Surgical Neurology International

SNI: Neurosurgical Developments on the Horizon, a supplement to SNI

OPEN ACCESS

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Editor: Michel Kliot, MD UCSF Medical Center San Francisco, CA 94143

The future of spine surgery: New horizons in the treatment of spinal disorders

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Received: 06 August 12 Accepted: 31 October 2012 Published: 19 March 13

This article may be cited as:
Kazemi N, Crew LK, Tredway TL. The future of spine surgery: New horizons in the treatment of spinal disorders. Surg Neurol Int 2013;4:S15-21.
Available FREE in open access from: http://www.surgicalneurologyint.com/text.asp?2013/4/2/15/109186

Abstract

Background and Methods: As with any evolving surgical discipline, it is difficult to predict the future of the practice and science of spine surgery. In the last decade, there have been dramatic developments in both the techniques as well as the tools employed in the delivery of better outcomes to patients undergoing such surgery. In this article, we explore four specific areas in spine surgery: namely the role of minimally invasive spine surgery; motion preservation; robotic-aided surgery and neuro-navigation; and the use of biological substances to reduce the number of traditional and revision spine surgeries.

Results: Minimally invasive spine surgery has flourished in the last decade with an increasing amount of surgeries being performed for a wide variety of degenerative, traumatic, and neoplastic processes. Particular progress in the development of a direct lateral approach as well as improvement of tubular retractors has been achieved. Improvements in motion preservation techniques have led to a significant number of patients achieving arthroplasty where fusion was the only option previously. Important caveats to the indications for arthroplasty are discussed. Both robotics and neuro-navigation have become further refined as tools to assist in spine surgery and have been demonstrated to increase accuracy in spinal instrumentation placement. There has much debate and refinement in the use of biologically active agents to aid and augment function in spine surgery. Biological agents targeted to the intervertebral disc space could increase function and halt degeneration in this anatomical region.

Conclusions: Great improvements have been achieved in developing better techniques and tools in spine surgery. It is envisaged that progress in the four focus areas discussed will lead to better outcomes and reduced burdens on the future of both our patients and the health care system.

Key Words: Future developments, minimally invasive surgery, navigation, robotics, spine surgery

Access this article online

Website: www.surgicalneurologyint.com

DOI: 10.4103/2152-7806.109186

Quick Response Code:

INTRODUCTION

Although it is difficult to predict the rapidly changing practice of spinal surgery, we focus this article on four areas of burgeoning interest: Minimally invasive spinal surgery, motion preservation, robotics and neuro-navigation and the use of biologics. All four of these areas will most likely see further significant

growth in the near, as well as distant future. Minimally invasive techniques have been developed and honed for decades; however, recent technological advances combined with the development of computer software to aid in robotic surgery and neuro-navigation will hopefully allow for safer and more efficacious minimally invasive procedures for our future patients. Moreover, the use of biologically active agents may actually reduce the number of traditional spinal surgeries while providing patients with reasonable non-operative treatment options. Definitive treatment will most likely be preventative in nature, which is in direct contrast to our current surgical treatment modalities which mainly focus on treating the "end-result" of spinal pathology. While this article is not intended to be a comprehensive menu of future products, techniques and trends in spinal neurosurgery, it is our goal to present the possibilities that will be available in our spinal armamentarium as we approach 2020.

MINIMALLY INVASIVE APPROACHES TO THE SPINE

The introduction of the tubular retractor system (METRx™, Medtronic, Memphis, TN, USA) by Foley and Smith in the late 1990s allowed spine surgeons to treat symptomatic herniated discs with minimally invasive techniques.[47] These pioneers of minimal access surgery demonstrated that a routine procedure, the microdiscectomy, could be performed using a novel retractor system combined with an attachable endoscope, allowing for excellent visualization with minimal obstruction for the passage of instruments through the diminutive working channel. This technique has also been employed over recent years to treat a variety of spinal pathologies including symptomatic spinal stenosis, synovial cysts, intradural-extramedullary tumors, intramedullary tumors, tethered cords, and spinal cord syrinxes[17,41,42,53,59,60] [Figure 1].

Accordingly, the tubular retractor system has undergone various modifications over the past 10 years and has allowed the spine surgeon to expand the role of minimally invasive approaches to include lumbar fusion techniques (i.e., minimally invasive transforaminal lumbar interbody fusions or MI-TLIFs) for treatment of spondylolisthesis, degenerative disc disease, short segment spinal deformity, as well as traumatic fractures. Excellent outcomes combined with fewer complications, shorter hospital stays, and less blood loss have been reported with this technique.[27,45] It is quite conceivable that this technique will be the "gold standard" utilized when evaluating emerging techniques for the treatment of degenerative disc disease and spondylolisthesis in the future.

