ \pm 8.5$ and $32.3^\circ \pm 10.6$, respectively ($p = 0.47$). The change in ER from pre-to post-TSA in SS and TL was $22.8^\circ \pm 11.2$ and $17.3^\circ \pm 4.9$ ($p = 0.48$).

3.6. Radiographic findings

Radiographic data is found in Table III.

Table 2
Range of motion.

Author	Year	Stem Length	Baseline			Post-op		
			Forward Flexion	External Rotation	Internal Rotation	Forward Flexion	External Rotation	Internal Rotation
Abduh et al.	2022	Short	85 ± 25.2	5 ± 13.6	–	133 ± 32	33 ± 17.7	–
Abduh et al.	2022	Short	84 ± 25.2	9 ± 14.1	–	125 ± 31.7	15 ± 17.3	–
Denard et al.	2018	Short	103 ± 28 119 ± 27	21 ± 15 26 ± 11	S1 L5	138 ± 27 147 ± 19	49 ± 22 55 ± 12	L2 L2
Cole et al.	2020	Traditional	116 ± 31	35 ± 17	L5	137 ± 25	50 ± 16	L2
Denard et al.	2018	Traditional	108 ± 25	27 ± 16	S1	142 ± 29	50 ± 18	L3
Denard et al.	2020	Traditional	88 ± 38	26 ± 18	–	130 ± 32	40 ± 18	–

Values are reported as mean ± standard deviation.

3.7. Cortical thinning and osteopenia (CNO)

TL showed higher rates of CNO in zone L1 ($p < 0.001$). SS showed higher rates of CNO in zones L2 and M2 ($p < 0.001$). There was no difference between groups in zones US or M1.

3.8. Condensation lines (CL)

There were no differences in the rate of patients exhibiting CL for any zone.

3.9. Spot welds (SW)

TL showed higher rates of SW in zones L1 and M1 ($p < 0.001$, $p = 0.008$). SS showed higher rates of SW in zones L2 and M2 ($p < 0.001$). There were no differences in spot weld rate under the stem.

3.10. Adaptive change scores

There was a significantly greater proportion of patients with low adaptive change scores in the TL group and a significantly greater proportion of patients with high adaptive change scores in the SS group ($p = 0.02$).

3.11. Complications and revisions

TL and SS stems had complication rates of 2.5 % and 3.3 %, respectively. Revision rates for TL and SS stems were 0.5 % and 0.9 %, respectively. There were no significant differences in the rate of complications or revision surgeries between groups.

3.12. Comparison of technique and stem length

The GLIMMIX procedure was performed to compare the effect that stem length and technique had on radiographic outcomes while accounting for heterogeneity between studies. Stem length resulted in the only significant F-Value in the random effects modeling, with Zone L2 CNO showing an F-Value of 19.72 ($p = 0.04$). Additionally, stem length was found to have the only significant effect on the odds of developing radiographic changes with traditional length stems having an odds ratio of 0.106 (95 %CI [0.012–0.932]) for developing CNO in Zone L2.

4. Discussion

The primary finding of this review was that TL stems show significantly higher rates of proximal stress shielding laterally when compared to SS. However, TL stems showed a significantly higher proportion of patients with low adaptive changes and similar rates of proximal stress shielding medially. Across zones, there were varying patterns of radiographic changes.

Table 3
Radiographic findings.^a

Author	Stem Length	Low Adaptive Change Score	High Adaptive Change Score	Zones														
				L1			L2			US			M2			M1		
				CNO	CL	SW	CNO	CL	SW	CNO	CL	SW	CNO	CL	SW	CNO	CL	SW
Abduh et al.	Short	–	–	18	0	2	10	3	23	0	11	0	4	2	17	55	0	2
Denard et al.	Short	43	34	37	12	0	31	3	18	0	15	22	26	6	14	61	6	3
Raiss et al.	Short	188	39	20	0	1	22	4	95	0	24	0	29	3	69	83	1	1
Schnetzke et al.	Short	–	–	18	4	1	24	1	37	0	6	6	18	2	26	43	3	3
Denard et al.	Traditional	45	13	21	5	3	5	3	15	0	23	6	3	3	10	43	2	2
Cole et al.	Traditional	32	15	27	–	–	1	–	–	1	–	–	1	–	–	24	–	–
Denard et al.	Traditional	90	3	50	2	8	0	1	7	0	2	2	0	0	1	53	3	6

CNO=Cortical Thinning and Osteopenia, CL=Condensation Lines, SW=Spot Welds, L1 = Superior lateral zone, L2 = Inferior lateral zone, US=Under stem, M2 = Inferior medial zone, M1 = Superior medial zone.

^a All values are reported as number of patients.

Traditional length stems exhibit high rates of stress shielding, leading to concerns about the survivability of TSA.^{14,15} As such, short stems were devised to mitigate this risk. While shorter stems lead to proximal stresses similar to natural cortical bone, results vary regarding the degree of stress shielding observed radiographically.^{9,11,16,17} This study showed no differences in medial proximal humerus CNO between TL and SS, however, TL stems possessed significantly higher rates of lateral proximal humerus CNO. This indicates that while both stems distribute loads similarly on the medial side, the increased extension of the TL stem into the diaphysis of the humerus results in reduced bone quality in the region of the greater tuberosity of the humerus. This increase did not impact complication or revision rates between groups. However, preserving greater tuberosity integrity is important when considering outcomes specifically with external rotation and deltoid wrapping in the setting of rTSA. In addition, preservation of the greater tuberosity is important in the setting of revision surgery. It is also important to consider the study’s relatively short-term follow-up of 34.8 months as the survivability of TSA exceeds 10 years and osteolysis secondary to stress shielding is a progressive change that increases with time and wear.

