JSES International 4 (2020) 739–744

Contents lists available at ScienceDirect

JSES International

journal homepage: www.jsesinternational.org

Treatment of nonunions of the humeral shaft with nonvascularized fibular strut allograft: postoperative outcomes and review of a surgical technique

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ARTICLE INFO

Keywords:
Fibular strut
allograft
nonunion
proximal third
humeral midshaft
distal shaft

Level of evidence: Level IV; Case Series; Treatment Study

Hypothesis: Persistent humeral shaft nonunions result in continued pain and disability of the affected arm and are difficult to treat even with several surgical procedures and locked plating. A fibular allograft provides bony purchase for fixation as well as rotational stability and bridging of nonunion defects.

Methods: We conducted a retrospective review of a single surgeon's clinical practice between July 1995 and January 2011. The inclusion criteria were patients aged $\geq$ 18 years who underwent revision surgery for a humeral shaft nonunion by open reduction and revision internal fixation with a supplementary fibular strut allograft.

Results: Thirteen patients who met the inclusion criteria were evaluated with physical examinations, validated functional outcome measures, and radiographs to assess union rates. The mean follow-up period was 7.5 years (range, 0.5-15.6 years); there were 11 women (85%) and 2 men (15%). Of the patients, 3 (23%) had proximal-third nonunions, 7 (54%) had middle-third nonunions, and 3 (23%) had distal-third nonunions. After revision surgery with fibular allograft, 10 of 13 patients went on to achieve healing, giving a union rate of 76.9%. The mean postoperative Disabilities of the Arm, Shoulder and Hand score was 38.1 points (standard deviation [SD], 27.6 points). The mean Constant score was 55.2 points (SD, 24.0 points), representing a 62% return of function compared with the contralateral side. The mean postoperative American Shoulder and Elbow Surgeons score was 65.4 points (SD, 28.5 points), and the average visual analog scale pain score (out of 10) was 2.1 (SD, 3.3) at final follow-up.

Conclusion: Fibular allograft is an effective and straightforward option for treating humeral midshaft and distal-shaft nonunions; however, treatment of proximal-third nonunions remains challenging.

The treatment of humeral shaft nonunions is considered a challenge for orthopedic surgeons. Nonunion of the humeral shaft is defined as the absence of bony union despite 6 months of treatment.[8] Humeral shaft nonunion occurs in 10%-23% of conservatively treated cases and in 2%-10% of cases treated with open reduction–internal fixation.[7,23]

Risk factors for nonunion include obesity, alcoholism, smoking, and other medical problems such as osteoporosis, yet these cannot be corrected prior to surgery in fracture cases.[26] Furthermore, the role of metabolic and endocrine abnormalities in causing nonunions has been discussed in the literature.[6] Currently, there are several options for treating nonunions, including external fixation, open reduction with internal plate fixation, and adjuncts such as autograft, allograft, stem cells, platelet-rich plasma, demineralized bone matrix, and bone morphogenetic proteins. There is no consensus regarding the standard of care when deciding among these surgical techniques, and the best treatment may depend on patient factors, surgeon preference, and fracture characteristics.[18] Many times, treatment modalities are used in combination.

The treatment goals of repair of humeral shaft nonunions, such as good postoperative functional outcomes, an improved rate of healing, and a faster recovery time, must be balanced against the potential for complications and the risk of additional surgical procedures. Open reduction–internal fixation with plating, supplemented with cancellous bone graft, yields some of the best results.[5,20] The procedure, however, is technically demanding, and

This study was approved by the Institutional Review Board at Columbia University Medical Center.

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https://doi.org/10.1016/j.jseint.2020.08.013
2666-6383/

the dissection required for plate fixation places several neurovascular structures at risk. Although the addition of bone graft has been shown to improve rates of healing, the best type of bone graft remains unclear. The main contenders include demineralized bone matrix, nonvascularized iliac crest autograft, vascularized fibular autograft, and nonvascularized fibular allograft. Each option has its advantages and disadvantages. The use of fibular allograft has several theoretical advantages that warrant further exploration.[4,14] The goal of this study was 2-fold: to present our technique for the treatment of humeral shaft nonunion using a nonvascularized fibular strut allograft and to evaluate results with radiographic imaging and validated outcome scores.