Another minimally invasive procedure for the thoraco-lumbar spine is the eXtreme lateral interbody fusion (XLIF®, NuVasive, San Diego, CA, USA) or direct lateral interbody fusion (DLIF). This lateral, trans-psoas

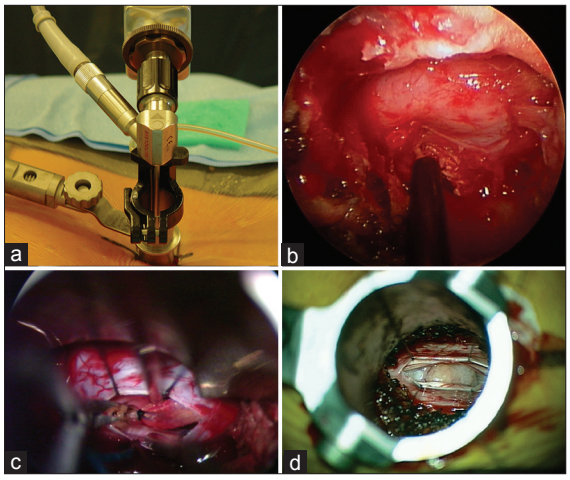

Figure 1: (a) METRx system with endoscope, (b) View of microendoscopic decompression for lumbar stenosis, (c) Microendoscopic view of filum detethering, (d) Minimally invasive resection of intradural schwannoma

muscle approach has been popularized by Pimenta and others for the treatment of degenerative disc disease and has also been utilized to treat a variety of spinal pathologies.[44] The direct lateral approach allows for excellent access to the thoracolumbar spine from either side. This novel approach also provides a working corridor to the disc space as well as the vertebral body and has been utilized to treat degenerative disease processes, infections, as well as tumors and fractures of the spine. It has also been used as a powerful adjuvant in deformity corrective surgery combined with posterior instrumentation.[24,25,57]

This direct lateral approach has been utilized for the placement of an intervertebral artificial disc outside of the United States and is currently in an FDA-Investigational Device Exemption (FDA-IDE) trial.[48] It is the authors' opinion that this approach, combined with disc replacement, may be the primary treatment for symptomatic degenerative disc disease since it may reduce the risk of injury to the iliac vessels, neural elements, and genitourinary tract that has been reported with anterior lumbar approaches. With its ever increasing popularity among spine surgeons, the direct lateral approach will continue to be utilized in the future treatment of thoraco-lumbar spinal disease.

MOTION PRESERVATION

The past decade has witnessed a change in philosophy regarding cervical and lumbar fusion surgery. Traditionally, the anterior cervical discectomy and fusion procedure has provided many patients with symptomatic relief of radicular, and occasionally, axial neck pain with excellent clinical outcomes and high fusion rates.[13,66] To a lesser degree, lumbar fusion techniques including posterior-lateral fusions, anterior lumbar interbody fusions (ALIFs), posterior lumbar

interbody fusions (PLIFs), and transforaminal lumbar interbody fusions (TLIFs) have provided some pain relief in carefully chosen patients with correlative symptoms and imaging studies. Since results have been varied and there has been much debate as to patient selection criteria and procedural success, a trend toward motion preservation in the form of disc arthroplasty has become more popular. The Charite disc (DePuy, Ranham, MA, USA) was the first device approved in the United States for use in the lumbar spine. Since its approval in 2004, there have been many reports documenting the benefit for relief of axial back pain, as well as some reports suggesting only modest improvement.[4,5,8,9,14,15,18,19,21,23,32,37,38,69,71] The ProDisc-L (Synthes, Paoli, PA, USA) was released in 2006 and has also demonstrated some encouraging results compared to historical fusion procedure success rates.[10,70,71] It is likely that longer follow-up may define the efficacy of these products as well as their comparison to previously reported outcomes in lumbar fusion surgery.

Cervical disc arthroplasty complications are rare; however, lumbar disc arthroplasty approaches carry well-documented risks to the lumbosacral vessels, neural elements, and genitourinary structures. This issue may be improved in the future with better preoperative imaging assessment and possibly through minimal access approaches. Furthermore, the direct lateral or extreme lateral approach may reduce these risks and thus become the preferred surgical approach by both spine and general access surgeons.

In regard to the commercially available artificial disc products, two of the FDA-approved cervical disc arthroplasty devices and both of the FDA-approved lumbar implants are composed of materials that do not allow for adequate visualization of the operative disc level and often obscure adjacent segments when evaluated with MRI. In a study evaluating the ability to visualize the spinal canal and adjacent segments after cervical disc arthroplasty, only the Bryan (Medtronic) and Prestige LP (Medtronic) allowed for adequate visualization.[54] The artifact produced by these implants can be circumvented with the use of non-ferromagnetic biomaterials allowing for postoperative imaging and evaluation in the future. Polymers and ceramics may also be employed in the design of future intervertebral disc prostheses. These products will provide mechanical support, motion sparing, and can be easily imaged with MRI[43] [Figure 2].