Beyond the proximal changes of the humerus, the pattern of CNO and SW post-TSA differed significantly between the different zones of the groups. In the distal lateral zone of the humeral prosthesis (Zone L2), we found that patients with a traditional length stem had 89.4 % lower odds of developing CNO compared to patients with short stems. While CNO has been implicated with clinical outcomes and is considered an indication of stress shielding,¹⁶ the clinical utility of SW is debatable. Denard et al.⁸ reported no correlation between rates of spot welding and clinical outcomes. However, SW may also be considered as a surrogate for stress shielding and may have equal concern for impending loosening of the implant and increased potential for revision surgery.^{10,18}

Adaptive change scores measure the overall radiographic changes of the humerus associated with stress shielding.^{13,16,19–21} The study found that a significantly higher proportion of patients in the TL group demonstrated low adaptive change scores compared to those in the SS group. This could be attributed to TL stems distributing forces along a greater area of the humerus as compared to SS distributing similar forces to a smaller area which would result in SS having greater remodeling and radiographic change.

Higher filling ratios of the metaphysis and diaphysis by the humeral component of TSA are associated with increased rates of proximal humerus stress shielding and humeral component loosening.^{22–24} While studies included in this review did record filling ratios of the metaphysis and diaphysis, data was not presented in a homogenous manner that would have allowed for comparative statistics to be performed between

TL and SS groups. However, all studies did agree that filling ratios were an important predictive factor of stress shielding and radiographic changes post-TSA.^{11,13,16,21,25} As such, this study’s ability to control for filling ratios was limited and should be used for caution when applying these results clinically.

Range of motion values were also assessed both pre-and post-operatively. Range of motion has historically been a key outcome of TSA.^{26–28} Post-operatively, FF was unchanged between groups and ER was significantly higher among those with TL stems. This is likely due to pre-operative ER values also being significantly higher in the TL group compared to the SS group. To support this, we found that the change in ER from baseline to final follow-up after TSA was insignificant between SS and TL groups.

This study found that technique (aTSA vs rTSA) had no significant impact on radiographic outcomes of any zone, and stem length resulted in the only significant effect in random effects modeling. This is important as it is postulated that rTSA results in unfavorable wear patterns and increased stress shielding compared to aTSA.²⁹ The current review reinforces previous studies that have found no differences in radiographic changes when comparing aTSA to rTSA²⁵; however, this study expanded these findings to over 600 patients with a longer average final follow-up. Since technique had no significant effect on radiographic outcomes in modeling, our rationale to not stratify patients by whether they received an rTSA or aTSA was strengthened as separating them would only lead to increased model complexity and reduced power without improving explanatory value to the overall premise of the study.

The main limitation of this study was the heterogeneity of the included studies. Only one of the included studies directly compared SS to TL,¹³ thus a meta-analysis was unable to be performed. Controlling for confounding variables such as patient demographics, follow-up period, brand and design of the humeral component, and the humeral component coating was also impossible due to the heterogeneity of included studies. Another limitation is the relatively short follow-up period of this study concerning the expected survivability of TSA. Despite these limitations, this review provides valuable insight into a common phenomenon that has large implications for the survivability of TSA.

4.1. Conclusion

This study demonstrated radiographic differences between short and traditional-length stems that suggest unique patterns of bone remodeling. While short stems may better preserve proximal lateral bone, the higher incidence of distal cortical changes warrants careful patient selection, and traditional-length stems may remain preferable when

metaphyseal fixation or bone quality is a concern.

CRediT authorship contribution statement

Maxwell Harrell: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Dev Dayal:** Formal analysis, Investigation, Data curation, Writing – review & editing. **Clay Rahaman:** Methodology, Validation, Resources, Writing – review & editing. **Matthew T. Sankey:** Validation, Investigation, Data curation, Writing – review & editing. **Caleb Berta:** Formal analysis, Investigation, Data curation, Writing – review & editing. **Jacques Van Zyl:** Validation, Investigation, Data curation. **Vamsisaikrishna Morla:** Validation, Investigation, Data curation. **Thomas Evely:** Resources, Supervision, Project administration, Writing – review & editing. **Walter Smith:** Resources, Supervision, Project administration, Writing – review & editing. **Aaron Casp:** Resources, Supervision, Project administration, Writing – review & editing. **Amit Momaya:** Resources, Supervision, Project administration, Writing – review & editing. **Eugene Brabston:** Resources, Supervision, Project administration, Writing – review & editing.

Consent statement

As this was a systematic review of published literature, there were no patients to consent.

Ethical statement

As this was a systematic review, there were no ethical concerns while conducting this study.

Funding statement

There was no source of internal or external funding for this study.

Declaration of interests

The following authors have the stated interests, all others have none to disclose: **Amit Momaya:** CONMED Corporation- Other Professional Activities; **Eugene Brabston:** EBSCO-Editorial or governing board, Link Orthopaedics-Paid consultant, Orthopaedic Design NA-Paid consultant; **Aaron Casp:** American Orthopaedic Society for Sports Medicine-Board or committee member, Arthrex, Inc-Paid consultant.

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