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Original Research

In Vitro Investigation of Column Fixation Constructs for Periacetabular Osteotomy: Which Provide the Greatest Stiffness and Strength?

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ABSTRACT

Background: Periacetabular osteotomy (PAO) is an effective surgical procedure for managing acetabular dysplasia. The purpose of this study was to analyze the biomechanical properties of novel PAO constructs that incorporate orthopaedic trauma techniques. We hypothesize that these fixation methods will create a stiffer construct that tolerates higher loads to failure.
Methods: Twenty bio-composite hemi-pelvises underwent PAO with the following fixation configurations: Group A: 4 iliac crest (IC) screws; Group B: 3 IC screws; Group C: 2 IC screws, 1 retrograde anterior column (AC) screw, and 1 lateral compression type-2 (LC2) screw directed from the anterior inferior iliac spine to the posterior inferior iliac spine; Group D: 1 AC screw, 1 LC2 screw, 1 posterior column screw; Group E: 2 LC2 screws, 1 AC screw. Constructs were loaded to failure on a material testing hydraulic press, and ultimate strength, stiffness, and osteotomy displacement were measured.
Results: The highest load to failure was seen in group D (2511 N), which was significantly more than groups A (1528 N, $P = .0114$) and B (1348 N, $P < .0001$). The stiffest construct was group E (602 N/mm) compared to groups A (315 N/mm, $P = .0439$) and B (243 N/mm, $P = .0008$). Failure occurred most often with a fracture in the posterior column.
Conclusions: This study supports column fixation methods used in orthopaedic trauma for PAO as biomechanically advantageous to traditional fixation techniques. These constructs may be beneficial to patients with weight-bearing concerns or early rehabilitation needs.

Introduction

Reinhold Ganz introduced a novel surgical technique in the 1980s to reorient the acetabulum in patients with hip dysplasia [1]. Although several surgical techniques to address the dysplastic acetabulum had been previously described, the Bernese osteotomy gained popularity in the surgical community due to the preservation of the posterior column, further increased intrinsic fragment stability, and the ability to correct significant deformities [2-4]. Utilization of the Bernese periacetabular osteotomy (PAO) has been successfully expanded to address hip pathologies such as acetabular retroversion and global overcoverage, not just classic hip dysplasia [5-7]. As the procedure enters its fourth decade of use, there is an abundance of data that supports its efficacy in hip preservation for the dysplastic hip [8-12]. There are several studies that describe the complications inherent to the technique including fracture, osteotomy fragment displacement, and fixation failure [13-16].

Traditional fixation technique includes 3 or 4 iliac crest (IC) screws traversing the osteotomy site into the acetabular fragment in a relatively unidirectional and parallel fashion. For additional fixation, it has been described to use an additional screw from the anterior acetabular fragment directed toward the sciatic buttress or supplemental fixation with pelvic reconstruction plates when necessary [17,18]. Despite current published descriptions of a variety of PAO fixation techniques, there is little knowledge on how

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additional fixation and or novel fixation may improve biomechanical stability in a PAO and theoretically allow immediate full weight-bearing. Additionally, there is a paucity of published literature describing a construct strong enough to support joint reactive forces seen with early full weight-bearing.

Percutaneous methods for treating pelvic ring injuries and acetabular fractures have become widely used over the last 2 decades in orthopaedic trauma. Biomechanical studies as well as surgical technique guides have described column fixation techniques that can be used in place of or to supplement open reduction and internal fixation [19-21]. Outcomes have also been favorable for these percutaneous techniques in the treatment of acetabular fractures [22-24].

The purpose of our study was to analyze the biomechanical properties of PAO constructs that incorporate orthopaedic trauma fixation techniques and to compare these constructs to more commonly used methods of PAO fixation. It was hypothesized that the addition of column screw fixation would increase the stability of the pelvic osteotomy compared to common fixation techniques for PAO. Additionally, we anticipate that column fixation may withstand physiologic loads seen in early weight-bearing.