Although disc arthroplasty may be a reasonable option for patients with cervical or lumbar disc disease, many patients do not fit the criteria for arthroplasty due to lumbar spondylolistheses, cervical subluxation, lack of motion related to severe spondylosis, and more commonly secondary to insurance-related denials. In this population, fusion surgery will most likely be the mainstay. Traditional titanium-alloy plates and screws are still popular; however, we are witnessing a trend toward bio-absorbable plates and screws, as well as significantly smaller plating systems that purportedly reduce the incidence of iatrogenic adjacent segment disease spondylosis. Bio-absorbable instrumentation has been utilized in plastic surgery and neurosurgery for craniofacial reconstruction for many years, but bio-absorbable anterior cervical plating systems have only been available in the United States since 2006[35,51] [Figure 3].

These products offer an alternative to their metal counterparts which can often be difficult to remove when re-operation is necessary. The absorbable plating system also negates the artifact that is often visualized on postoperative MRIs.

ROBOTICS AND NEURO-NAVIGATION

There are many potential hazards associated with spine surgery, which include risks to vital structures including important vessels, viscera and of course neural elements. In addition, if instrumentation is utilized, there is a risk of malpositioning of the hardware leading to compromise of the anatomy required for spinal stability. Therefore, good control and accuracy in the operative

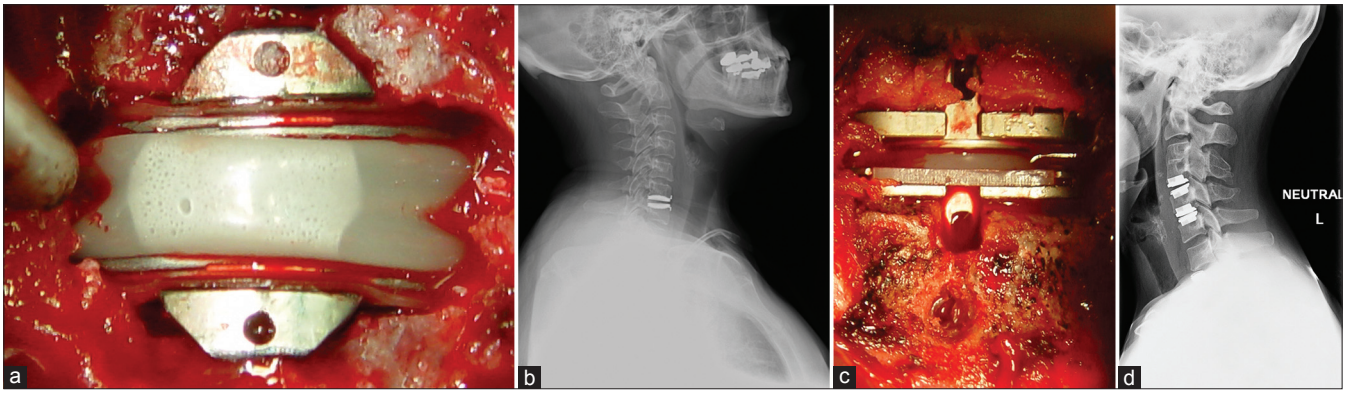

Figure 2: (a) Intraoperative view of bryan Artificial Disc (Medtronic, Memphis, TN, USA), (b) Postoperative radiograph of Bryan Artificial Disc (Medtronic), (c) Intraoperative view of ProDisc-C Artificial Disc (Synthes, Paoli, PA, USA), (d) Postoperative radiograph of ProDisc-C Artificial Disc (Synthes)

approach is a necessity in spine surgery. For example, it has been estimated that a dural breach occurs in 3.5% of primary initial discectomies and around 13% of revision discectomies.[55] This could arise as a result of surgical technique mistakes in terms of visualization or instrument control. Faced with these challenges as well as problems with ergonomics, surgical dexterity and the surgeon–instrument interface, robotic spine surgery has been conceptualized and developed.

Although robotics has been employed for longer than a decade in many surgical subspecialties, it has only recently been utilized in the area of spine surgery. The advantage of the current robotic platform is that it allows the surgeon real-time procedural manipulation combined with heuristic instrument control, real-scale magnification, and elimination of tremor. All of this can now be combined with anatomical spine navigation to allow precise surgical technique with minimal spinal bony damage and blood loss. However, until recently, robotics has always had limited application in spine surgery due to the challenges of visualization, cost, adequate training, and the development of minimally invasive techniques that have offered a viable and more widely utilized alternative.

Several procedures have been recently tested using the Da Vinci robotic system (Intuitive Surgical Inc., Sunnyvale, CA, USA) including laminectomy, laminotomy, discectomy, and dural repairs on an *in vivo* porcine model.[49] In the same model, it has also been used in an ALIF procedure[28,68] [Figure 4]. In humans, the Da Vinci robotic model has been utilized in assisted transoral odontoid resection for decompression of the craniocervical junction.[31] It has also been used laparoscopically in robotic-assisted resection of a thoracolumbar neurofibroma,[40] thoracoscopically for resection of a mediastinal schwannoma, and transperitoneally in the resection of paravertebral lumbosacral masses.[52,67]

