Spondylolysis Repair Using a Minimally Invasive Modified Buck Technique with Neuronavigation and Neuromonitoring in High School and Professional Athletes: Technical Notes, Case Series, and Literature Review

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■ BACKGROUND: **Spondylolysis is a defect in the pars interarticularis of the vertebra that occurs frequently in high-performance young athletes. Although nonsurgical management is the mainstay of treatment, surgery is an option for patients with persistent symptoms despite multiple cycles of nonsurgical treatment. Performing a minimally invasive technique reduces complications, postsurgery pain, and hospitalization time and leads to a quick recovery. The aim of this study was to report the clinical results of a series of 3 patients treated with a modification of the Buck technique with a minimally invasive approach.**

■ METHODS: **Three high-performance athletes between 17 and 18 years old who were managed nonsurgically for at least 6 months underwent a modified Buck technique repair with a minimally invasive approach using cannulated compression screws, with neuronavigation and neuromonitoring. Patients were followed at least 6 months with computed tomography scans to assess consolidation and fixation status. Following rehabilitation and in the absence of pain, all 3 athletes returned to their respective sports. No complications were reported.**

■ RESULTS: **All patients presented with bilateral spondylolysis, at L3 in 1 case and at L5 in 2 cases. Patients received conservative management for 12–36 months before surgery. After surgery, consolidation was obtained at 4 months in all patients, who returned to their sports activities in <6 months.**

■ CONCLUSIONS: **The proposed technique shows the advantages of performing minimally invasive surgery in young high-performance athletes, ensuring consolidation and early return to sports activity without complications.**

INTRODUCTION

Spondylolysis is a bone defect in the pars interarticularis (or isthmus) of the vertebra, involving the pars interarticularis of L5 in 95% of patients and generally bilateral.[1-6] This pars lesion is a combination of interposed fibrous, cartilaginous, or bone tissue that leads to chronic pseudarthrosis, with or without bone union.[7] Union is evident in only 3% of patients over the natural history of the disease.[8] The estimated incidence of spondylolysis in the general adolescent population is approximately 6%–8%,[9,10] and it is more commonly observed in patients >10 years old.[8] Its incidence is affected by the level of activity of the child or adolescent, with large increases observed in athletes,[11] as high as 47% in adolescent athletes.[12] Spondylolysis can be asymptomatic, when found incidentally, or symptomatic, manifesting as low back pain.[13] It accounts for about 50% of cases of low back pain in adolescent athletes[14,15] and is especially common in dancers, gymnasts, figure skaters, weightlifters, and football players.[13]

Nonsurgical treatment, including activity modification, bracing, and physiotherapy, continues to be the mainstay of treatment for pars defects, producing successful resolution of symptoms in up to 95% of cases.[16,17] However, surgery is indicated when symptoms persist for at least 6 months[18] and affect the quality

Key words
- Athletes
- Buck technique
- Minimally invasive approach
- Neuromonitoring
- Neuronavigation
- Spondylolysis

Abbreviations and Acronyms
CT: Computed tomography
MIS: Minimally invasive surgery

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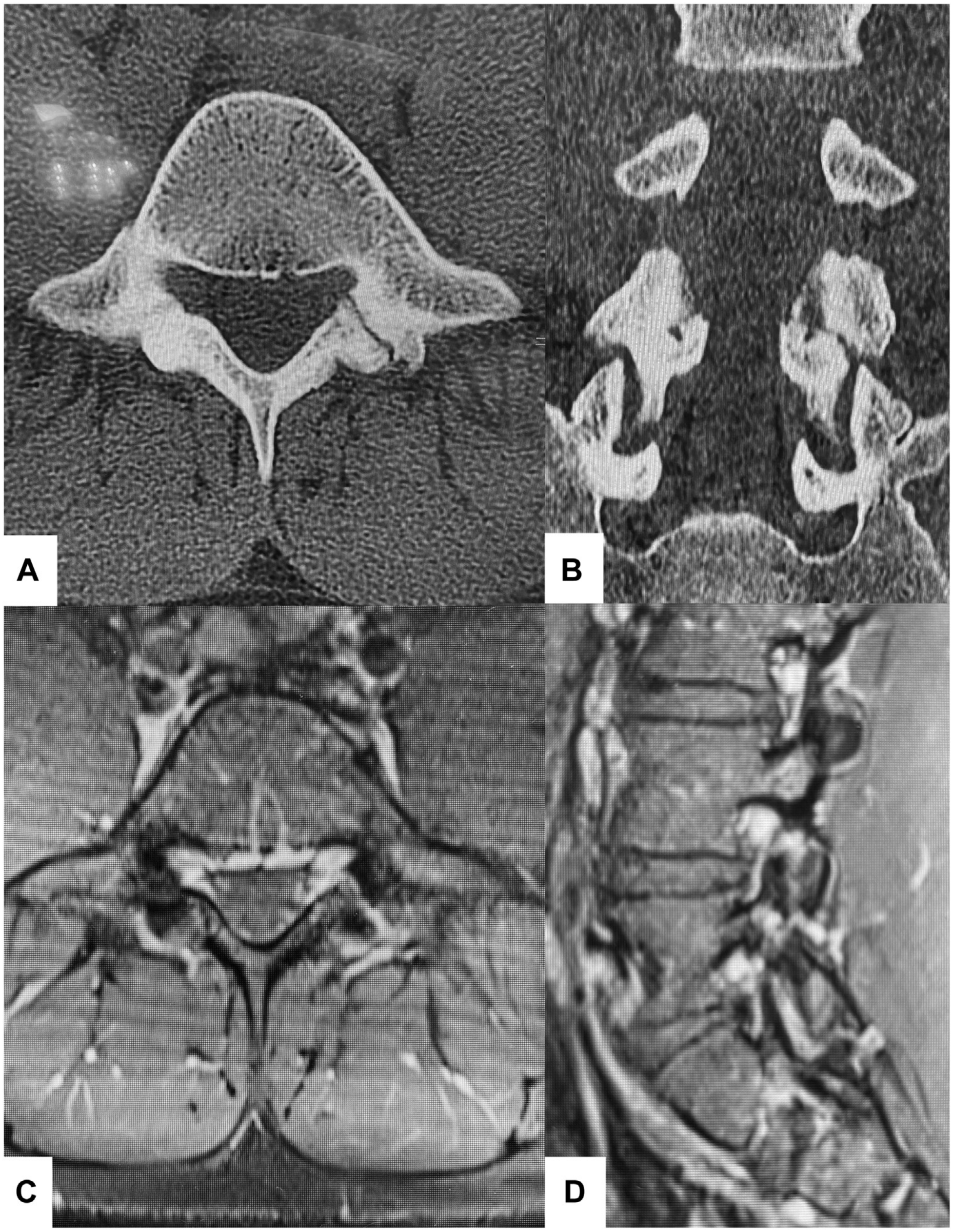