Materials and methods

A retrospective review of procedures performed by the senior author between July 1995 and January 2011 was conducted. We identified 13 patients with humeral shaft nonunions who underwent surgery with open reduction and revision internal fixation using plate fixation and a supplementary fibular strut allograft. At the time of data collection, 3 patients had died of causes unrelated to their humerus, but their radiographs and clinical charts were available for review. Because it was impossible to measure functional results, these patients were left out of the analysis of functional outcomes. Each patient in this consecutive case series elected to undergo surgery to treat a painful humeral shaft nonunion with associated functional deficits.

The mean age of the patients at the time of surgery was 60.7 years (range, 31-85 years); there were 11 women and 2 men. The left arm was involved in 11 patients, and the right arm, in 2; the nondominant arm was treated in 10 patients, and the dominant arm, in 3. The average follow-up period was 7.5 years (range, 0.55-15.6 years; standard deviation [SD], 4.6 years). The arm was fully healed at 6 months postoperatively in 1 patient, who was therefore included in the study despite the short duration of follow-up.

The most common mechanism of injury was a low-energy fall (5 patients), followed by a motor vehicle accident (3 patients). One patient was injured during a motorcycle accident, one was injured by a bicycle accident, and one was a pedestrian struck by a motor vehicle. Of the remaining 2 patients, 1 had a pathologic fracture due to osteosarcoma and 1 had nonunion after resection of osteosarcoma. One fracture was classified as a grade 3B open fracture, whereas all other injuries were closed injuries. All patients in this series had undergone ≥1 operation prior to the nonunion repair with placement of fibular strut allograft. The mean number of previous surgical procedures was 2.7 (median, 2; range, 1-7; SD, 1.7); the range is skewed by 1 patient in the cohort with an extremely difficult nonunion of a pathologic fracture due to osteosarcoma who required 7 surgical procedures. Six patients (46%) were smokers. On presentation, 4 patients (31%) had documented radial nerve palsies. The nonunion involved the proximal third of the humeral shaft in 3 patients (23%), the middle third of the humeral shaft in 7 (54%), and the distal third of the humeral shaft in 3 (23%). Clinical information is summarized in Tables I and II.

Preoperative and postoperative radiographs, along with notes from the treating surgeon, were reviewed. Follow-up radiographs were used to confirm bony union, defined as the appearance of bridging calcified bone across the nonunion site. During postoperative physical examination, a dynamometer (Jamar; Sammons Preston Rolyan, Bolingbrook, IL, USA) was used to record shoulder strength in pounds of force, and a standard goniometer was used to measure range of motion in degrees. Patients also completed the Disabilities of the Arm, Shoulder and Hand (DASH) functional outcome survey and were assessed with the Constant shoulder score and the American Shoulder and Elbow Surgeons (ASES) scoring system. Both the operated and contralateral uninjured sides were assessed for comparison. Pain at rest was measured using a visual analog scale (VAS).

Table I
Baseline clinical characteristics of study patients

Patient characteristic	Data
Sex, n	
Male	2
Female	11
Age, yr	
Average	60.7
Range	31-85
Side of injury, n	
Dominant side	3
Nondominant side	10
No. of prior surgical procedures	
Average	1.8
Range	1-7
Comorbidities, n (%)	
Smoking	6 (46)
Hypertension	5 (38)
Diabetes	3 (23)
Osteoporosis	1 (8)
Mechanism of injury, n	
Fall	5
MVA	3
Tumor	2
Motorcycle accident	1
Bicycle accident	1
Pedestrian struck	1

MVA, motor vehicle accident.

The DASH questionnaire is a validated outcome measure that was jointly developed by the American Academy of Orthopaedic Surgeons and the Institute for Work and Health.[11] The minimal clinically significant difference is considered 10 points, with a variance of 14.68 points.[3,12,16,17] The Constant shoulder score is a 100-point scale with items pertaining to pain and the ability to perform the normal tasks of daily living, including questions about range of motion, function, and strength. A higher Constant shoulder score indicates better function.[8,9] There is no established minimal clinically important difference for the Constant score; however, 10 points is often regarded as relevant.[13] The ASES score, rated on a 100-point scale, has a minimal clinically significant difference of 6.4 points.[19,21,24] The VAS is a pain-scoring instrument with a scale of 0, indicating no pain, to 10, indicating the most severe pain.

