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Original Article

Comparison of pullout strength of the thoracic pedicle screw between intrapedicular and extrapedicular technique: a meta-analysis and literature review

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Abstract: Background: Intrapedicular fixation in thoracic spine is often limited, because of high risk of complication, especially in scoliosis patients. Extrapedicular screws fixation techniques provide an alternate solution for extremely small or abnormal thoracic pedicles deformity. However, the pullout resistance of extrapedicular screws has not been clearly defined. The aim of our study was to systematically review the existing evidence regarding the pullout resistance of thoracic extrapedicular screws compared with intrapedicular screws. Methods: A systematic search of all studies published through Nov 2014 was performed using Medline, EMBASE, OVID and other databases. All studies that compared the pullout resistance of thoracic extrapedicular screws with intrapedicular screws were selected. The data from the included studies were extracted and analyzed regarding pullout resistance force. Forest plots were constructed to summarize the data and compare the biomechanical stability achieved. Results: Five studies were included, with a total of 27 cadaveric specimens and 313 screws. The vertebral levels of the cadavers potted were T1-T8, T2-T12, T7-T9, T6-T11 and T4-T12 respectively. Overall, the results demonstrated that there was no significant difference in ultimate pullout strength between intrapedicular screws and extrapedicular screws (95% CI=-63.73 to 27.74; P=0.44); extrapedicular screws significantly increased the length of placements by a mean of 6.24 mm (95% CI=5.38 to 7.10; P<0.001); while the stiffness in intrapedicular screws was significantly stronger by a mean of 45.82 N/mm compared with extrapedicular screws (95% CI=-70.09 to -21.56; P<0.001). Conclusions: Meta-analysis of the existing literature showed that thoracic extrapedicular screws provided comparable but slightly lower pullout strength compared with intrapedicular screws, extrapedicular screws placement is much safer than intrapedicular screws. So thoracic extrapedicular screws offer a good alternative when it is hard to insert by intrapedicular approach, especially in scoliosis patients with severe vertebral deformities.

Keywords: Thoracic spine, intrapedicular screw, extrapedicular screw, biomechanics, meta-analysis

Introduction

In 1969, Harrington et al [1] showed their first use of pedicle screw through isthmus of the pedicle, which was a revolutionary change in the science of spinal surgery. Since then, pedicle screw fixation was widely accepted as an effective way of rigid fixation in spine, especially for the surgical treatment of scoliosis and spinal deformity [2]. It has been demonstrated that in comparison to hooks or wires, pedicle screws fixation could achieve better scoliosis correction, less failure rate, and shorter fusion levels [3]. However, when pedicle screws are used in the thoracic spine, attention should be paid to minimize complications, because anatomical and clinical work demonstrated potential complications, such as vascular, neural, spinal cord and viscous injury. Vaccaro [4] demonstrated that T4 toT8 are the narrowest segment with mean pedicular transverse diameter less than 5 mm. Besides, secondary deformities like scoliosis can make an intrapedicular screw placement almost impossible [5]. In severely rotated scoliotic spine, the extremely small thoracic pedicle diameter is less than 2 mm. As a result, pedicle perforation occurs commonly in the thoracic spine. In

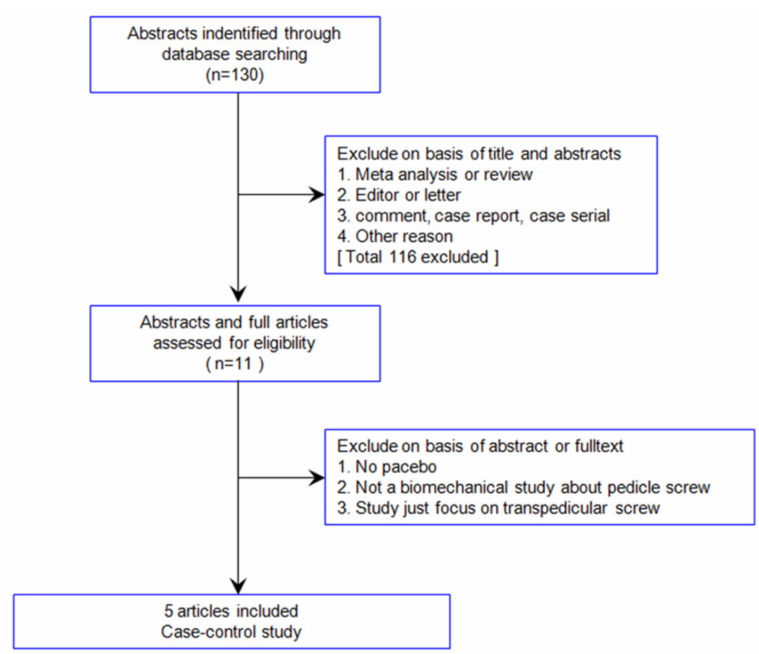

Figure 1. Summary of the article selection and exclusion process.