Figure 1. (**A**–**D**) Computed tomography and magnetic resonance imaging of the patient showing chronic lysis of left pars interarticularis.

of life of young patients, particularly athletes.[19] In a young patient with painful spondylolysis, a still intact disc,[20] and no relevant spondylolisthesis,[21] direct repair of the spondylolysis without fusing the segment is the treatment of choice, with the objectives of 1) obtaining reduction and fusion of the isthmus, 2) restoring spinal stability, and 3) preserving segment mobility.[22]

Many techniques have been proposed to repair defects involving the pars interarticularis, including simple placement of a bone graft without osteosynthesis material, fusion of ≥1 vertebrae to achieve stability, fusion by means of cerclage, a screw positioned within the pars interarticularis defect, pedicle screws and laminar hooks, and a rod-screw construction, among others.[6,23-29] In 1970, Buck[30] described an internal approach to treating the fracture, which included less aggressive dissection, débridement of the fracture site, insertion of a 4.5-mm cortical screw, and placement of an autologous iliac crest graft, reporting 88% good or excellent results.

At the present time, alternative, less invasive procedures are being sought that allow for Buck's fundamental objectives to be

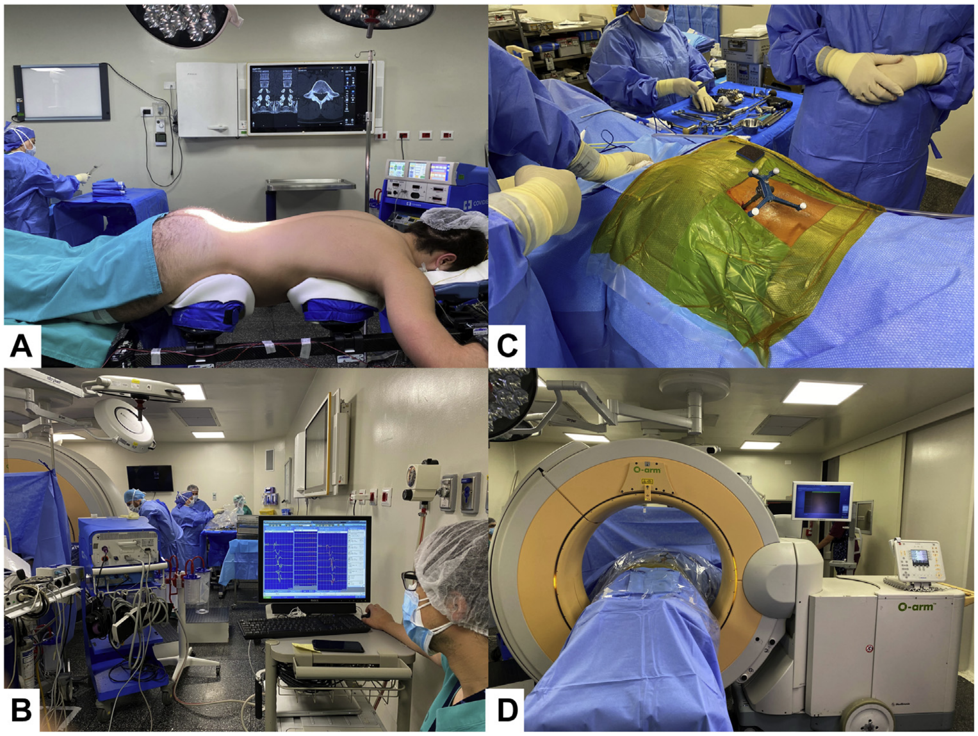

Figure 2. Intraoperative setup. (**A**) Patient positioning. (**B**) Electrophysiological monitoring. (**C**) Iliac crest percutaneous navigation reference. (**D**) Intraoperative tomography acquisition.

achieved—débridement of the lytic lesion, placement of an autologous graft to ensure consolidation, and performance of compressive and stable osteosynthesis in the pars defect. Performing Buck's technique using a minimally invasive surgery (MIS) technique reduces the extent of iatrogenic injury to the soft tissues and paravertebral muscles, thereby potentially reducing complications, postoperative pain, and hospitalization time, while providing faster recovery.[31] This is of particular importance in young, high-performance athletes who seek the earliest possible return to athletic activities.[22] In this article, we report our

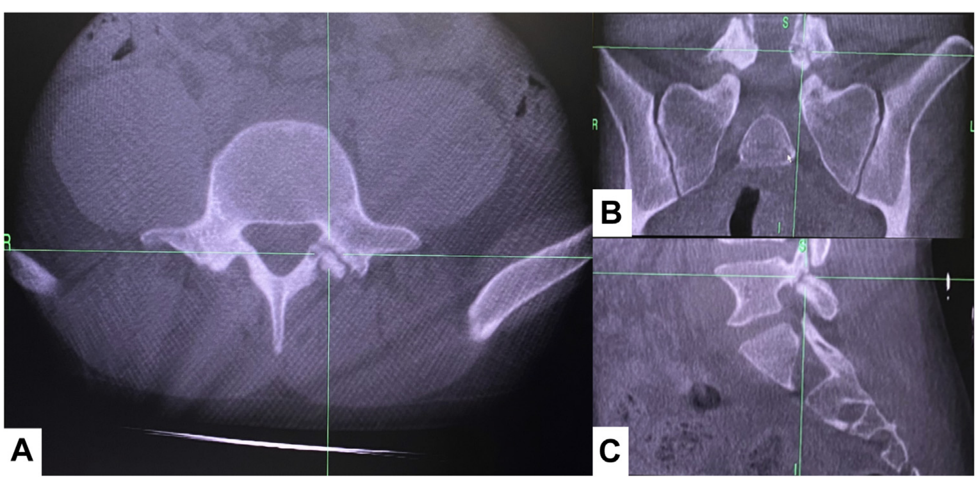

Figure 3. (**A**–**C**) Intraoperative tomography reconstruction images.