Renaissance™ (Mazor Robotics, Inc., Caesarea, Israel) is a miniature robotic guidance system which can be either mounted on table or on the patient's spinous process. This system together with its precursor, Spine Assist® (Mazor Robotics, Inc.) has now been employed for longer than 5 years. In its development, it has been cadaverically tested using percutaneous placement of pedicle and translaminar facet screws, as well as being employed for the placement of transpedicular screws via open and percutaneous techniques in PLIFs.[3,34,46,56]

In a retrospective multi-center trial, using the Spine Assist, screw placement was determined to be clinically acceptable in 98% of cases based on intraoperative X-ray imaging. Postoperative imaging demonstrated that 98.3% of the screws fell within a safe zone, whereas in 9%, screws breached the pedicle by up to 2 mm. The remainder of the screws breached between 2 and 4 mm, and in only two cases was there a breach greater than 4 mm. Neurological deficit was seen in four patients, but following revision of the instrumentation, all of these deficits resolved.[12]

Overall, robotic-assisted surgery provides several advantages to the surgeon. These include a significant improvement of dexterity with a reduction in physiological tremor, significant reduction in X-ray–induced radiation, visualization in three dimensions, and significant improvement in ergonomics with significantly less pain, strain, and stiffness.[26,31,36,39,40,49,52,68] Other potential advantages could include the possibility of minimal muscle dissection, retraction, and bleeding.[28,34,49] The learning curve does not seem to be too steep as has been reported in performing radical nephrectomy using the Da Vinci system.[2]

There are of course several disadvantages to robotics in spine and these include the lack of haptic feedback

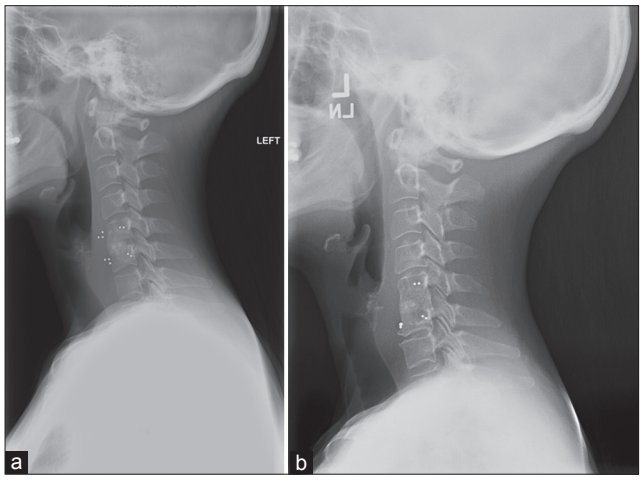

Figure 3: (a) Mystique resorbable plate (Medtronic, Memphis, TN, USA) immediate postoperative radiograph. (b) Mystique resorbable plate (Medtronic) 5 years postoperative

Figure 4: Da Vinci robotic system console (Intuitive Surgical Inc., Sunnyvale, CA, USA)

from tissue manipulation, increased operating time, and the need for increased training not just for the surgeon but also other operating room staff. There is also the issue of significant cost. The estimated cost of acquiring a Da Vinci system, for example, lies in the $1.1-$1.7 million range.[49] This does not include the additional costs of increased operating time, increased education, and additional funds needed to transform this particular platform into that applicable to spine. For example, this could include additional attachments such as bone drills and rongeurs. Despite the disadvantages, it appears clear that the future of spine surgery will have to include devices and tools that will increase patient safety, improve surgical outcomes, improve surgeon dexterity while reducing discomfort and do so in a seamless and expedient fashion.

In concert with robotics, spinal and neuro-navigational devices can be utilized. Many large hospitals offering complex spine surgery do not consider navigation a routine component of current treatment. Often, the reasons for this include the significant investment in cost, space, and the belief that its utility does not improve outcomes significantly over and above non-navigation techniques.

Although intraoperative navigation has been available for the past decade, it has evolved from plain fluoroscopy to 2D and then 3D fluoroscopy acquired intraoperatively and then co-registered with preoperative imaging.[22] Further development in navigation has led to the creation of an intraoperative CT scanner. The O-arm® (Medtronic, Inc., Louisville, CO, USA) is a CT scanner that permits imaging of the screws intraoperatively. In this system, a reference pin or anatomical landmark is co-registered with an acquired CT scan and is linked with a navigational software program.

A recent study compared navigated and non-navigated pedicle screws using the O-arm system and assessed their relative accuracy. The study found that 4.9% of the non-navigated screws needed to be removed intraoperatively compared with 0.6% of the navigated screws. It also reported that a "significant" medial breach, as defined by 50% excursion of the screw diameter, was almost 8 times more likely to occur without navigation. Image guidance leads to more accurate placement of pedicle screws.[61]

Overall, navigation appears to improve accuracy of surgical instrumentation while also significantly reducing radiation exposure. However, as with robotic-assisted platforms, it can be associated with increased operative time, risk of exposure to infection during draping and un-draping process, and the required learning for both surgical and non-surgical operating room staff. We predict that while it may add little benefit to routine surgical cases where bony anatomical landmarks are sufficient for placement of screws and instrumentation, its greatest application may be observed in cases with significant deformity or dysplastic changes in the spine. For example, it could be of benefit in scoliosis cases with significant rotational deformity of the spine and perhaps in the thoracic region where accuracy is critical.