another fresh cadavers study, Vaccaro [6] demonstrated 41% screws placed outside the boundaries of the pedicle, several other studies also reported pedicle perforations rate is 25% to 55% [7], which indicated intrapedicular fixation in thoracic spine is limited, and degree of error is often high.

In order to overcome the defect and complications associated with screw misplacement and iatrogenic fracture of pedicles in intrapedicular approach, Dvorak et al [8] presented a novel extrapedicular screw fixation technique in thoracic spine, and some biomechanical and cadaveric studies have demonstrated its feasibility [9-11]. Extrapedicular screw fixation techniques provide an alternate solution for extremely small or abnormal thoracic pedicles. Thanks to the direction of extrapedicular screw, the risk of the spinal cord or nerve root injury is assumed as minimal [11].

So generally, the extrapedicular technique provides the advantage of increased distance to the neural canal, reduced risk for neurological complications, but the reports of biomechanical advantages of extrapedicular screw are controversial. A current overview of the evidence for the biomechanical strength on extrapedicular and intrapedicular screws is lacking. This systemic review aimed to compare the pullout resistance of intra- and extrapedicular thoracic pedicle screws on in vitro data from the literature.

Material and methods

Study design

A meta-analysis was conducted according to the predefined guidelines provided by the Cochrane Collaboration. All the data were reported according to the Handbook for Systematic Reviews of Interventions (Version 5.0.0) [12].

Search strategy

A computerized search of electronic databases was conducted, including the Cochrane Central Register of Controlled Trials, PubMed, EMBASE, ISI Web of Knowledge, ScienceDirect and Google Scholar for studies published through the end of Nov 2014. Following key terms were used to maximize search specificity and sensitivity: extrapedicular, intrapedicular, screw, biomechanical, or pullout strength. The search strategy, encompassing studies conducted in humans and written in the English language is presented in **Figure 1**. Secondary searches for additional relevant studies, such as those of the European Federation of National Associations of Orthopedics and the British Orthopedic Association Annual Congress, as well as conference proceedings until the end of Nov. 2014, were also performed along with reference searches of the included articles to identify any additional studies that were not previously identified in the initial literature search.

Inclusion and exclusion criteria

The studies that met the following criteria were included: (1) the study evaluated the pull-out strength of intrapedicular and extrapedicular screws; (2) the study was an in-vitro biomechanical study; and (3) the study provided sufficient raw data for the weighted mean difference (WMD) with 95% confidence intervals (CI). Articles were excluded from our meta-analysis if they were duplicate publications or did not contain raw or usable data.

Table 1. The demographic characteristics of the included studies

Reference	Country	Carveric No.	Location	Age (year)	Screw No.	Screw properties	Year
Dvorak M [25]	Canada	6	Thoracic T2-T12	Adult No exact age		No exact screw properties	1993
Extrapedicular					51	The intrapedicular screw in one pedicle and the extrapedicular screw on the opposite side.	
Intrapedicular					51		
Fu CF [26]	China	5	Thoracic T1-T8	Mean 44 (28-49)		The extrapedicular screw was 10 mm longer than the pedicle screw for the same vertebral, but the diameter was the same.	2006
Extrapedicular (Gourp 1)					21		
Extrapedicular (Group 2)					19	The intrapedicular screw in one pedicle and the extrapedicular screw on the opposite side.	
Intrapedicular					40		
White KK [27]	CA	6	Thoracic T4-T12	Mean 62 (54-71)		Screw length was customized to each vertebral body, more 45 mm screws were used for extrapedicular screw.	2006
Extrapedicular					36	Polyaxial 5.0 mm (Moss-Miami, Depuy Spine).	
Intrapedicular					37	The intrapedicular screw in left pedicle and the extrapedicular screw on the right side.	
Yüksel KZ [28]	USA	4	Thoracic T6–T11	Mean 29.5 (22-44)		Monoaxial tapered pedicle screws (4.5 mm diameter; Xia Spinal System).	2007
Extrapedicular					11	The intrapedicular screw in one pedicle and the extrapedicular screw on the opposite side.	
Intrapedicular					11		
Fürderer S [29]	Germany	6	Thoracic T7-T9	60-96		Length of 50 mm and diameter of 6 mm (Advanced Medical Technologies).	2011
Extrapedicular (Gourp 1)					12	The intrapedicular and extrapedicular screw insertion techniques were tested unilaterally	
Extrapedicular (Group 2)					12		
Intrapedicular					12		

