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Biomechanics of posterior instrumentation in L1–L3 lateral interbody fusion: Pedicle screw rod construct vs. transfacet pedicle screws

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ABSTRACT

Background: The use of pedicle screws is the gold standard for supplemental posterior fixation in lateral interbody fusion. Information about the performance of transfacet pedicle screws compared to standard pedicle screws and rods in the upper lumbar spine with or without a lateral interbody fusion device in place is limited.

Methods: Fifteen fresh frozen human cadaveric lumbar spine segments (T12-L4) were studied using standard pure moment flexibility tests. Specimens were divided into two groups to receive either bilateral transfacet pedicle screws ($n = 8$) or bilateral pedicle screws ($n = 14$). Stability of each motion segment (L1–L2 and L2–L3) was evaluated intact, with posterior instrumentation with an intact disc, with posterior instrumentation and a lateral interbody fusion device in place, and following cyclic loading with the interbody device and posterior instrumentation still in place. Both raw values of motion (range of motion, lax zone and stiff zone) and normalized mobility (ratios to intact) were analyzed for each case.

Findings: In terms of immediate stability, transfacet pedicle screws performed equivalent to similarly sized pedicle screws, both with intact disc and with lateral interbody fusion device in all directions of loading. Stability following cyclic loading decreased significantly during lateral bending and axial rotation.

Interpretation: Posterior fixation with transfacet pedicle screws provides equivalent immediate stability to similarly sized pedicle screws. However, in the presence of a lateral interbody fusion device, pedicle screws seem to resist loosening more and may be a better option for fusion in the upper lumbar spine.

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1. Introduction

Lateral interbody fusion has become popular because it avoids many of the disadvantages of direct anterior lumbar interbody fusion techniques (blood vessel injury, neurological deficits and dural injury) (Phan et al., 2015; Richter et al., 2015) and provides space for a large cage spanning the endplate for greater stability (Ozgur et al., 2006). However, experience with anterior standalone interbody lumbar fusion (BAK cage) has shown a high incidence of subsidence and pseudoarthrosis (Beutler and Peppelman, 2003; Chen et al., 2003). Therefore supplemental posterior fixation is suggested for interbody approaches and has been shown to improve fusion rates (Fritzell et al., 2002).

Pedicle screws are the gold standard for posterior fixation even though the first lumbar fixation was described in 1948 using facet screws (King, 1948). Transfacet pedicle screws (TFPS) and pedicle screws rods (PSR) have been demonstrated to have biomechanically similar stability at L1–L2 and L3–L4 after repetitive loading in flexion, with an interbody device in place (Ferrara et al., 2003). Also, biomechanical comparison of translaminar facet screws, TFPS, and PSR with anterior lumbar interbody fusion has demonstrated similar initial posterior stabilization (Beaubien et al., 2004). However, these previous studies used older style facet screws without the large washer head utilized by modern facet screws. Additionally, no direct comparisons were made between TFPS and PSR fixation with an intact disc, or in the setting of a lateral cage following cyclic loading in directions of loading other than flexion. We have found only one recent biomechanical study comparing lateral lumbar interbody used in the setting of either facet screws or pedicle screws for posterior fixation (Kretzer et al., 2013), but these scenarios were not compared with the native disc nor did they consider the effects of cyclic loading.

The objectives of this study were to characterize the biomechanics of L1–L2 and L2–L3 lumbar motion segments instrumented with TFPS fixation (Fig. 1A) or PSR fixation (Fig. 1B), with or without a lateral interbody cage, and to see which posterior instrumentation type would provide better stability following cyclic loading in all directions of movement.

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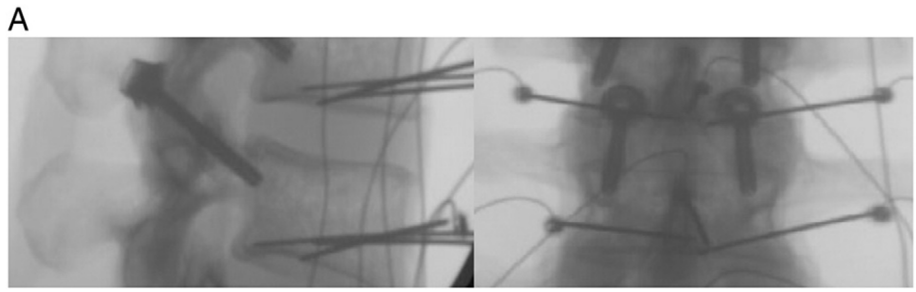

Fig. 1A. X-rays (lateral and A/P views) showing spines instrumented with bilateral TFPS (before SLIFT) at L2–L3.