Material and methods

Construct design

A total of 20 bio-composite artificial hemi-pelvises (Sawbones #3409, Pacific Research Lab, Vashon Island, WA) with standardized material properties underwent PAO by 2 senior authors with fellowship training in hip preservation and were fixed using one of 5 different fixation constructs (Groups A-E) under direct observation [25]. The 5 constructs tested included: Four IC screws (Group A, Fig. 1); 3 IC screws (Group B, Fig. 2); 2 IC screws with one retrograde anterior column (AC) screw and one screw directed from the anterior inferior iliac spine to the posterior inferior iliac spine described as a lateral compression-2 (LC-2) screw (Group C, Fig. 3); one AC screw, one LC-2, and one IC screw that traverses the osteotomy fragment into the ischium following the posterior column (Group D, Fig. 4); 2 LC-2 screws with one AC screw (Group E, Fig. 5). The IC screws used in constructs A through C as well as the LC-2 screws used in constructs C through E were done with 4.5 mm cortical screws. The AC screws and the IC screws that traverse the osteotomy into the ischium used in constructs C through E were

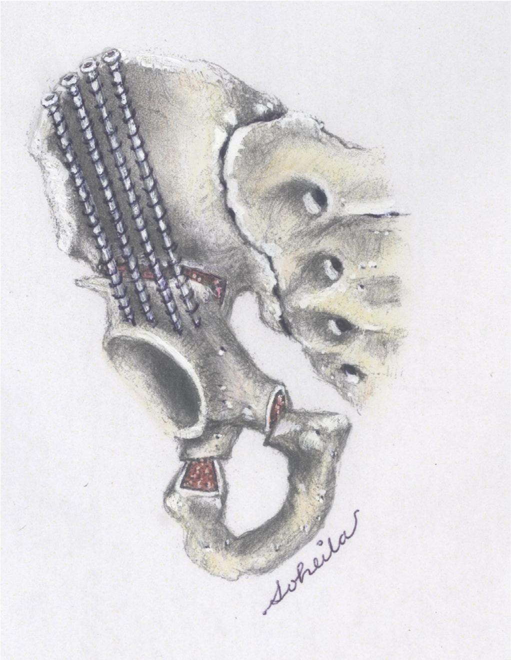

Figure 1. Illustration representing Construct A (4 iliac crest screws).

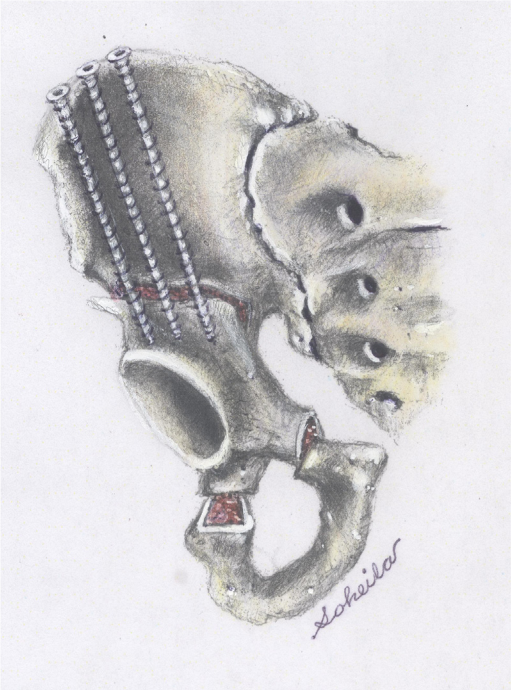

Figure 2. Illustration representing Construct B (3 iliac crest screws).

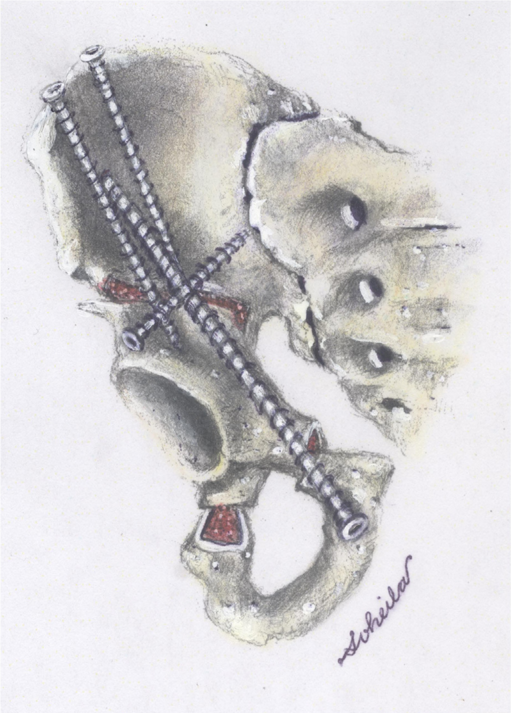

Figure 3. Illustration representing Construct C (2 iliac crest screws, 1 lateral compression-2 screw, 1 anterior column screw).