Study or Subgroup	Extrapedicular Mean	SD	Total	Transpedicular Mean	SD	Total	Weight	Mean Difference IV, Fixed, 95% CI
Dvorak 1993	679.4	243.8	51	392.4	226.7	51	25.1%	287.00 [195.63, 378.37]
Fu 2006	827.01	260	19	1,001.23	220	40	11.4%	-174.22 [-309.56, -38.88]
Fu 2006	954.25	254	21	1,001.23	220	40	12.7%	-46.98 [-175.24, 81.28]
Fürderer 2011	268.3	130	12	400	140	12	17.9%	-131.70 [-239.79, -23.61]
Fürderer 2011	368.3	145	12	400	140	12	16.1%	-31.70 [-145.74, 82.34]
White 2006	638	250	36	845	325	37	11.9%	-207.00 [-339.80, -74.20]
Yüksel 2007	715	272	11	932	215	11	5.0%	-217.00 [-421.89, -12.11]
Total (95% CI)			**162**			**203**	**100.0%**	**-17.99 [-63.73, 27.74]**

Heterogeneity: Chi² = 63.83, df = 6 (P < 0.00001); I² = 91%
Test for overall effect: Z = 0.77 (P = 0.44)

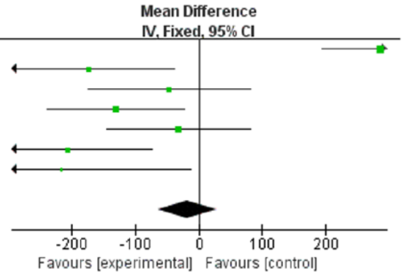

Figure 2. Forest plot and tabulated data illustrating the mean difference (MD) in the pullout resistance force between intrapedicular screw and extrapedicular screw group, showing that there was no significant difference in ultimate pullout strength between intrapedicular screw and extrapedicular screw.

Data extraction

Two authors (Hua Wang and Huafeng Wang) independently reviewed the titles and abstracts related to the inclusion criteria. Full-text article reviews were performed for final inclusion into the study. Any discrepancy between these reviewers was resolved by discussion with a third author (Zhaomin Zheng). Two authors (Hua Wang and Huafeng Wang) independently extracted the following data: study demographic data, type of screw fixation, screw length, pull-out strength, the relationship between BMD and pull-out strength. All the extracted data were reassessed by a third author.

Data analysis

Meta-analysis of the data was performed using the inverse-variance procedure by RevMan Version 5.1 (The Cochrane Collaboration, Copenhagen, Denmark). For continuous outcomes such as pullout strength, the means ± standard deviations were pooled to a mean difference (MD) and 95% CI. For dichotomous outcomes, the risk ratio (RR) and 95% CI were applied. A probability of P<0.05 was regarded as statistically significant. The assessment for statistical heterogeneity was assessed using the chi-square and I-square tests. A *P*-value <0.1 and an I-square value >50% were considered suggestive of statistical heterogeneity. Sensitivity analysis was performed by rejecting the study with higher statistical heterogeneity.

Results

Search results

A total of 134 citations were reviewed. All the articles were strictly selected according to the criteria described above. Of the 134 reviewed articles, 5 studies [8-10, 13, 14] met the inclusion criteria (**Table 1**). Fixation procedures were performed on 27 cadaveric specimens with 313 screws. The vertebral levels of the cadavers potted were T1-T8, T2-T12, T7-T9, T6-T11 and T4-T12 respectively. They all performed biomechanical human cadaver investigation of the intrapedicular and extrapedicular techniques. The study selection process and reasons for exclusion are summarized in **Figure 1**.