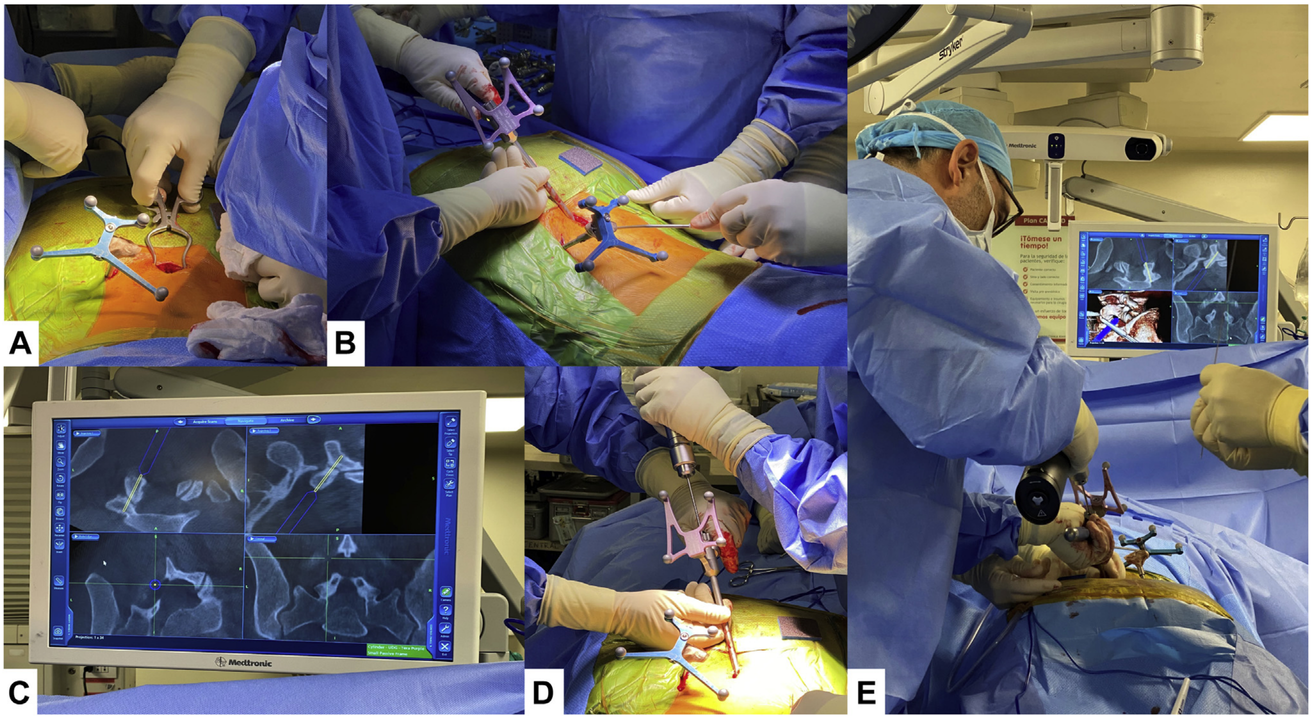

Figure 4. Navigated surgery. (**A**) Small midline incision over the spinous process of L5, dissecting the paravertebral spinal muscle and exposing the inferior aspect of the L5 lamina over each side. (**B**) Positioning of the navigated drilling guide. (**C**) Virtual selection of entry point and projection of the drill direction throughout the pars crossing the fracture. (**D** and **E**) Drilling following the selected pathway.

surgical results in 3 patients treated with a modified, minimally invasive Buck technique aided by three-dimensional neuronavigation and neuromonitoring.

MATERIALS AND METHODS

Cases

Reporting of these 3 cases was approved by the bioethics committee of the School of Medicine Clínica Alemana-Universidad del Desarrollo. Two high-school athletes and 1 professional athlete, all between 17 and 18 years old, presented with chronic mechanical low back pain that prevented them from continuing their sports activities. For our purposes, high school athletes were defined as athletes training at least 3 times per week and participating in at least 1 competitive event weekly, whereas professional athletes were defined as athletes participating in the national team of their sport. All 3 patients initially had functional lumbar spine radiographs and underwent computed tomography (CT) and nuclear magnetic resonance imaging to confirm the diagnosis of lumbar spondylolysis (**Figure 1**). Before being referred for surgery, all 3 had been managed nonsurgically with physiotherapy and analgesia for at least 6 months and conservative treatment was considered to be a failure owing to persistent pain and nonreturn to sports activities associated with a lack of fusion caused by the defect. In all patients, a modified, minimally invasive Buck technique repair was performed by the same surgeon (RY) and surgical team at the same institution between 2019 and 2020. All procedures were assisted by neuronavigation and neuromonitoring.

Surgical Technique

All 3 patients were placed under general anesthesia using intravenous and inhaled anesthetic agents, with multimodal neuromonitoring installed, and positioned prone on an Allen table with all support areas protected (**Figure 2**). Aseptic and antiseptic techniques were employed to create a sterile field. Percutaneous navigation antenna pins (StealthStation Surgical Navigation System; Medtronic, Minneapolis, Minnesota, USA) were installed in the posterior superior iliac crest after a minimum 5-mm incision was created. This was performed guided by cone-beam CT (O-arm; Medtronic) and antenna with images acquired for navigation (**Figure 3**).

Under neuronavigation, the lytic site of the involved segment was identified with a pointer and the level of approach was marked, after which a 30-mm midline incision was created in the skin and subcutaneous tissue, thereby providing sufficient length for proper positioning of a METRx tube (Medtronic). To permit the use of minimally invasive techniques, a fascial incision was created 20 mm from the spinous process (Wiltse approach), with dilators and a METRx tube positioned up to 20 mm in diameter over the pars defect, identifying the defect directly and confirming its position with a navigated pointer, and fibrotic tissue débridement of the lysis was performed with a motorized Midas Rex drill (Medtronic) with neuronavigation bilaterally and on alternate sides (**Figure 4**).