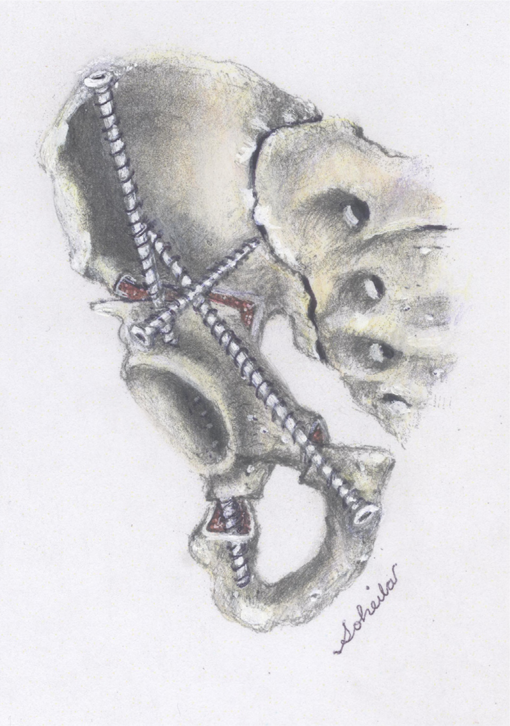

Figure 4. Illustration representing Construct D (1 iliac crest screw traversing osteotomy into the ischium, 1 lateral compression-2 screw, 1 anterior column screw).

done with cannulated 6.5 mm screws. Standardized screw placement within groups was confirmed using radiographs.

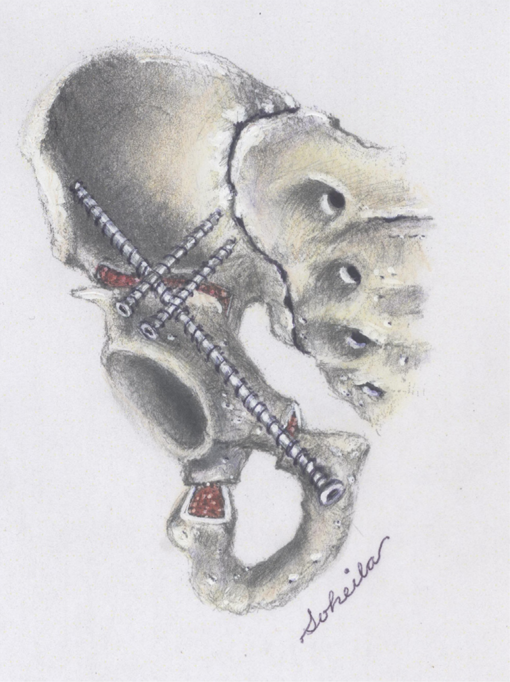

Figure 5. Illustration representing Construct E (2 lateral compression-2 screws, 1 anterior column screw).

Biomechanical testing

A two-part mold that is intimately conformed to the posterior superior iliac spine of the sawbones model was made using a two-part polyurethane resin (Smooth-Cast 300Q, Smooth-On Inc., Macungie, PA). This potting method allowed each Sawbones model to be removed and replaced for sequential material testing in our material testing system (BOSE Electro-force AT 3300, TA Instruments, Eden Prairie, MN, and Bionix 858, MTS Eden Prairie, MN). An axial force was applied to the acetabulum with a combination of 25° superomedial and 25° posterior orientation in order to simulate the anatomic position during the push-off phase of gate, as described by Widmer et al [26]. This orientation could be repeatedly maintained for each specimen by using a 3-way compound vise grip with the same polyurethane mold. The forces were applied to the acetabulum fragment via a 50-mm polyethylene ball (Delrin, DuPont, Wilmington, DE) that was attached to a 3000 N (650Lb) load cell (Fig. 6).