Pullout resistance force

The mean ultimate pullout strength of intrapedicular and extrapedicular screws was evaluated in 5 studies, in which 151 intrapedicular screws and 162 extrapedicular screws were compared. The pullout strength was defined as the maximum force followed by a loss of resistance of at least 20% of the maximum force. The pooled WMD for all screws was calculated, and the data demonstrated that there was no significant difference in ultimate pullout strength between intrapedicular and extrapedicular screws (95% CI=-63.73 to 27.74; P=-0.44), with significant heterogeneity observed (P<0.001; I^2=91%), while the pullout strength of intrapedicular screws was slightly higher than extrapedicular screws (**Figure 2**).

Screw length

The length of intrapedicular and extrapedicular screws was provided in 2 studies. The pooled WMD for all screws was calculated, and the data demonstrated that extrapedicular screws significantly increased the length of placements by a mean of 6.24 mm (95% CI=5.38 to 7.10; P<0.001), with significant heterogeneity (P<0.001; I^2=99%) (**Figure 3**). The orientation and diameter of the screw also influence the pull-out strength, however due to not enough

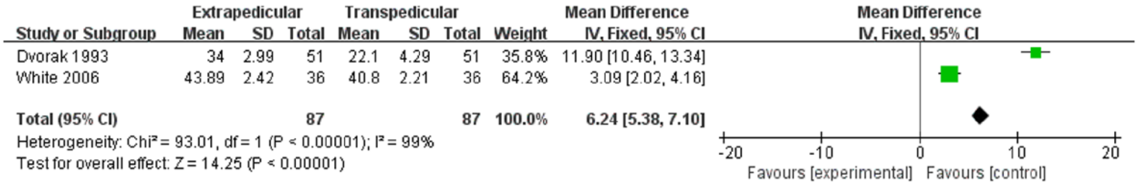

Figure 3. Forest plot and tabulated data illustrating the MD in the screw length between the intrapedicular and extrapedicular screw group, showing that extrapedicular screws significantly increased the length of placements by a mean of 6.24 mm.

data presented in the included studies, we were unable to do the analysis.

BMD and pullout strength

The correlation between BMD and pullout strength was available in 3 studies. Dvorak et al [8] showed strong correlation between BMD and pullout strength in extrapedicular group (r=0.497; P<0.001); Yuksel et al [9] also showed that pullout strength of extrapedicular screws correlated strongly with BMD (r=0.778; P=0.005); Furderer et al [15] got weak correlation between BMD and pullout strength of extrapedicular screws with r=0.33. While there was no significant correlation between BMD and the pullout strength of intrapedicular screws in Yuksel et al [9] (r=-0.063) and Furderer et al [15] (r=0.28) studies, weak correlation between BMD and pullout strength of intrapedicular screws in Dvorak et al [8] (r=0.205, P<0.005). However, as we cannot get the 95% CI from these studies, so unable to make a meta-analysis in this filed (**Table 2**).

Screw stiffness

Data of screw stiffness were available on intrapedicular and extrapedicular screws in 2 studies encompassing 95 screws. The pooled results indicated that the mean stiffness in intrapedicular screws was significantly stronger by a mean of 45.82 N/mm compared with extrapedicular screws (95% CI=-70.09 to -21.56; P<0.001) (**Figure 4**).

Discussion

Several studies have demonstrated the safety- and efficiency of lumbar screw placement in both pediatric and adult scoliosis deformities [16]. Lenke et al [17] claimed that pedicle screw fixation is the state of art in spinal deformity correction. However, their patients were mostly adults and most of the screws were placed in the lower thoracic spine. Several anatomic studies reported mid orupper thoracic pedicles are much smaller than lumbar pedicle [4, 6, 18, 19]. Particularly, the extremely small pedicles diameter is less than 2 mm in children [20]. In severely rotated spine, the adjacent spinal cord and major soft tissues or organs such as the aorta, esophagus or lungs makes mid and upper thoracic intrapedicular placement at risk [6]. Studies reported the perforation rate of thoracic pedicle screws to be 25% to 55% [21]. Thus, intrapedicular fixation in mid and upper thoracic segments is often limited.

As an alternative to conventional screw placement, Dvorak et al [8] first described an extrapedicular technique almost a decade ago. The Morphometric studies showed that the pedicle-rib unit was significantly larger than pedicle at all thoracic levels [22, 23]. Lilje nqvist et al [24] confirmed that while the pedicles were rather small on their concave side of scoliotic spine, the dimension of pedicle-rib units were much greater than pedicle. According to the morphometric anatomy, the potential benefits of extrapedicular screw technique include increased safety of neural tissue structures and enhanced stability at the bone screw interface, compared with intrapedicular screw technique.