Statistical analysis

Descriptive statistics were performed on baseline demographic characteristics. Nominal data were expressed as numbers and corresponding percentages. The distribution of continuous data was checked for normality by visually inspecting the histograms and box plots. Normally distributed data were shown as means with SDs.

Statistical imputation was performed where missing values were discovered. Imputation is a statistical method to search for the

Table II
Fracture characteristics

Fracture location	n	Open	Periprosthetic	Pathologic
Proximal	3	0	1	0
Middle	7	0	0	2
Distal	3	1	1	0

Regarding fracture characteristics, either 1 displayed element or a combination of the displayed elements can exist.

most probable value of missing data and is considered a reliable and accepted method to cope with missing data in statistical research.[2] To determine whether data were missing completely at random (MCAR), the Little MCAR test was applied. If the outcome of this test was not statistically significant, the data were MCAR. Single imputations were then used to impute the missing data, applying predictive mean matching and the other follow-up measurements as predictors.

Both imputation of missing values and calculation of statistical outcomes were performed using IBM SPSS Statistics (version 19; IBM, Armonk, NY, USA). For imputation, the multiple imputation method was used.

Surgical technique

All patients were given preoperative prophylactic antibiotics. Under regional anesthesia, patients were placed in the beach-chair position for an approach to the proximal humeral shaft or a slightly lateral position for more extensile approaches. A sterile tourniquet was occasionally used to approach distal nonunions. The previous incision was used when possible and extended as needed to gain adequate exposure. Otherwise, an extensile deltopectoral skin incision from the coracoid down to the midshaft of the humerus was used. The interval between the anterior deltoid and the pectoralis was found and elevated proximally, and dissection was continued down distally in an anterior approach to the humerus via a brachialis split. Distal-third fractures were approached via the interval between the brachialis and the brachioradialis. Neurovascular structures were identified and protected, particularly regarding the radial nerve with fractures in the middle junction to distal third of the shaft. In the distal third, care was also taken regarding the ulnar nerve. The nonunion site was visualized, assessed for motion, and then taken down. All fibrous connective tissue was removed. If a pseudarthrosis was present and/or infection was suspected, fluid or tissue was submitted for culture and sensitivity analyses. Bony defects were measured with a ruler in anticipation of placement of the properly sized allograft.

The fibular allograft was first cut to size on a separate, sterile back table according to intraoperative measurements. Both ends were tapered to facilitate placement in the intramedullary canal such that the allograft strut bridged the cortical defect. The intramedullary canal was reamed by hand in certain cases to accommodate the graft. By use of a mallet, the graft was tapped into either the proximal or distal end of the humeral fragment for a press fit.

In cases in which the intramedullary canal was not patent (eg, periprosthetic fracture) or in which reaming the canal was considered undesirable because of bone quality, the allograft strut could be placed in an extramedullary position that still bridged the site of nonunion. Three cases in this study were deemed undesirable for intramedullary placement, so extramedullary placement was performed. The graft was then placed on the anterolateral aspect of the humerus, with care taken to avoid the neurovascular structures as mentioned earlier.

Whether intramedullary or extramedullary, a dynamic compression plate was then placed in a bridging fashion across the nonunion site and allograft. The plate was required to be of sufficient length to allow placement of $\geq$3 screws above and below the nonunion site or, in cases of questionable fixation, placement of 4 screws on either side. Depending on bone quality and local purchase, locked and/or unlocked screws were placed in the proximal humeral fragment, distal humeral fragment, and fibular allograft. The fibular allograft gave the screws extra purchase with quadricortical fixation. An important technical point is to avoid drilling too many unfilled holes in the fibular graft as this could result in a fracture of the graft.

Once proper length, alignment, and stability of the humerus were achieved, the wound was copiously irrigated, the tissues were closed in layers, and a bulky soft dressing was applied. The arm was splinted, and the patient was given a sling. Gentle range-of-motion exercises began at approximately 4-8 weeks postoperatively and progressed as tolerated. Full weight bearing was allowed when radiographic healing was confirmed. Figure 1 shows a clinical example.