With neuronavigation support, the ideal entry point and access route to the pars defect was planned. Compression screw guide needles were drilled and installed under neuronavigation support through the same incision or a lower medial 4-mm incision, in

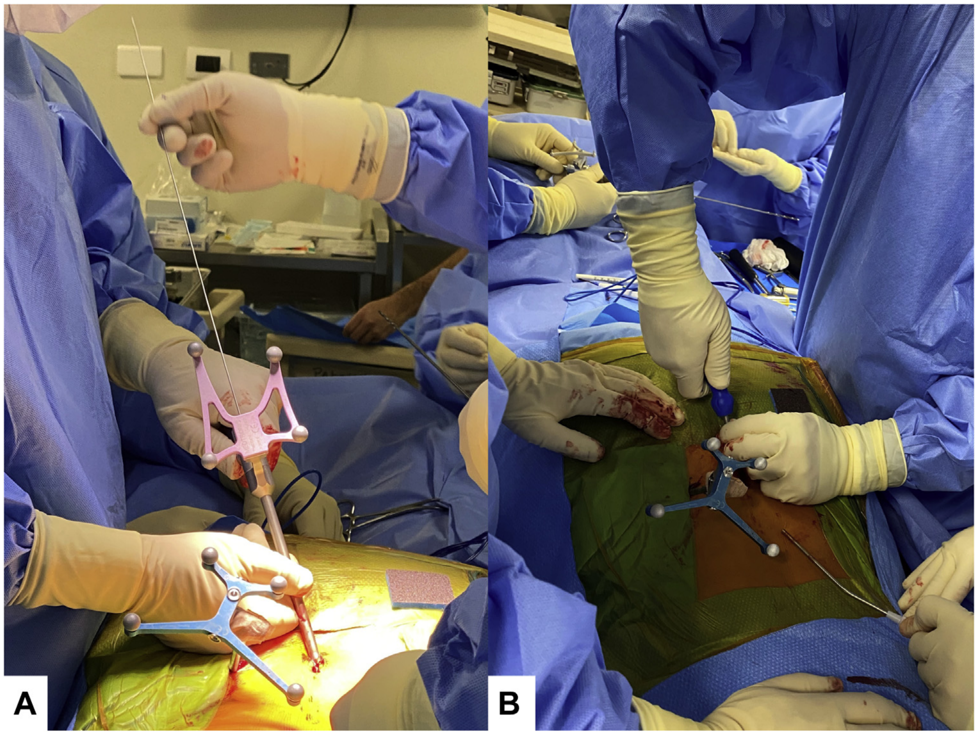

Figure 5. Navigated surgery. (**A**) Insertion of a Kirschner wire in the previously drilled hole. (**B**) Insertion of a cannulated screw.

accordance with the original Buck technique. Drilling was accomplished using guide wires with a 2.5-mm drill perpendicular to the pars defect, with drilling depth determined by navigation. The drill then was removed and replaced with a 2.0-mm Longitude guide wire (Medtronic) to allow the passage of compression screws (Figure 5).

The navigation antenna was temporarily removed from the iliac crest via the same MIS approach, and an autologous bone graft was taken from the iliac crest with trephine. The antenna was then returned to its previous position.

The autologous graft was delivered to and compacted in the débrided lytic area using METRx tubes. Then, 4.5-mm titanium compression cannulated screws with short threads and a threaded head (In2Bones, Memphis, Tennessee, USA) were installed to allow adequate compression of the lytic defect (length 34—44 mm, depending on the case) (Figure 6). Postoperative assessment using posterior O-arm CT confirmed adequate screw position and compression of the pars defect (Figure 7). The procedure was completed with irrigation with physiological solution, followed by closure of all tissue planes and the skin.

Follow-Up and Rehabilitation

After surgery, the patients were hospitalized for 24—48 hours. Medications prescribed postoperatively included an intravenous nonsteroidal anti-inflammatory drug and oral acetaminophen, both on a schedule, with opioids administered as required, depending on each patient's level of pain. Each patient's pain level was monitored closely, as were any local complications involving the wound or potential neurological symptoms or deficits. Lumbar anteroposterior and lateral radiographs were routinely obtained to confirm correct positioning of the osteosynthesis.

During hospitalization, patients were instructed to walk in their room aided by a physiotherapist, to move freely in bed, and to sit, again aided into position by the physiotherapist, throughout their hospitalization. Once patients were able to move on their own with minimal pain, they were discharged with oral analgesia and instructed to maintain a state of relative rest, restricted performing household chores and driving for 4 weeks until complete wound healing was achieved. Subsequently, they were authorized to progressively increase these activities. One month after surgery, progressive physiotherapy was initiated with sports reintegration therapy starting after 3 months, guided by an institutional physiotherapy team that specialized in sports reintegration and spinal pathology.

Patients were monitored once weekly by the treating physician until complete wound healing, then every 2 weeks, and then monthly, with a CT scan repeated at 4—6 months to assess consolidation and fixation status. Once consolidation was confirmed on CT, the rehabilitation program was completed, and they were pain-free, patients were permitted to gradually resume their former athletic activities, with the goal of ultimately returning to their preinjury exercise level.