SPINAL BIOLOGICS

Perhaps the most exciting area in the future treatment of spinal disorders is best witnessed in the development of biologically active agents used to augment and possibly restore the function of the spine. One of the first biologics to be approved in the United States was rhBMP-2 (Infuse, Medtronic). This powerful osteoinductive agent stimulates the production of bone and is utilized to augment fusion surgeries of the spine. Further development of the commercially available product has revolutionized the spine surgeon's ability to obtain a fusion mass in patients that may have problems achieving an adequate fusion. Another biologically active product that was approved by the United States FDA was rhBMP-7 or OP-1 (Stryker, Kalamazoo, MI, USA). This product also promotes bone growth and was marketed in a putty form compared to the absorbable sponge carrier utilized with Infuse. This adjuvant to achieving successful fusion has been documented in preclinical as well as clinical studies.[7,11,29,50,62-65] Over the past decade, surgeons have theorized the potential benefit of these biologics and their impact on the future of spinal surgery.[6,20] Although there are few biologics available for the spine surgeon to date, the future promises a number of products that may alter the way in which we practice. The concept of placing a biologically active agent in the intervertebral disc to help regenerate or stabilize the degenerative processes of aging has been theorized for decades.[16,30,58]

Studies have demonstrated the feasibility of placing these agents through minimally invasive procedures.[33] An and colleagues demonstrated that by placing osteogenic protein-1 via needle injection into a New Zealand white rabbit model, changes in the disc degeneration process were halted as evidenced by changes observed on MRI.[1] Of course, data gathered from animal models need to be evaluated for safety and efficacy in humans through the clinical trial process. It is the authors' belief that this type of preventative intervention may in fact reduce the number of spinal surgeries performed in the future.

As we progress through this decade, we must keep in mind that predicting the future of spine surgery may also be affected by the economic impact on healthcare that looms in the United States and throughout the world. It is conceivable that we will be asked to provide care for more individuals while possibly receiving less payment in return. This could greatly impact the amount of innovation and interest that has allowed our specialty to improve care

for our patients. It is also important that our leaders in innovation be allowed to work with industry in an open and honest collaboration in order to benefit our future patients.