Data analysis

The relative displacement of each fragment was measured using a 3D motion capture system (Optotrak, Northern Digital, Waterloo, ON). Load/displacement curves were plotted and analyzed for initial stiffness and the ultimate strength. Each specimen was then subjected to load-to-failure in stroke control at a rate of 20 mm/second while recording the applied load and relative displacements of each fragment. Failure was defined as a fracture of the sawbones model, screw pull-out, fracture of the screw, or displacement of the acetabular fragment by more than a centimeter. Ultimate strength (load force at point of failure) measured in Newton (N) and initial stiffness (N/mm) were compared between each construct group.

Statistical analysis

The data was fit into a linear model to interpret the least square means, and then a Tukey multiple comparison procedure was performed for pairwise comparison. Statistical analyses were carried out using SAS software, version 9.4 (SAS Institute, Inc., Cary, NC). The level of significance was set at $\alpha = 0.05$ (two-tailed).

Results

Mean compressive load-to-failure for our 5 constructs are presented in Table 1. Group D was the strongest construct overall at

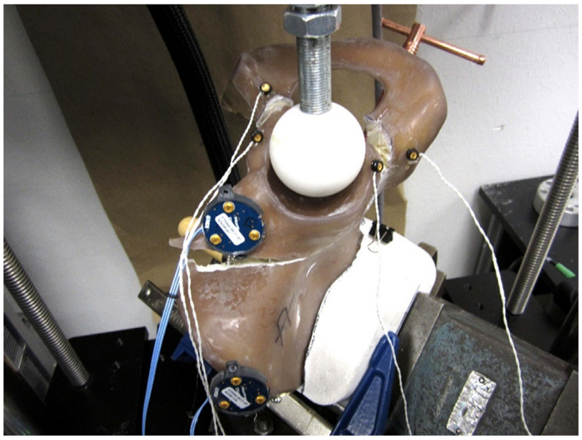

Figure 6. Picture of sawbone model that has undergone PAO mounted for biomechanical testing.

Table 1
PAO construct mean compressive load-to-failure (ultimate strength) and initial stiffness.

Construct	Ultimate strength		Stiffness	
	Mean (N)	Range (N)	Mean (N/mm)	Range (N/mm)
A	1529	1037-2020	316	177-455
B	1348	1312-1384	243	184-303
C	1818	1339-2311	414	284-544
D	2511	2284-2738	372	201-544
E	2014	1748-2279	602	468-735

2511N and showed an ultimate strength that was 60% greater than group A (1529N, $P = .0113$) and 86% greater than group B (1348N, $P < .0001$). Group D had greater overall strength than constructs C (1818N) and E (2014N), though the difference was not statistically significant. Construct E was found to be 49% stronger than Construct B ($P = .0007$). Pairwise comparisons between constructs are presented in Table 2.

Initial mean stiffnesses measured in N/mm for our 5 constructs are presented as well in Table 1. Construct E was the stiffest overall construct at 602 N/mm, which was significantly greater than constructs A (316 N/mm, $P = .0439$) and B (242 N/mm, $P = .0008$). There was no statistically significant difference between any of the other constructs analyzed with pairwise comparison (Table 2).

Three-dimensional motion analysis showed that displacement was greatest at the pubic osteotomy site for groups A and B at 2.53 mm and 2.32 mm, respectively. Whereas displacement was greatest at the ischial osteotomy site in groups A and D at 2.04 mm and 3.28 mm, respectively. There was no statistically significant difference between displacements among groups at either osteotomy site. Sixteen of 20 constructs demonstrated failure due to fracture of the cortical bone in the sawbone pelvic model, most commonly at the posterior column. Four of 20 demonstrated failure secondary to screw pullout and/or displacement of the osteotomy fragment greater than 1 centimeter. Data for displacement at the pubic and ischial osteotomies is presented in Figure 7.

Discussion

The PAO is becoming more widely accepted and utilized for a multitude of diagnoses because of its ability to correct acetabular morphology. Accelerated rehab protocols and faster return to weight-bearing may help further improve PAO outcomes. Accelerated rehab protocols for hip and knee arthroplasty procedures have decreased the length of stay, improved time to early mobilization, and accelerated return to activities of daily living [27,28]. This has improved health-care cost-savings and health-related quality of life outcomes without increasing complications. Early mobilization and early advancement of weight-bearing have been identified as some of the most important factors for decreasing the length of stay and cost following elective arthroplasty [29,30]. There is no consensus in the literature on the amount of time required to progress patient weight-bearing status following PAO.