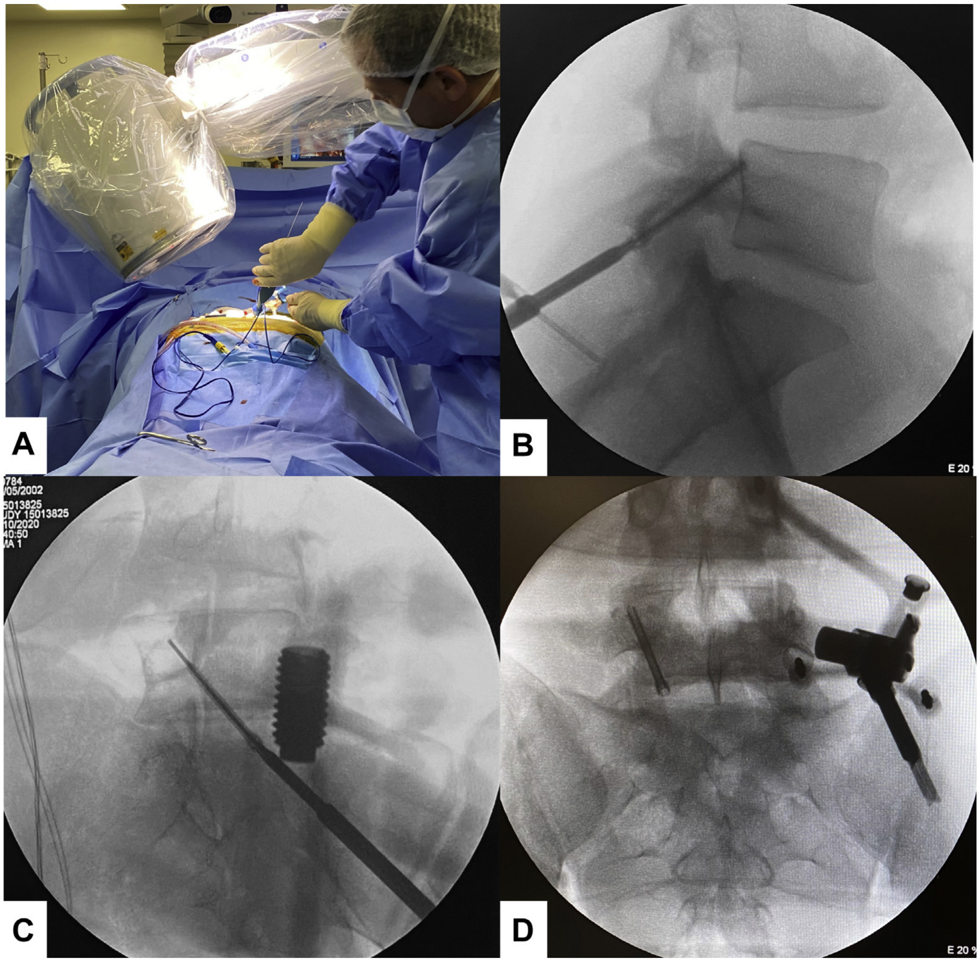

Figure 6. (**A**) C-arm confirmation of correct placement of the screw. (**B**) Sagittal view showing the screw throughout the pars crossing the fracture, achieving compression of the fracture. (**C**) Oblique view of insertion of a cannulated screw. (**D**) Anteroposterior view showing the medial to lateral trajectory of the screw.

RESULTS

All 3 patients presented with bilateral spondylolysis, 1 at the level of the L3 vertebra and 2 at the level of L5. Conservative management was sustained for 12–36 months without achieving satisfactory results. The average duration of the 3 surgeries was 215 minutes (range, 180–260 minutes). After surgery, consolidation was obtained within 4 months in all cases (**Figure 8**), with all patients returning to full sports activities within months. **Table 1** summarizes the cases.

No patient experienced any intraoperative or postoperative complications. Comparing patients with L3 and L5 spondylolysis, the only difference was surgical time, which was longer in the patient with L3 spondylolysis, at 260 minutes, versus 205 and 180 minutes in the 2 patients with L5 spondylolysis.

DISCUSSION

Although nonsurgical management is the mainstay of treatment, succeeding in most patients with a symptomatic pars defect, surgery is an option for patients with persistent symptoms despite multiple cycles of nonsurgical treatment.[17] This is of special relevance in high-performance athletes seeking early reinstatement.[32]

In this article, we have described a modified, minimally invasive Buck technique using partially threaded cannulated screws and neuronavigation, the use of MIS limiting muscle injury to a minimum, ensuring the correct position of screws, compressing the fracture focus, and using an iliac crest autograft, agreeing with most authors promoting its use as an ideal graft,[33] with no need to add other components to achieve consolidation. The surgical results our patients achieved were highly favorable, characterized by total pain resolution and functional restoration, bone consolidation in all cases, and complete reintegration into high-level sports within 6 months, all with no complications.

The concept of using direct fixation to repair spondylolysis has existed since the 1960s, with subsequent variations over time. Now it is the technique of choice because biomechanical studies have documented superior resistance to extension forces

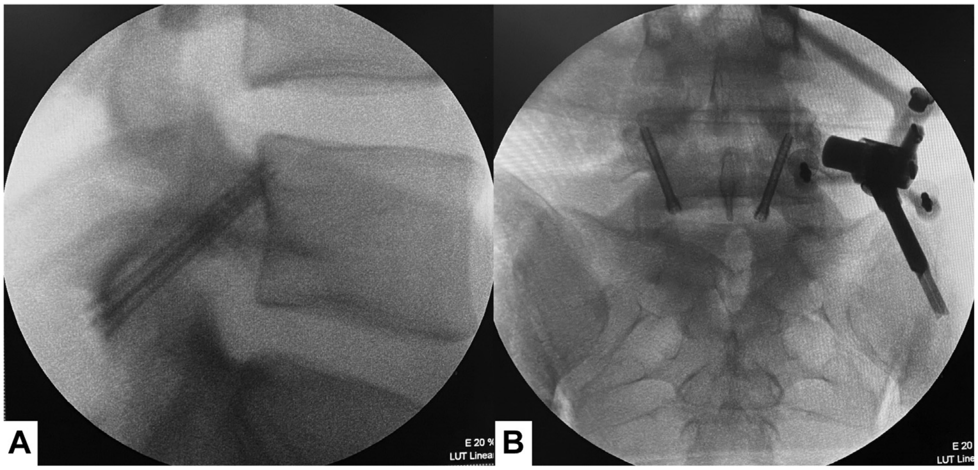

Figure 7. (**A**) C-arm sagittal view confirmation of correct placement of the screw. (**B**) Anteroposterior view showing both screws throughout the pars crossing the fracture.

through the pars, stabilizing the posterior segment and allowing the defect to heal,[34] thereby allowing the Buck technique to restore the stress of the disc adjacent to the defect[35] and obtain the greatest degree of rotational stability.[36] The classic Buck technique and subsequent modifications all involve a large incision in the skin and broad exposure of the deep tissues, which is associated with appreciable morbidity.[29] Although there is no consensus on the most appropriate surgical technique, with comparable pain management results described for the various modifications,[17] our current focus has been to achieve complete sports reintegration as soon as possible by adopting an MIS approach.