REFERENCES

1. An HS, Takegami K, Kamada H, Nguyen CM, Thonar EJ, Singh K, *et al.* Intradiscal administration of osteogenic protein-1 increases intervertebral disc height and proteoglycan content in the nucleus pulposus in normal adolescent rabbits. Spine (Phila Pa 1976) 2005;30:25-31; discussion 31-2.
2. Artibani W, Fracalanza S, Cavalleri S, Iafrate M, Aragona M, Novara G, *et al.* Learning curve and preliminary experience with daVinci-assisted laparoscopic radical prostatectomy. Urol Int 2008;80:237-44.
3. Barzilay Y, Liebergall M, Fridlander A, Knoller N. Miniature robotic guidance for spine surgery-introduction of a novel system and analysis of challenges encountered during the clinical development phase at two spine centres. Int J Med Robot 2006;2:146-53.
4. Blumenthal S, McAfee PC, Guyer RD, Hochschuler SH, Geisler FH, Holt RT, *et al.* A prospective, randomized, multicenter Food and Drug Administration investigational device exemptions study of lumbar total disc replacement with the CHARITE artificial disc versus lumbar fusion: Part I: Evaluation of clinical outcomes. Spine (Phila Pa 1976) 2005;30:1565-75; discussion E387-91.
5. Blumenthal SL, Ohnmeiss DD, Guyer RD, Hochschuler SH. Prospective study evaluating total disc replacement: Preliminary results. J Spinal Disord Tech 2003;16:450-4.
6. Boden SD. Biology of lumbar spine fusion and use of bone graft substitutes: Present, future, and next generation. Tissue Eng 2000;6:383-99.
7. Brown A, Stock G, Patel AA, Okafor C, Vaccaro A. Osteogenic protein-1: A review of its utility in spinal applications. BioDrugs 2006;20:243-51.
8. Caspi I, Levinkopf M, Nerubay J. Results of lumbar disk prosthesis after a follow-up period of 48 months. Isr Med Assoc J 2003;5:9-11.
9. Cinotti G, David T, Postacchini F. Results of disc prosthesis after a minimum follow-up period of 2 years. Spine (Phila Pa 1976) 1996;21:995-1000.
10. Delamarter RB, Bae HW, Pradhan BB. Clinical results of ProDisc-II lumbar total disc replacement: Report from the United States clinical trial. Orthop Clin North Am 2005;36:301-13.
11. Delawi D, Dhert WJ, Rillardon L, Gay E, Prestamburgo D, Garcia-Fernandez C, *et al.* A prospective, randomized, controlled, multicenter study of osteogenic protein-1 in instrumented posterolateral fusions: Report on safety and feasibility. Spine (Phila Pa 1976) 2010;35:1185-91.
12. Devito DP, Kaplan L, Dietl R, Pfeiffer M, Horne D, Silberstein B, *et al.* Clinical acceptance and accuracy assessment of spinal implants guided with Spine Assist surgical robot: Retrospective study. Spine (Phila Pa 1976) 2010;35:2109-15.
13. Gaetani P, Tancioni F, Spanu G, Rodriguez y Baena R. Anterior cervical discectomy: An analysis on clinical long-term results in 153 cases. J Neurosurg Sci 1995;39:211-8.
14. Geisler FH, Blumenthal SL, Guyer RD, McAfee PC, Regan JJ, Johnson JP, *et al.* Neurological complications of lumbar artificial disc replacement and comparison of clinical results with those related to lumbar arthrodesis in the literature: Results of a multicenter, prospective, randomized investigational device exemption study of Charite intervertebral disc. Invited submission from the Joint Section Meeting on Disorders of the Spine and Peripheral Nerves, March 2004. J Neurosurg Spine 2004;1:143-54.
15. Geisler FH. The CHARITE Artificial Disc: Design history, FDA IDE study results, and surgical technique. Clin Neurosurg 2006;53:223-8.
16. Gruber HE, Hanley EN Jr. Recent advances in disc cell biology. Spine (Phila Pa 1976) 2003;28:186-93.
17. Guiot BH, Khoo LT, Fessler RG. A minimally invasive technique for decompression of the lumbar spine. Spine (Phila Pa 1976) 2002;27:432-8.
18. Guyer RD, McAfee PC, Banco RJ, Bitan FD, Cappuccino A, Geisler FH, *et al.* Prospective, randomized, multicenter Food and Drug Administration investigational device exemption study of lumbar total disc replacement with the CHARITE artificial disc versus lumbar fusion: Five-year follow-up. Spine J 2009;9:374-86.
19. Guyer RD, McAfee PC, Hochschuler SH, Blumenthal SL, Fedder IL, Ohnmeiss DD, *et al.* Prospective randomized study of the Charite artificial disc: Data from two investigational centers. Spine J 2004;4:252S-9S.