Table 2
PAO construct pairwise comparison for ultimate strength and stiffness.

Construct 1	Construct 2	Ultimate strength (Adjusted P-value)	Stiffness (Adjusted P-value)
A	B	.9328	.8418
A	C	.8869	.8055
A	D	.0113	.9804
A	E	.3832	.0439
B	C	.2761	.1335
B	D	<.0001	.5659
B	E	.0007	.0008
C	D	.0968	.9935
C	E	.9473	.2518
D	E	.0551	.2156

The hip joint withstands high contact forces near 2.1 to 3.3 times body weight during normal, level walking and as high as 4.1 times body weight during slow walking [31,32]. Dynamic activities greatly affect hip contact forces, as jogging and running have been shown to increase contact forces through the hip joint ranging from 4.3 to 5 times body weight [33,34]. Ascending and descending stairs provide a challenge for the postoperative hip patient and cause changes in joint loading for peak contact and torsional forces. Ascending stairs has been shown to increase peak force by 10% compared to forces seen in normal walking and descending stairs as high as 20% [34]. Given these estimations on joint reactive forces, our strongest construct demonstrates a mean ultimate strength (Group D: 2511 N) that could theoretically withstand joint reactive forces seen in normal walking in a 170-pound (77.1 kg) patient based on free body diagram calculations in a prior study where the average hip contact force in normal walking was 238% of body weight, or approximately 1800 N in this example [34].

Non-weight-bearing and restricted weight-bearing protocols are not without their own physiologic effects on patients postoperatively. In a healthy patient, restricted weight-bearing results in a 4-fold increase in energy expenditure compared with full weight-bearing [35]. Studies on complete weight-bearing restriction through the operative extremity have demonstrated delays in bony union and a minimum of 2.4 to 2.6 times an individual's body weight applied through the femoral head secondary to exertion of the iliopsoas to provide joint stability [36]. Other corrective pelvic osteotomies for hip dysplasia such as the Colorado University PAO have been described, which attempt to increase bony contact along the weight-bearing zone, which would in theory allow for immediate, full weight-bearing postoperatively [37]. However, more biomechanical studies would need to be performed to validate this theoretical benefit.

While there is not an abundance of literature on early weight-bearing with PAO, there is some support in the trauma literature, specifically for acetabular fractures, that patients can undergo early weight-bearing without placing them at excessive risk for fracture displacement [38]. A study by Kazemi et al showed in a series of 22 patients who underwent percutaneous fixation for acetabular fractures who were permitted full weight-bearing immediately postoperatively resulted in no loss of reduction and similar outcomes to other studies at 12-month follow-up [39]. Another recent study by Marmor et al supported the use of full weight-bearing after total hip arthroplasty for geriatric patients with posterior wall acetabular fractures [40].

Although accelerated rehab protocols have been successful in hip and knee arthroplasty, there has been an increase in complications with advanced early weight-bearing in PAO patients. Ito et al described an accelerated rehab protocol with weight-bearing as tolerated, achieved at 4.2 months in the accelerated rehab group and 6.9 months in the standard rehab group. They found that the fracture rate increased from 1.25% (1/80) in the standard rehab group to 10.5% in the accelerated rehab group [41]. These studies have suggested that traditional PAO fixation methods would be too risky to allow advanced weight-bearing in the early postoperative period. However, the constructs we describe are stiffer and stronger than those mentioned in the accelerated rehab PAO studies. At minimum, column fixation in PAO warrants further investigation as the enhanced biomechanical construct strength may provide better opportunities for advancing accelerated rehab protocols and patient outcomes.