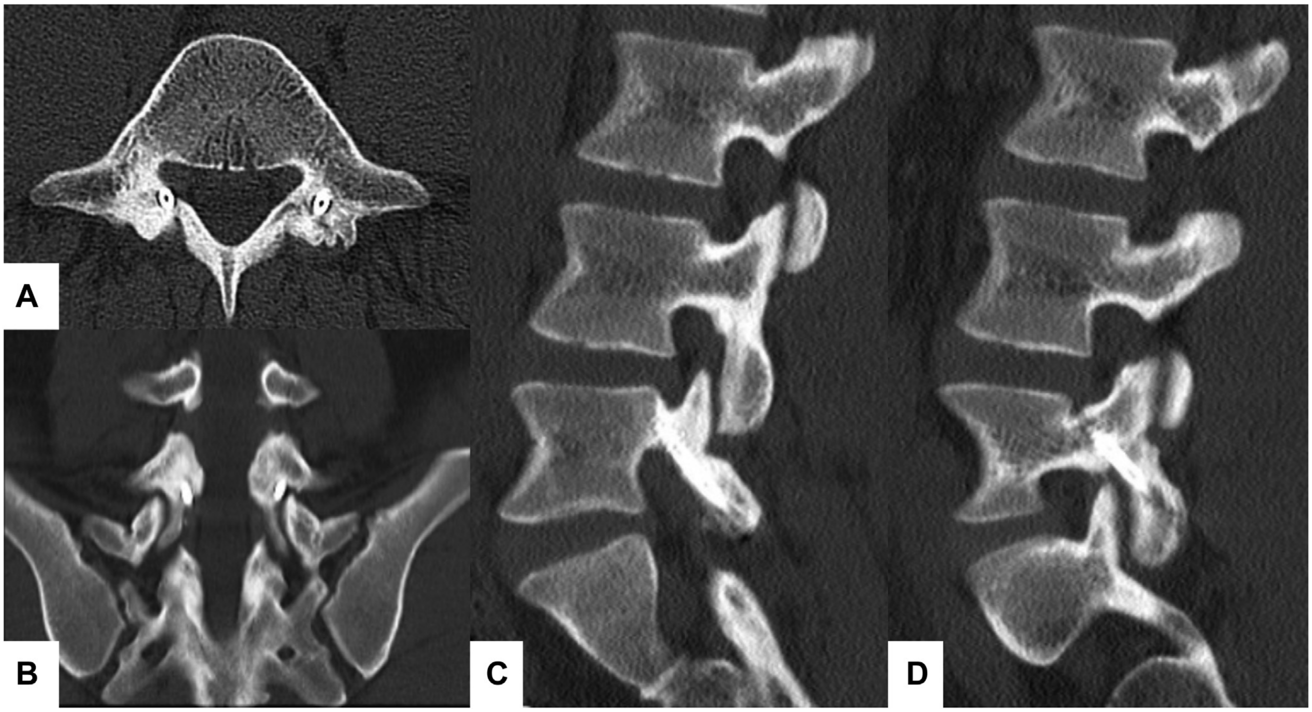

Figure 8. Computed tomography scan of patient 1 after 4 months of follow-up. (**A**) Axial reconstruction of the repaired pars. (**B**) Coronal reconstruction. (**C** and **D**) Parasagittal reconstruction of each pars repaired with screws following the pars axis.

Table 1. Characteristics of Patients Including Postoperative Outcomes

Case	Age (Years)/ Sex	Primary Sport	Sports Level	Pars Lysis Level	Laterality	Conservative Treatment Duration (Months)	Time to Consolidation After Surgery (Months)	Time to Return to Preinjury Level Athletics (Months)
1	17/male	Rugby	Professional	L5	Bilateral	19	4	6
2	18/male	Volleyball	High school	L3	Bilateral	36	4	6
3	17/male	Soccer	High school	L5	Bilateral	12	5	6

In the present era of minimally invasive spinal surgery, using a microscope or endoscope, with or without neuronavigation, has allowed for direct observation of the focus of fractures, their curettage, bone grafting, and correct placement of osteosynthesis material with minimal soft tissue dissection.[6,37,38] This is crucial because back muscles are often injured during posterior lumbar surgeries.[39,40] It is especially crucial in high-level athletes.[41]

The first authors to describe a less invasive approach using the Buck osteosynthesis technique were Higashino et al. in 2007,[37] who added direct endoscopic observation while performing lysis repair. In 2008, Brennan et al.[6] reported a minimally invasive variation of the Buck technique using intraoperative three-dimensional images and frameless navigation. Similarly, Wilson et al. in 2016[31] described a percutaneous variation using a partially threaded compression screw to achieve maximum compression over the defect, also via endoscopic assistance.

Although endoscopic techniques achieve the same good results as other forms of MIS, the same authors who initially developed this technique recommend a direct MIS approach, concluding that endoscopy is otherwise difficult to perform in athletes who typically are quite slim and increases the risk of laminar rupture during screw placement,[41] thereby delaying the athletes' return to their sports.

Goncalves-Ramírez et al.[42] described a neuronavigation technique based on the MIS concept, using a 2.5- to 3.0-cm midline incision at the lower edge of the spinous process of the affected level to obtain bilateral paravertebral access to the spinous base of L5, exposing the lamina and the pars to permit direct microscopic visualization and the capacity to observe passage of the screw through the fracture. Meanwhile, with our technique, rather than dissecting the paravertebral muscles to the pars, we propose instead approaching with transmuscular tubes via a Wiltse approach. This minimizes muscle dissection, which we thought was especially important in the young athletes we were treating, as opposed to the much older, nonathletic patients reported by Goncalves-Ramírez et al.

Regarding screw selection, we decided to use a 4.5-mm cannulated headless compression screw at the fracture site, similar to the screws used by Goncalves-Ramírez et al.[42] It has been proved that compression screws provide more stability than classic cortex screws,[43-46] traditionally used to repair spondylolysis.[17]

Delays of 6–12 months before patients can return to sports after pars repair have been classically described.[23,47,48] In a systematic review by Grazina et al.,[32] 81% of athletes returned to their preinjury level (70%–100%) over an average of 6.4 months (range, 6–7 months) with conventional surgical techniques, though not all these patients were elite athletes. Many authors fail to specify the time period between surgical repair and a return to sports. Three studies examining MIS variations estimated a mean time to return to sports of approximately 3 months,[38,41,49] but all failed to specify the patients' level of athletic prowess or whether they had returned to their preinjury function level.