20. Helm GA, Alden TD, Sheehan JP, Kallmes D. Bone morphogenetic proteins and bone morphogenetic protein gene therapy in neurological surgery: A review. Neurosurgery 2000;46:p. 1213-22.
21. Hochschuler SH, Ohnmeiss DD, Guyer RD, Blumenthal SL. Artificial disc: Preliminary results of a prospective study in the United States. Eur Spine J 2002;11:S106-10.
22. Holly LT, Foley KT. Intraoperative spinal navigation. Spine (Phila Pa 1976) 2003;28:S54-61.
23. Hopf C, Heeckt H, Beske C. [Disc replacement with the SB Charite endoposthesis-experience, preliminary results and comments after 35 prospectively performed operations]. Z Orthop Ihre Grenzgeb 2002;140:485-91.
24. Hsieh PC, Koski TR, Sciubba DM, Moller DJ, O'Shaughnessy BA, Li KW, *et al.* Maximizing the potential of minimally invasive spine surgery in complex spinal disorders. Neurosurg Focus 2008;25:E19.
25. Isaacs RE, Hyde J, Goodrich JA, Rodgers WB, Phillips FM. A prospective, nonrandomized, multicenter evaluation of extreme lateral interbody fusion for the treatment of adult degenerative scoliosis: Perioperative outcomes and complications. Spine (Phila Pa 1976) 2010;35:S322-30.
26. Kantelhardt SR, Martinez R, Baerwinkel S, Burger R, Giese A, Rohde V. Perioperative course and accuracy of screw positioning in conventional, open robotic-guided and percutaneous robotic-guided, pedicle screw placement. Eur Spine J 2011;20:860-8.
27. Karikari IO, Isaacs RE. Minimally invasive transforaminal lumbar interbody fusion: A review of techniques and outcomes. Spine (Phila Pa 1976) 2010;35:S294-301.
28. Kim MJ, Ha Y, Yang MS, Yoon do H, Kim KN, Kim H, *et al.* Robot-assisted anterior lumbar interbody fusion (ALIF) using retroperitoneal approach. Acta Neurochir (Wien) 2010;152:675-9.
29. Leach J, Bittar RG. BMP-7 (OP-1) safety in anterior cervical fusion surgery. J Clin Neurosci 2009;16:1417-20.
30. Leckie AE, Akens MK, Woodhouse KA, Yee AJ, Whyne CM. Evaluation of thiol-modified hyaluronan and elastin-like polypetide composite augmentation in early-stage disc degeneration: Comparing two minimally invasive techniques. Spine (Phila Pa 1976) 2012;37:E1296-303.
31. Lee JY, Lega B, Bhowmick D, Newman JG, O'Malley BW Jr, Weinstein GS, *et al.* Da Vinci Robot-assisted transoral odontoidectomy for basilar invagination. ORL J Otorhinolaryngol Relat Spec 2010;72:91-5.
32. Lemaire JP, Carrier H, Sariali el-H, Skalli W, Lavaste F. Clinical and radiological outcomes with the Charite artificial disc: A 10-year minimum follow-up. J Spinal Disord Tech 2005;18:353-9.
33. Leung VY, Tam V, Chan D, Chan BP, Cheung KM. Tissue engineering for intervertebral disk degeneration. Orthop Clin North Am 2011;42:575-83, ix.
34. Lieberman IH, Togawa D, Kayanja MM, Reinhardt MK, Friedlander A, Knoller N, *et al.* Bone-mounted miniature robotic guidance for pedicle screw and translaminar facet screw placement: Part I-Technical development and a test case result. Neurosurgery 2006;59:641-50.
35. Lowe TG, Coe JD. Resorbable polymer implants in unilateral transforaminal lumbar interbody fusion. J Neurosurg 2002;97:464-7.
36. Matern U, Koneczny S. Safety, hazards and ergonomics in the operating room. Surg Endosc 2007;21:1965-9.
37. McAfee PC, Cunningham B, Holsapple G, Adams K, Blumenthal S, Guyer RD, *et al.* A prospective, randomized, multicenter Food and Drug Administration investigational device exemption study of lumbar total disc replacement with the CHARITE artificial disc versus lumbar fusion: Part II: Evaluation of radiographic outcomes and correlation of surgical technique accuracy with clinical outcomes. Spine (Phila Pa 1976) 2005;30:1576-83;discussion E388-90.
38. McAfee PC, Fedder IL, Saiedy S, Shucosky EM, Cunningham BW. SB Charite disc replacement: Report of 60 prospective randomized cases in a US center. J Spinal Disord Tech 2003;16:424-33.
39. Mirbod SM, Yoshida H, Miyamoto K, Miyashita K, Inaba R, Iwata H. Subjective complaints in orthopedists and general surgeons. Int Arch Occup Environ Health 1995;67:179-86.
40. Moskowitz RM, Young JL, Box GN, Paré LS, Clayman RV. Retroperitoneal transdiaphragmatic robotic-assisted laparoscopic resection of a left thoracolumbar neurofibroma. JSLS 2009;13:64-8.
41. O'Toole JE, Eichholz KM, Fessler RG. Minimally invasive insertion of