Results

Seventy-seven percent of the humeral shaft nonunions showed bony healing with incorporation of the allograft on plain radiographs from the most recent follow-up, including those in all 3 patients who died. The mean postoperative DASH score was 38.1 points (SD, 27.6 points). The mean postoperative ASES score was 65.4 points (SD, 28.5 points), representing a 71% return of function, on average, compared with the contralateral side. The mean Constant score was 55.2 points (SD, 24.0 points), representing a 62% return of function compared with the contralateral side. Patients reported an average VAS pain score of 2.1 (SD, 3.3) at latest follow-up. For postoperative range of motion, mean maximum forward shoulder elevation was 132° and mean maximum shoulder abduction was 91°-110°. On average, patients were able to externally rotate the arm enough for the hand to reach the top of the head with the elbow forward, and they were able to internally rotate to the level of L3. Patients were able to recover, on average, 83.0% of the abduction strength of the contralateral arm and had the ability to do work at the level of the neck. Patient outcomes as assessed via the DASH, ASES, Constant, and VAS questionnaires are summarized in Table III.

A total of 3 patients did not achieve union after revision with fibular allograft: 2 with proximal-third fractures and 1 with a middle-third nonunion related to osteosarcoma. One patient with treatment failure and a proximal-third nonunion later underwent revision surgery to shoulder hemiarthroplasty with satisfactory results. The other patient with a proximal-third nonunion requested hardware removal, which resulted in a painless nonunion; the patient then declined further surgery. The third patient had a nonunion of the middle third of the humeral shaft related to osteosarcoma with several prior surgical procedures and radiation. Three years after the fibular allograft treatment failure with nonunion, this patient underwent a final revision operation with an intramedullary vascular fibular strut graft supplemented with bone morphogenetic protein 2 (BMP-2) and stem cells aspirated from the iliac crest. This patient ultimately went on to achieve bony union and good functional scores. The nonunion rate in the entire cohort after revision with fibular allograft is presented in Table IV. Of the 6 patients who were smokers, 1 (16.7%) did not achieve union after revision with fibular allograft.

If a pseudarthrosis was present and/or infection was suspected, fluid or tissue was submitted for culture and sensitivity analyses. No positive culture results were found in this study. Complications after the procedure included radial neurapraxia and periprosthetic fracture. One patient fell postoperatively, resulting in a fracture adjacent to the plate. This was treated conservatively in a brace and went on to achieve excellent healing. Another patient experienced perioperative radial neurapraxia, which completely recovered. Three patients had presented with radial nerve palsies preoperatively. Of these patients with pre-existing radial nerve palsies, 1 had full recovery of the nerve after exploration in conjunction with the fibular allograft operation, 1 had partial radial nerve recovery, and 1 did not recover. Neither superficial nor deep postoperative infections developed in any patient. Of the 6 patients who were smokers, 4 (66.7%) did not have any postoperative complications