Kolcun et al.[50] conducted a review in which they compared clinical results and return to play with conventional surgery versus MIS and found that patients who underwent MIS had significantly higher rates of pain resolution and shorter recovery times. In both treatment groups there were low complication rates, and most patients returned to previous levels of activity.

Although using compression screws is a stable construct, we believe in waiting for signs of consolidation before authorizing any return to sports, owing to the possible risks of osteosynthesis failure and malunion. As such, we have not observed these complications.

Caution must be exercised interpreting the results of our current series. The greatest limitation is the small number of cases; however, this we saw as unavoidable given the rarity of the condition being studied. A larger number of patients and a control group are clearly needed to compare the safety, precision, operating time, and costs associated with the currently proposed technique against standard techniques. Second, long-term follow-up is required to assess good results over time; we followed our patients for only 6 months. This said, all 3 of our patients exhibited complete bone consolidation and a return to full athletic activities within 6 months. Finally, access to the equipment necessary for this type of surgery as well as a dearth of adequately trained personnel and high associated costs are limitations to universal implementation of our approach.

CONCLUSIONS

The minimally invasive modified Buck technique exhibits all the advantages of MIS surgery, using cannulated compression screws for greater stability, allowing effective compression in the pars defect, and using neuronavigation to ensure correct positioning of the osteosynthesis material, thereby avoiding complications while achieving good consolidation and an early return to full activities. All these benefits appear especially advantageous in young athletes.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Ratko Yurac: Conceptualization, Methodology, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **José T. Bravo:** Writing – original draft, Writing – review & editing, Visualization. **Álvaro Silva:** Writing – review & editing, Visualization, Supervision. **Bartolomé Marré:** Writing – review & editing, Visualization, Supervision.

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REFERENCES

1. Leone A, Cianfoni A, Cerase A, Magarelli N, Bonomo L. Lumbar spondylolysis: a review. *Skeletal Radiol*. 2011;40:683-700.
2. Lovell WW, Winter RB, Morrissy RT, Weinstein SL, eds. *Lovell and Winter's Pediatric Orthopaedics*. Philadelphia, PA: Lippincott Williams & Wilkins; 2006.
3. Grogan JP, Hemminghytt S, Williams AL, Carrera GF, Haughton VM. Spondylolysis studied with computed tomography. *Radiology*. 1982;145:737-742.
4. Floman Y. Progression of lumbosacral isthmic spondylolisthesis in adults. *Spine (Phila Pa 1976)*. 2000;25:342-347.
5. Hammerberg KW. New concepts on the pathogenesis and classification of spondylolisthesis. *Spine (Phila Pa 1976)*. 2005;30(6 Suppl):S4-S11.
6. Brennan RP, Smucker PY, Horn EM. Minimally invasive image-guided direct repair of bilateral L-5 pars interarticularis defects. *Neurosurg Focus*. 2008;25:E13.
7. Ulmer JL, Mathews VP, Elster AD, King JC. Lumbar spondylolysis without spondylolisthesis: recognition of isolated posterior element subluxation on sagittal MR. *AJNR Am J Neuroradiol*. 1995;16:1393-1398.
8. Fredrickson BE, Baker D, McHolick WJ, Yuan HA, Lubicky JP. The natural history of spondylolysis, and spondylolisthesis in children and adolescents. *J Bone Joint Surg Am*. 1984;66:699-707.
9. Wiltse L, Rothman L. Spondylolisthesis: classification, diagnosis and natural history. *Semin Spine Surg*. 1989;1:78-94.
10. Brooks BK, Southam SL, Mlady GW, Logan J, Rosett M. Lumbar spine spondylolysis in the adult population: using computed tomography to evaluate the possibility of adult onset lumbar spondylosis as a cause of back pain. *Skeletal Radiol*. 2010;39:669-673.
11. Merbs CF. Spondylolysis: its nature and anthropological significance. *Int J Anthropol*. 1989;4:163-169.
12. Letts M, Smallman T, Afanasiev R, Gouw G. Fracture of the pars interarticularis in adolescent athletes: a clinical-biomechanical analysis. *J Pediatr Orthop*. 1986;6:40-46.
13. Standaert CJ, Herring SA. Spondylolysis: a critical review. *Br J Sports Med*. 2000;34:415-422.
14. Patel DR, Nelson TL. Sports injuries in adolescents. *Med Clin North Am*. 2000;84:983-1007.
15. Micheli LJ, Wood R. Back pain in young athletes: significant differences from adults in causes and patterns. *Arch Pediatr Adolesc Med*. 1995;149:15-18.
16. Kurd MF, Patel D, Norton R, Picetti G, Friel B, Vaccaro AR. Nonoperative treatment of symptomatic spondylolysis. *J Spinal Disord Tech*. 2007;20:560-564.
17. Menga EN, Kebaish KM, Jain A, Carrino JA, Sponseller PD. Clinical results and functional outcomes after direct intralaminar screw repair of spondylolysis. *Spine (Phila Pa 1976)*. 2014;39:104-110.
18. Aebi M. Direct screw fixation of the spondylolysis without fusion. *Eur Spine J*. 2010;19:1803-1805.
19. Debnath UK, Scammell BE, Freeman BJC, McConnell JR. Predictive factors for the outcome of surgical treatment of lumbar spondylolysis in young sporting individuals. *Global Spine J*. 2018;8:121-128.
20. Pfirrmann CW, Metzdorf A, Zanetti M, et al. Magnetic resonance classification of lumbar intervertebral disc degeneration. *Spine (Phila Pa 1976)*. 2001;26:1873-1878.
21. Meyerding HW. Spondylolisthesis; surgical fusion of lumbosacral portion of spinal column and interarticular facets; use of autogenous bone grafts for relief of disabling backache. *J Int Coll Surg*. 1956;26:566-591.
22. Berjano P, Ristori G, Ismael Aguirre MF, et al. A novel technique for spondylolysis repair with pedicle screws, rod and polyester band: case report with technical note and systematic literature review. *Spine (Phila Pa 1976)*. 2020;45:E1682-E1691.
23. Drazin D, Shirzadi A, Jeswani S, et al. Direct surgical repair of spondylolysis in athletes: indications, techniques, and outcomes. *Neurosurg Focus*. 2011;31:E9.
24. Dai LY, Jia LS, Yuan W, Ni B, Zhu HB. Direct repair of defect in lumbar spondylolysis and mild isthmic spondylolisthesis by bone grafting, with or without facet joint fusion. *Eur Spine J*. 2001;10:78-83.
25. Coelho BPM, Moreira C, D'Alessandro R, et al. Treatment of symptomatic spondylolysis with direct repair by modified Buck's technique. *Coluna/Columna*. 2009;8:32-37.
26. Debusscher F, Troussel S. Direct repair of defects in lumbar spondylolysis with a new pedicle screw hook fixation: clinical, functional and CT-assessed study. *Eur Spine J*. 2007;16:1650-1658.
27. Johnson GV, Thompson AG. The Scott wiring technique for direct repair of lumbar spondylolysis. *J Bone Joint Surg Br*. 1992;74:426-430.
28. Mihara H, Onari K, Cheng BC, David SM, Zdeblick TA. The biomechanical effects of spondylolysis and its treatment. *Spine (Phila Pa 1976)*. 2003;28:235-238.
29. Yoichiro T, Sakai T, Fumitake T, Yuichiro G, Kosaku H, Sairyo K. Clinical outcome of minimally invasive repair of pars defect using percutaneous pedicle screw and hook-rod system in adults with lumbar spondylolysis. *Ann Orthop Rheumatol*. 2014;2:1013-1018.
30. Buck JE. Direct repair of the defect in spondylolisthesis: preliminary report. *J Bone Joint Surg Br*. 1970;52:432-438.
31. Wilson L, Altaf F, Tyler P. Percutaneous pars interarticularis screw fixation: a technical note. *Eur Spine J*. 2016;25:1651-1654.
32. Grazina R, Andrade R, Santos FL, et al. Return to play after conservative and surgical treatment in athletes with spondylolysis: a systematic review. *Phys Ther Sport*. 2019;37:34-43.
33. Ondra SL, Marzouk S. Revision strategies for lumbar pseudoarthrosis. *Neurosurg Focus*. 2003;15:E9.
34. Kip PC, Esses SI, Doherty BI, Alexander JW, Crawford MJ. Biomechanical testing of pars defect repairs. *Spine (Phila Pa 1976)*. 1994;19:2692-2697.
35. Sairyo K, Goel VK, Faizan A, Vadapalli S, Biyani S, Ebraheim N. Buck's direct repair of lumbar spondylolysis restores disc stresses at the involved and adjacent levels. *Clin Biomech (Bristol, Avon)*. 2006;21:1020-1026.
36. Deguchi M, Rapoff AJ, Zdeblick TA. Biomechanical comparison of spondylolysis fixation techniques. *Spine (Phila Pa 1976)*. 1999;24:328-333.
37. Higashino K, Sairyo K, Katoh S, Sakai T, Kosaka H, Yasui N. Minimally invasive technique for direct repair of the pars defect in young adults using a spinal endoscope: a technical note. *Minim Invasive Neurosurg*. 2007;50:182-186.
38. Widi GA, Williams SK, Levi AD. Minimally invasive direct repair of bilateral lumbar spine pars defects in athletes. *Case Rep Med*. 2013;2013:65907.
39. Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery. Part 1: Histologic and histochemical analyses in rats. *Spine (Phila Pa 1976)*. 1994;19:2590-2597.
40. Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery. Part 2: Histologic and histochemical analyses in humans. *Spine (Phila Pa 1976)*. 1994;19:2598-2602.
41. Sairyo K, Sakai T, Yasui N. Minimally invasive technique for direct repair of pars interarticularis defects in adults using a percutaneous pedicle