With regard to the stability and strength of the extrapedicular screw technique, many studies have focused on the comparison of biomechanics of extrapedicular screw system with intrapedicular screw, especially on pull out strength. Dvorak et al [8] showed extrapedicular screws achieved good 3-dimensional stability which was comparable or even superior to intrapedicular screw fixation, followed by Morgenstern et al [25] who also found similar result. Fürderer et al [15] tested intrapedicular and two different extrapedicular techniques in thoracic screw fixation in vitro, and they found no significant differences in the pullout resistance forces of intrapedicular and extrapedicular thoracic

Table 2. The relationship between pullout strength and BMD

Reference	Carveric No.	Location	BMD Measure	BMD	Correlation coefficient	*P* value
Dvorak M [25]	6	Thoracic T2-T12	BMD was estimated by measuring the cancellous bone density utilizing 4 mm cuts and a standard area of 1.56 square centimeters of cancellous vertebral body bone. Three vertebral for each cadaver, and got average value.	Not mention		
Extrapedicular					0.497	<0.001
Intrapedicular					0.205	<0.005
Yüksel KZ [28]	4	Thoracic T6-T11	BMD was determined from lateral dual energy Xray absorptiometry using a clinical scanner, XR-36, Norland medical systems, Inc.	Not mention		
Extrapedicular					0.778	0.005
Intrapedicular					-0.063	0.85
Fürderer S [29]	6	Thoracic T7-T9	BMD was determined using quantitative computed tomography HA method using a spiral CT scanner, MX8000 IDT, Philips.	Not mention		Not mention
Extrapedicular (Gourp 1)					0.33	
Extrapedicular (Group 2)					-0.03	
Intrapedicular					0.28	

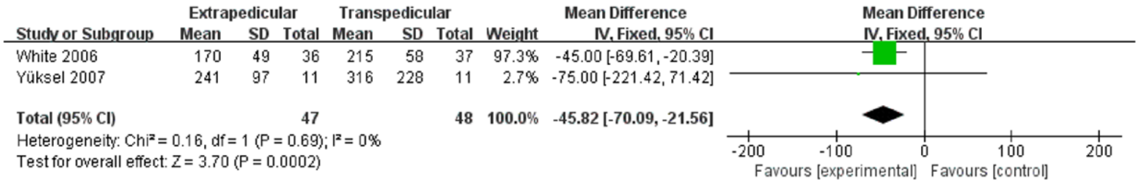

Figure 4. Forest plot and tabulated data illustrating the screw stiffness between the intrapedicular and extrapedicular screw group, showing that the mean stiffness in intrapedicular screws was significantly stronger by a mean of 45.82 N/mm compared with extrapedicular screws.

screw fixation. White [10], Yuksel [9] and Fu et al [13] showed slightly lower pullout resistance force and sagittal load resistance of extrapedicular screws compared with intrapedicular screws, but with little difference. In our knowledge, the present study is the first comprehensive meta-analysis combining data from 5 cohort studies on the biomechanical strength between intrapedicular and extrapedicular screws technique. The overall results from this meta-analysis suggest no significant difference in the pullout resistance forces of intrapedicular and extrapedicular thoracic screw fixation system.

In term of the correlation between extrapedicular screw and BMD, two studies found strong correlation between pullout strength and BMD in extrapedicular group (r=0.778 and r=0.497), one showed weak correlation (r=0.33), while another two didn't test the correlation. However, no correlation between BMD and intrapedicular screw placement were reported. Traditionally intrapedicular screws depend on the fixation in cancellous bone of the pedicle and vertebral body [26]. While extrapedicular screws penetrated up to 3 or 4 cortices as well as engaging the vertebral body cancellous bone, so it is more likely to be influenced by the BMD of the vertebrae. The possible reason for different result of extrapedicular and intrapedicular screws may be due to the possible difference in BMD within the pedicle and vertebral bodies [27].

As for the absolute value of pullout strength, Fu et al [13] and Yüksel et al [9] reported a pullout resistance much greater than other studies, which may due to the influence of BMD. Because the mean age of their cadaveric specimen was 44 and 29.5 years respectively, their cadavers' BMD is much higher than others. Take along the fact which was confirmed by several studies that BMD is the most significant predictor of the pullout strength [28]. It is not difficult to understand the pullout resistance reported by Fu et al [13] and Yüksel et al [9] is higher than the others.