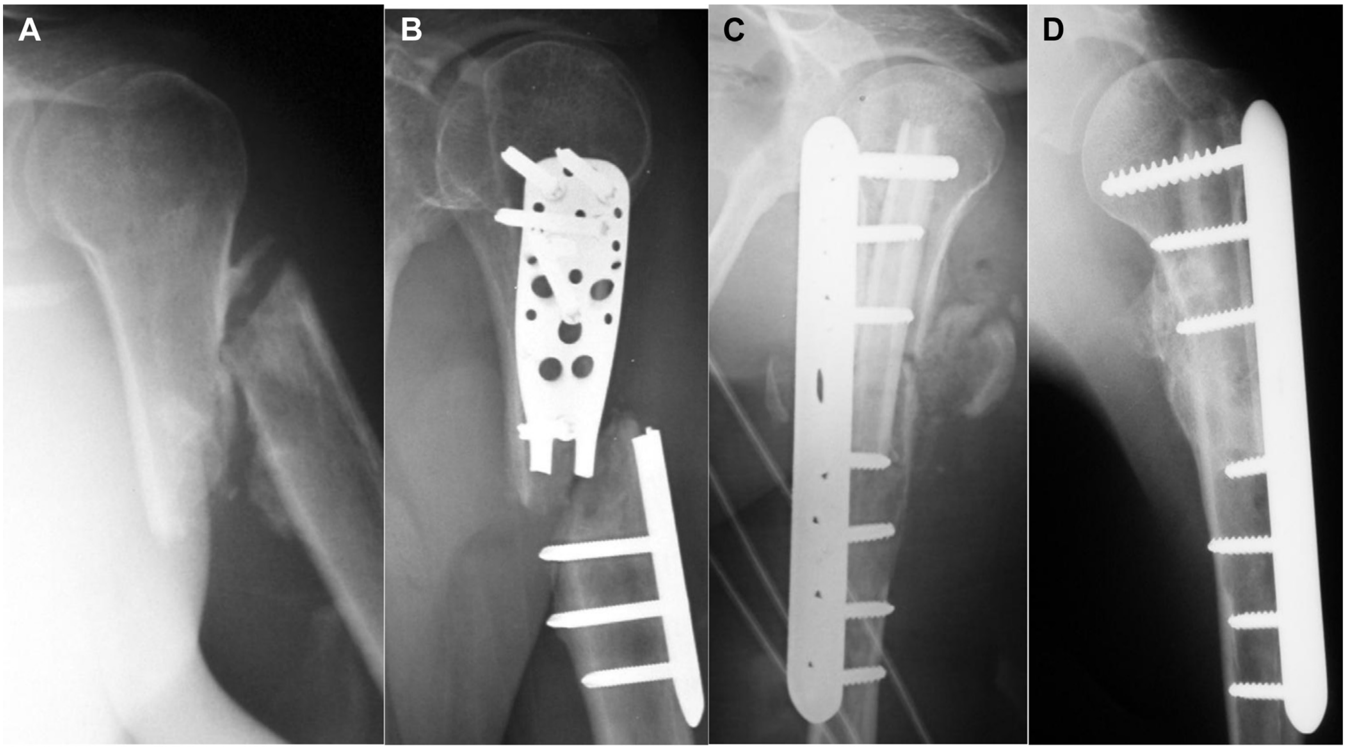

Figure 1 A 31-year-old female patient was injured in a motor vehicle accident and sustained a proximal humeral shaft fracture that was treated nonoperatively but went on to nonunion. Open reduction–internal fixation with locked plating subsequently failed, but healing with union was finally achieved after revision with a fibular strut allograft. (**A**) Anteroposterior radiograph of proximal humeral nonunion. (**B**) Anteroposterior radiograph revealing failure of locked-plating fixation with persistent proximal humeral nonunion. (**C**) Anteroposterior radiograph (internal-rotation view of humerus) showing early postoperative appearance of revision open reduction–internal fixation with use of fibular strut allograft. (**D**) Anteroposterior radiograph at 1.5 years postoperatively showing healed fracture in good alignment with incorporation of fibular allograft.

Table III
Average postoperative functional scores after open reduction and internal plate fixation using fibular allograft

	DASH score, points	Constant score, points		ASES score, points		VAS pain score
		Injured side	Uninjured side	Injured side	Uninjured side	
Mean	38.1	55.2	88.47	65.4	92.0	2.1
SD	27.6	24.0	3.3	28.5	13.0	3.3

DASH, Disabilities of the Arm, Shoulder and Hand; *ASES*, American Shoulder and Elbow Surgeons; *VAS*, visual analog scale; *SD*, standard deviation.

whereas 1 experienced periprosthetic fracture and 1 reported radial neurapraxia.

Discussion

A persistent nonunion of the humerus results in continued pain and disability of the affected arm and may be difficult to resolve despite repeated surgical procedures. This difficulty is emphasized by the fact that attempts to repair humeral nonunions, to date, have been multimodal, nonstandardized, and often unsuccessful. This study demonstrates that the technique of repairing humeral shaft nonunions with a fibular strut allograft can result in high union rates with a low risk of needing further surgery. An important technical note is to be sure to not overstress the press fit, which could cause a longitudinal split. Once this juncture was secure, fine-tuning of the length and dovetailing could be performed at the other juncture. Before the second juncture is secured, the length and rotation of the humerus should be confirmed relative to the transepicondylar axis. Despite the complexity of the injury and a mean of 2.7 surgical procedures prior to revision with fibular allograft, 77% of patients in this study achieved bony healing. The patients overall had good functional scores, with a mean DASH score of 38.1 points, close to the normal range of 0-25 points; overall, excellent-grade Constant scores of shoulder function were achieved. The majority also had low VAS and ASES pain scores, with 7 patients (70%) reporting no pain at all.