There have been previous biomechanical studies that have assessed different constructs for pelvic osteotomy fixation. A study

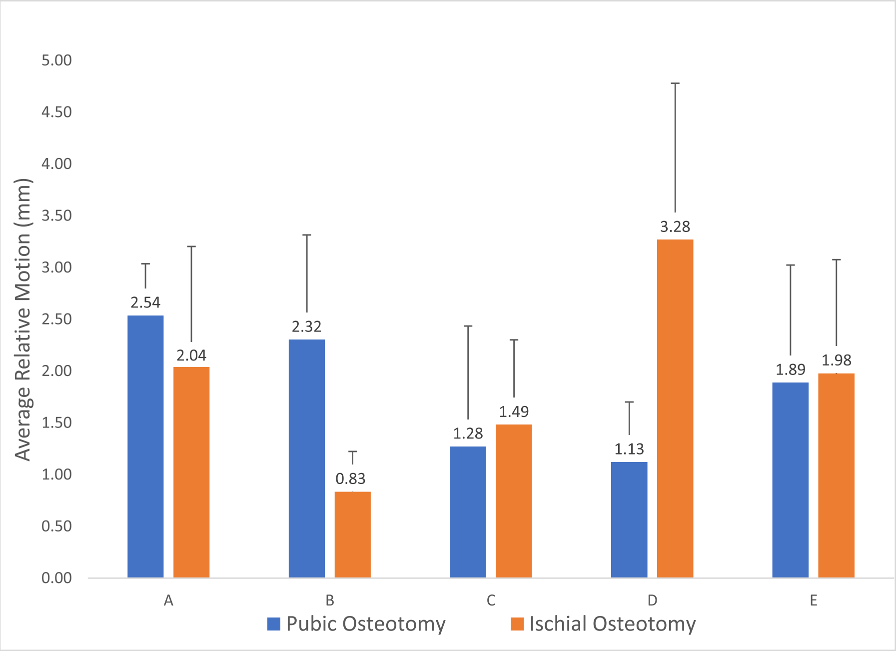

Figure 7. Average relative motion measured at the pubic and ischial osteotomies (mm).

by Widmer et al showed the addition of a transverse screw from the anterior inferior iliac spine toward the sciatic buttress increased loads to failure and decreased overall displacement when compared to standard 3-iliac screw crest constructs [26]. The same was true when they evaluated a pelvic reconstruction plate with a transverse screw vs the standard 3 iliac screws. Another biomechanical study by Yassir et al evaluated different fixation constructs for Ganz and Tonnis osteotomies. They found that the addition of an anterior pubic tension band wire in a Tonnis osteotomy increased stability in fragment displacement [42]. Our novel PAO constructs incorporate the addition of an AC screw that nearly doubles the construct strength when compared to traditional fixation.

These novel surgical techniques may allow for earlier weight-bearing in the postoperative period and decreased likelihood of fragment displacement or construct failure following PAO. These constructs may be useful for patients who require earlier rehabilitation or have difficulty maintaining a limited weight-bearing status. This study provides insight into the biomechanical advantages of column fixation following PAO and serves as a stepping stone to advancing a surgical technique that has remained relatively unchanged over 3 decades. Understandably, surgeons may be reluctant to adopt these techniques, while classic fixation methods have resulted in good long-term outcomes. However, with the success of these techniques in the trauma literature and the known benefits of early weight-bearing in total hip arthroplasty, this study may encourage clinical research necessary to validate these constructs. In an era in which healthcare utilization cost is highly scrutinized, postoperative rehabilitation advancements must be made to improve post-operative recovery time, length of stay, return to work, and return to activities of daily living.

This exploratory investigation possesses some limitations. The primary limitation of the in vitro model of composite pelvises is their inability to perfectly mirror the mechanical properties of natural bone. Additional limitations involve the lack of dynamic force application and cyclic loading through the pelvises, as well as a lack of muscular forces. Acetabular fragments were shifted according to senior surgeons' evaluation of ideal positions to place relevant screws and not a predefined distance. Therefore, intergroup correction distance was variable. In vitro construct designs created under direct observation may be impractical for some patients, especially without a linear column path, or difficult to obtain access without additional incisions and approaches. The superior direct visibility of IC screws may offer accessibility to surgeons less familiar with the acetabular corridor on fluoroscopy and reduce occurrence of damage to surrounding structures. Small group sizes also limit the generalizability of the results.

Conclusions

In summary, an exploration of novel constructs for the Bernese PAO that employ column fixation methods well-described and utilized in orthopaedic trauma was performed. This study supports column fixation in PAO as biomechanically advantageous to possibly sustaining early weight-bearing forces when compared to traditional fixation techniques. More clinical research is ultimately required to validate the feasibility of implementing these constructs and accelerating rehabilitation following PAO.

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Conflicts of interest

The authors declare there are no conflicts of interest.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2023.101291.

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