It was well acknowledged that both screw diameter and length influenced the strength of screw fixation [29], and a larger diameter screw decreases the risk of screw breakage. The extrapedicular screw technique allows the use of a larger diameter screw irrelevant to the size of pedicle, and a screw up to 50% longer than intrapedicular pedicle screw. In this meta-analysis we found that extrapedicular screws significantly increased the length of placements by a mean of 6.24 mm. White et al [10], Yüksel et al [9] and Fu et al [13] used longer screws in extrapedicular technique than intrapedicular fixation, Fürderer S et al [15] used the same screw in each group. None of them reported the larger diameter screw in extrapedicular group.

There was a high prevalence of heterogeneity in this meta-analysis, which may be the result of small number of specimen in the included studies. Other limitation including the range of databases by language selection, publications biased towards positive results, different theoretical in vitro models. Standardized methods in cadaveric models of intrapedicular and extrapedicular screws implacement may help reduce statistical confidence intervals and provide more convincing results.

Conclusions

Our meta-analysis and systematic review of literatures revealed that thoracic extrapedicular screws provided comparable but slightly lower pullout strength compared with intrapedicular screws. So thoracic extrapedicular screws offer a good alternative when it is hard to insert by intrapedicular approach. Additional biomechanical and clinical studies are needed to compare the effect of thoracic extrapedicular screws, and also to confirm the advantages of thoracic extrapedicular screws.

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Disclosure of conflict of interest

None.

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References

[1] Harrington PR and Tullos HS. Reduction of severe spondylolisthesis in children. South Med J 1969; 62: 1-7.
[2] Halm H, Niemeyer T, Link T and Liljenqvist U. Segmental pedicle screw instrumentation in idiopathic thoracolumbar and lumbar scoliosis. Eur Spine J 2000; 9: 191-197.
[3] Delorme S, Labelle H, Aubin CE, de Guise JA, Rivard CH, Poitras B and Dansereau J. A three-dimensional radiographic comparison of Cotrel-Dubousset and Colorado instrumentations for the correction of idiopathic scoliosis. Spine (Phila Pa 1976) 2000; 25: 205-210.
[4] Vaccaro AR, Rizzolo SJ, Allardyce TJ, Ramsey M, Salvo J, Balderston RA and Cotler JM. Placement of pedicle screws in the thoracic spine. Part I: Morphometric analysis of the thoracic vertebrae. J Bone Joint Surg Am 1995; 77: 1193-1199.
[5] Parent S, Labelle H, Skalli W, Latimer B and de Guise J. Morphometric analysis of anatomic scoliotic specimens. Spine (Phila Pa 1976) 2002; 27: 2305-2311.
[6] Vaccaro AR, Rizzolo SJ, Balderston RA, Allardyce TJ, Garfin SR, Dolinskas C and An HS. Placement of pedicle screws in the thoracic spine. Part II: An anatomical and radiographic assessment. J Bone Joint Surg Am 1995; 77: 1200-1206.
[7] Lonstein JE, Denis F, Perra JH, Pinto MR, Smith MD and Winter RB. Complications associated with pedicle screws. J Bone Joint Surg Am 1999; 81: 1519-1528.
[8] Dvorak M, MacDonald S, Gurr KR, Bailey SI and Haddad RG. An anatomic, radiographic, and biomechanical assessment of extrapedicular screw fixation in the thoracic spine. Spine (Phila Pa 1976) 1993; 18: 1689-1694.
[9] Yuksel KZ, Adams MS, Chamberlain RH, Potocnjak M, Park SC, Sonntag VK and Crawford NR. Pullout resistance of thoracic extrapedicular screws used as a salvage procedure. Spine J 2007; 7: 286-291.
[10] White KK, Oka R, Mahar AT, Lowry A and Garfin SR. Pullout strength of thoracic pedicle screw instrumentation: comparison of the transpedicular and extrapedicular techniques. Spine (Phila Pa 1976) 2006; 31: E355-358.
[11] Husted DS, Yue JJ, Fairchild TA and Haims AH. An extrapedicular approach to the placement of screws in the thoracic spine: an anatomic and radiographic assessment. Spine (Phila Pa 1976) 2003; 28: 2324-2330.
[12] Moher D, Cook DJ, Eastwood S, Olkin I, Rennie D and Stroup DF. [Improving the quality of reports of meta-analyses of randomized controlled trials: the QUOROM Statement]. Rev Esp Salud Publica 2000; 74: 107-118.
[13] Fu CF, Liu Y, Zhang SK and Song ZM. Biomechanical study on pullout strength of thoracic extrapedicular screw fixation. Chin J Traumatol 2006; 9: 374-376.
[14] Fuerderer S, Vonhoegen J, Coenen O, Michael J, Koebke J and Eysel P. In vitro comparison of the pullout strength of 3 anterior double-screw fixation techniques with different screw angulations. J Neurosurg Spine 2011; 14: 367-371.
[15] Furderer S, Scholten N, Coenen O, Koebke J and Eysel P. In-vitro comparison of the pullout strength of 3 different thoracic screw fixation techniques. J Spinal Disord Tech 2011; 24: E6-10.
[16] Brown CA, Lenke LG, Bridwell KH, Geideman WM, Hasan SA and Blanke K. Complications of pediatric thoracolumbar and lumbar pedicle screws. Spine (Phila Pa 1976) 1998; 23: 1566-1571.
[17] Lenke LG, Kuklo TR, Ondra S and Polly DW Jr. Rationale behind the current state-of-the-art treatment of scoliosis (in the pedicle screw era). Spine (Phila Pa 1976) 2008; 33: 1051-1054.
[18] Berry JL, Moran JM, Berg WS and Steffee AD. A morphometric study of human lumbar and selected thoracic vertebrae. Spine (Phila Pa 1976) 1987; 12: 362-367.
[19] Zindrick MR, Wiltse LL, Doornik A, Widell EH, Knight GW, Patwardhan AG, Thomas JC, Rothman SL and Fields BT. Analysis of the mor-