Table IV
Nonunion rates after revision with fibular allograft

Fracture type	No. with nonunion after fibular allograft	Rate of nonunion within fracture type, %	Rate of nonunion within entire cohort, %
Proximal third (n = 3)	2	66.7	15
Middle third (n = 7)	1	14	7.7
Distal third (n = 3)	0	0	0

The most challenging nonunions in this series were those involving the proximal third of the humeral shaft; 2 of 3 did not reach union with fibular allograft. On the basis of the outcomes, it is recommended to exercise caution when using a fibular allograft as a treatment for nonunion of the proximal third of the humeral shaft. In 1 patient in this cohort, hemiarthroplasty of the shoulder provided a solution in terms of both functional improvement and pain relief. It should be noted that this hemiarthroplasty was performed before reverse arthroplasty was widely available in the United States and that reverse shoulder replacement should also be considered an option now. Although prosthetic replacement does not always guarantee satisfactory functional results, it may be a treatment option to consider for proximal-third humeral nonunions given the difficulties noted in this study.[1,22] Patients with tumors also represent a challenging subset of humeral nonunion patients. In this study, 1 of 2 pathologic nonunions required a vascularized fibular graft to heal.

When evaluating fibular allografts as a treatment for complex proximal humeral fractures, Berkes et al[4] (2014) looked at primary fracture management, excluding revision or salvage cases. They reported that reduction and fixation were enhanced in a cohort of 14 patients, allowing for early postoperative movement. Crosby et al[10] (2000) conducted a retrospective review of 12 patients with humeral shaft nonunions treated with intramedullary allograft and compression plating. Two failures (16.7%) were noted in patients with multiple comorbidities. The authors concluded that use of fibular allograft in conjunction with compression plating can produce satisfactory results. Padhye et al[23] (2013) described a cohort of 9 women and 26 men with humeral shaft nonunions in a study comparing treatment modalities (plating, nailing, external fixation, or fibular strut allograft). They concluded that although compression plating achieved the best results overall, fibular strut grafting can be a useful adjunct with particularly unstable nonunions. Finally, Vidyadhara et al[25] (2009) discussed humeral nonunion management in the osteoporotic patient. They reported on 6 patients with successful implementation of a fibular strut graft, with none requiring additional iliac crest bone grafting.

There are several limitations in our study. No preoperative patient-reported outcome scores were collected, thus making comparison postoperatively potentially difficult. However, all patients included had nonunions with a flail extremity. Additionally, the sample size for this analysis was small ($N = 13$). As such, our results may not be generalizable to a wider audience. However, the sample size is comparable to cohort sizes in other relevant studies. Furthermore, this was a single-surgeon study, making the technique more reproducible within this cohort but potentially limiting generalizability. We were not blinded to the treatment arm when administering the DASH and Constant tests.

In this study, fibular allograft was used in the revision setting for humeral nonunions. The fibular allograft has several advantages: Like all bone allografts, it is osteoconductive. In contrast to demineralized bone matrix or cancellous allograft, a fibular allograft is corticocancellous, which possesses structural integrity that is able to resist compression and bending forces, reducing the stress on the plate. In the case of an atrophic nonunion or osteopenia, a fibular strut enhances screw fixation and screw purchase by providing better-quality bone matrix, resulting in a more stable architecture of repair.[10,25] The improved purchase and added stability are achieved by both the intramedullary and extramedullary techniques. In addition, there is no donor-site morbidity as with autologous grafts, such as cancellous autograft, corticocancellous iliac crest autograft, and autologous vascularized or nonvascularized fibular graft. The donor-site morbidity of these autograft options, which may include infection or continued pain, must be considered in this patient population that frequently already has multiple comorbidities.[15] Another advantage is that the technique does not require specialized microvascular training or advanced equipment. One issue to consider, however, is the risk of disease transmission or infection when using the fibular allograft, although the risk is minimal in frozen specimens and this was not a complication observed in our study.[14]

Conclusion

Our technique for treating difficult humeral shaft nonunions with a fibular allograft strut, especially those in the middle and distal thirds, represents a reasonable alternative to vascularized bone grafting with comparable union rates and function. However, nonunions of the proximal third of the humeral shaft were the most challenging to treat in this study; these may require adjunctive treatments such as arthroplasty or a combination of other established treatment modalities and could be the subject of future research.

Disclaimer

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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