screw and hook-rod system. *J Neurosurg Spine*. 2009;10:492-495.

42. Goncalves-Ramírez FJ, Serrano MT, Lee SH, Dominguez CJ, Manuel-Rimbau J. Headless compression screw in the neuronavigation-guided and microscope-assisted treatment of spondylolysis. *Neurocirugia (Astur: Engl Ed)*. 2018;29:122-130.

43. Gruszka DS, Burkhart KJ, Nowak TE, Achenbach T, Rommens PM, Müller LP. The durability of the intrascaphoid compression of headless compression screws: in vitro study. *J Hand Surg Am*. 2012;37:1142-1150.

44. Assari S, Darvish K, Ilyas AM. Biomechanical analysis of second generation headless compression screw. *Injury*. 2012;43:1159-1165.

45. Lenehan B, Street J, Murphy B, Brennan L, McHugh P, Curtain W. A biomechanical study comparing the compressive forces generated by a conventional 4.5 AO/ASIF cortical lag screw with a differentially pitched cortical compression screw. *Acta Bioeng Biomech*. 2009;11:31-35.

46. Reihsner R, Huber WO, Beer R. Biomechanical criterion for selecting cancellous bone screws: arthrodesis in the hindfoot. *Acta Bioeng Biomech*. 2007;9:27-33.

47. Radcliff KE, Kalantar SB, Reitman CA. Surgical management of spondylolysis and spondylolisthesis in athletes: indications and return to play. *Curr Sport Med Rep*. 2009;8:35-40.

48. Bouras T, Korovessis P. Management of spondylolysis and low-grade spondylolisthesis in fine athletes: a comprehensive review. *Eur J Orthop Surg Traumatol*. 2015;25:S167-S175.

49. Noggle JC, Sciubba DM, Samdani AF, Anderson DG, Betz RR, Asghar J. Minimally invasive direct repair of lumbar spondylolysis with a pedicle screw and hook construct. *Neurosurg Focus*. 2008;25:E15.

50. Kolcun JPG, Chieng LO, Madhavan K, Wang MY. Minimally-invasive versus conventional repair of spondylolysis in athletes: a review of outcomes and return to play. *Asian Spine J*. 2017;11:832-842.

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