syringosubarachnoid shunt for posttraumatic syringomyelia: Technical case report. Neurosurgery 2007;61:E331-2;discussion E332.
42. Ogden AT, Fessler RG. Minimally invasive resection of intramedullary ependymoma: Case report. Neurosurgery 2009;65:E1203-4;discussion E1204.
43. Oskouian RJ, Whitehill R, Samii A, Shaffrey ME, Johnson JP, Shaffrey CI. The future of spinal arthroplasty: A biomaterial perspective. Neurosurg Focus 2004;17:E2.
44. Ozgur BM, Aryan HE, Pimenta L, Taylor WR. Extreme Lateral Interbody Fusion (XLIF): A novel surgical technique for anterior lumbar interbody fusion. Spine J 2006;6:435-43.
45. Ozgur BM, Yoo K, Rodriguez G, Taylor WR. Minimally-invasive technique for transforaminal lumbar interbody fusion (TLIF). Eur Spine J 2005;14:887-94.
46. Pechlivanis I, Kiriyanthan G, Engelhardt M, Scholz M, Lücke S, Harders A, *et al*. Percutaneous placement of pedicle screws in the lumbar spine using a bone mounted miniature robotic system: First experiences and accuracy of screw placement. Spine 2009;34:392-8.
47. Perez-Cruet MJ, Foley KT, Isaacs RE, Rice-Wyllie L, Wellington R, Smith MM, *et al*. Microendoscopic lumbar discectomy: Technical note. Neurosurgery 2002;51:S129-36.
48. Pimenta L, Oliveira L, Schaffa T, Coutinho E, Marchi L. Lumbar total disc replacement from an extreme lateral approach: Clinical experience with a minimum of 2 years' follow-up. J Neurosurg Spine 2011;14:38-45.
49. Ponnusamy K, Chewning S, Mohr C. Robotic approaches to the posterior spine. Spine (Phila Pa 1976) 2009;34:2104-9.
50. Rihn JA, Gates C, Glassman SD, Phillips FM, Schwender JD, Albert TJ. The use of bone morphogenetic protein in lumbar spine surgery. Instr Course Lect 2009;58:677-88.
51. Robbins MM, Vaccaro AR, Madigan L. The use of bioabsorbable implants in spine surgery. Neurosurg Focus 2004;16:E1.
52. Ruurda JP, Hanlo PW, Hennipman A, Broeders IA. Robot-assisted thoracoscopic resection of a benign mediastinal neurogenic tumor: Technical note. Neurosurgery 2003;52:462-4.
53. Sandhu FA, Santiago P, Fessler RG, Palmer S. Minimally invasive surgical treatment of lumbar synovial cysts. Neurosurgery 2004;54:107-11;discussion 111-2.
54. Sekhon LH, Duggal N, Lynch JJ, Haid RW, Heller JG, Riew KD, *et al*. Magnetic resonance imaging clarity of the Bryan, Prodisc-C, Prestige LP, and PCM cervical arthroplasty devices. Spine (Phila Pa 1976) 2007;32:673-80.
55. Tafazal SI, Sell PJ. Incidental durotomy in lumbar spine surgery: Incidence and management. Eur Spine J 2005;14:287-90.
56. Togawa D, Kayanja MM, Reinhardt MK, Shoham M, Balter A, Friedlander A, *et al*. Bone-mounted miniature robotic guidance for pedicle screw and translaminar facet screw placement: Part 2-Evaluation of system accuracy. Neurosurgery 2007;60:129-39.
57. Tormenti MJ, Maserati MB, Bonfield CM, Okonkwo DO, Kanter AS. Complications and radiographic correction in adult scoliosis following combined transpsoas extreme lateral interbody fusion and posterior pedicle screw instrumentation. Neurosurg Focus 2010;28:E7.
58. Tow BP, Hsu WK, Wang JC. Disc regeneration: A glimpse of the future. Clin Neurosurg 2007;54:122-8.
59. Tredway TL, Musleh W, Christie SD, Khavkin Y, Fessler RG, Curry DJ. A novel minimally invasive technique for spinal cord untethering. Neurosurgery 2007;60:ONS70-4;discussion ONS74.
60. Tredway TL, Santiago P, Hrubes MR, Song JK, Christie SD, Fessler RG. Minimally invasive resection of intradural-extramedullary spinal neoplasms. Neurosurgery 2006;58:ONS52-8;discussion ONS52-8.
61. Ughwanogho E, Patel NM, Baldwin KD, Sampson NR, Flynn JM. Computed tomography-guided navigation of thoracic pedicle screws for adolescent idiopathic scoliosis results in more accurate placement and less screw removal. Spine (Phila Pa 1976) 2012;37:E473-8.
62. Vaccaro AR, Anderson DG, Patel T, Fischgrund J, Truumees E, Herkowitz HN, *et al*. Comparison of OP-1 Putty (rhBMP-7) to iliac crest autograft for posterolateral lumbar arthrodesis: A minimum 2-year follow-up pilot study. Spine (Phila Pa 1976) 2005;30:2709-16.
63. Vaccaro AR, Lawrence JP, Patel T, Katz LD, Anderson DG, Fischgrund JS, *et al*. The safety and efficacy of OP-1 (rhBMP-7) as a replacement for iliac crest autograft in posterolateral lumbar arthrodesis: A long-term (>4 years) pivotal study. Spine (Phila Pa 1976) 2008;33:2850-62.
64. Vaccaro AR, Patel T, Fischgrund J, Anderson DG, Truumees E, Herkowitz HN, *et al*. A pilot study evaluating the safety and efficacy of OP-1 Putty (rhBMP-7) as a replacement for iliac crest autograft in posterolateral lumbar arthrodesis for degenerative spondylolisthesis. Spine (Phila Pa 1976) 2004;29:1885-92.
65. Vaccaro AR, Patel T, Fischgrund J, Anderson DG, Truumees E, Herkowitz H, *et al*. A 2-year follow-up pilot study evaluating the safety and efficacy of op-1 putty (rhbmp-7) as an adjunct to iliac crest autograft in posterolateral lumbar fusions. Eur Spine J 2005;14:623-9.
66. Wang JC, McDonough PW, Kanim LE, Endow KK, Delamarter RB. Increased fusion rates with cervical plating for three-level anterior cervical discectomy and fusion. Spine (Phila Pa 1976) 2001;26:643-6;discussion 646-7.
67. Yang MS, Kim KN, Yoon do H, Pennant W, Ha Y. Robot-assisted resection of paraspinal Schwannoma. J Korean Med Sci 2011;26:150-3.
68. Yang MS, Yoon do H, Kim KN, Kim H, Yang JW, Yi S, *et al*. Robot-assisted anterior lumbar interbody fusion in a Swine model *in vivo* test of the da vinci surgical-assisted spinal surgery system. Spine (Phila Pa 1976) 2011;36:E139-43.
69. Zeegers WS, Bohnen LM, Laaper M, Verhaegen MJ. Artificial disc replacement with the modular type SB Charite III: 2-year results in 50 prospectively studied patients. Eur Spine J 1999;8:210-7.
70. Zigler JE, Burd TA, Vialle EN, Sachs BL, Rashbaum RF, Ohnmeiss DD. Lumbar spine arthroplasty: Early results using the ProDisc II: A prospective randomized trial of arthroplasty versus fusion. J Spinal Disord Tech 2003;16:352-61.
71. Zigler JE. Clinical results with ProDisc: European experience and U.S. investigation device exemption study. Spine (Phila Pa 1976) 2003;28:S163-6.