phometric characteristics of the thoracic and lumbar pedicles. Spine (Phila Pa 1976) 1987; 12: 160-166.
[20] Krag MH. Biomechanics of thoracolumbar spinal fixation. A review. Spine (Phila Pa 1976) 1991; 16: S84-99.
[21] Xu R, Ebraheim NA, Ou Y and Yeasting RA. Anatomic considerations of pedicle screw placement in the thoracic spine. Roy-Camille technique versus open-lamina technique. Spine (Phila Pa 1976) 1998; 23: 1065-1068.
[22] O'Brien MF, Lenke LG, Mardjetko S, Lowe TG, Kong Y, Eck K and Smith D. Pedicle morphology in thoracic adolescent idiopathic scoliosis: is pedicle fixation an anatomically viable technique? Spine (Phila Pa 1976) 2000; 25: 2285-2293.
[23] Husted DS, Haims AH, Fairchild TA, Kershaw TS and Yue JJ. Morphometric comparison of the pedicle rib unit to pedicles in the thoracic spine. Spine (Phila Pa 1976) 2004; 29: 139-146.
[24] Liljenqvist UR, Allkemper T, Hackenberg L, Link TM, Steinbeck J and Halm HF. Analysis of vertebral morphology in idiopathic scoliosis with use of magnetic resonance imaging and multiplanar reconstruction. J Bone Joint Surg Am 2002; 84-A: 359-368.
[25] Morgenstern W, Ferguson SJ, Berey S, Orr TE and Nolte LP. Posterior thoracic extrapedicular fixation: a biomechanical study. Spine (Phila Pa 1976) 2003; 28: 1829-1835.
[26] Roy-Camille R SG, Berteaux D, et al. Early management of spinal injuries, recent advances in orthopaedics. New York: Churchill Livingstone; 1979.
[27] Inceoglu S, Burghardt A, Akbay A, Majumdar S and McLain RF. Trabecular architecture of lumbar vertebral pedicle. Spine (Phila Pa 1976) 2005; 30: 1485-1490.
[28] Reitman CA, Nguyen L and Fogel GR. Biomechanical evaluation of relationship of screw pullout strength, insertional torque, and bone mineral density in the cervical spine. J Spinal Disord Tech 2004; 17: 306-311.
[29] Krag MH, Weaver DL, Beynnon BD and Haugh LD. Morphometry of the thoracic and lumbar spine related to transpedicular screw placement for surgical spinal fixation. Spine (Phila Pa 1976) 1988; 13: 27-32.