2. Methods

2.1. Specimen preparation

Fifteen fresh human cadaveric lumbar spine segments (T12-L4) were included. The mean donor age was 54.1(SD 10.6) years, and there were 5 males and 10 females. Dual energy x-ray absorptiometry (DEXA) scans were performed on the L4 vertebra of each specimen to assess bone mineral density (BMD), to ensure that specimens were divided into equivalent groups, and that no specimens were osteoporotic (Table 1). Specimens were carefully cleaned of muscular tissue while keeping all of the ligaments, the joint capsules, and the discs intact. For testing, the L4 vertebra was reinforced with household wood screws, embedded in polymethylmethacrylate or fast-curing resin or (Smooth-Cast 300Q, Smooth-On, Inc., Easton, PA, USA) in a cylindrical metal fixture, and attached to the base of the testing apparatus. The T12 vertebra was similarly embedded in a cylindrical metal fixture for application of loads.

Two groups were created to simulate surgical intervention using less exposure surgery (LES) techniques for patients with degenerative disc disease treated with TFPS or PSR in the upper lumbar spine.

Group 1 (TFPS) consisted of 8 motion segments and Group 2 (PSR) comprised of 14 motion segments. The motion segments in Group 1 were L1–L2 ($n = 4$) and L2–L3 ($n = 4$) from 8 spines, and those in Group 2 were L1–L2 ($n = 7$) and L2–L3 ($n = 7$) from 7 spines.

All 15 spine segments were tested in their intact conditions followed by 3 instrumented conditions (Table 2). All instrumented cases involved posterior instrumentation at L1–L2 or L2–L3, with Group 1 specimens first receiving bilateral 4.5×35 mm transfacet screws with 12 mm multiaxial washers (TFPS), and Group 2 specimens receiving bilateral 5.0×35 mm screws and rods (PSR), (Table 2). Instrumented motion segments in Group 2 were tested sequentially (i.e. posterior rods attached at L1–L2 but not at L2–L3, followed by rods attached at L2–L3 but disengaged from L1–L2). The 4.5×35 mm TFPS in Group 1 were then replaced with 5.0×35 mm TFPS. In both groups, a Sagittal Lumbar Interbody Fixation Technology (SLIFT) cage, SpineFrontier Inc. Beverly, MA, USA, (Fig. 2) was implanted at L1–L2 (or L2–L3), and testing was repeated (condition 3, Table 2). Specimens were then subjected to cyclic loading in all directions of movement and flexibility tests in all directions of movement were repeated.

2.2. Fixation technique

Pilot holes were drilled before the initial TFPS placement using a 3.5 mm diameter drill bit. Pilot holes for pedicle screws were prepared using an awl. Top-locking pedicle screw interconnecting rods were 5.5 mm in diameter and were secured using a locking cap. SLIFT graft height was 8 to 10 mm in the TFPS group and 8 to 12 mm in the PSR group, according to the anatomy of each specimen and as would be done in *in vivo* conditions. For SLIFT placement, a complete discectomy was performed using ronguers and curette from a unilateral extraforaminal approach, sparing the facet joints. Fluoroscopy was used to ensure correct positioning of the SLIFT grafts and screws.

2.3. Biomechanical testing

The specimens were studied using standard and well-established pure moment flexibility tests. For these tests, an apparatus was used in which a system of cables and pulleys imparts non-destructive, non-constraining torques in conjunction with a standard servohydraulic test system (MTS, Minneapolis, Minnesota, USA), as has been described in detailed previously (Crawford et al., 1995), (Fig. 3). This type of loading is distributed evenly to each motion segment, regardless of the distance from the point of loading (Panjabi, 1988). Loads of 7.5 Nm maximum were applied about the appropriate anatomical axes to induce three different types of motion: flexion–extension, lateral bending (right and left), and axial rotation (right and left). Post-fatigue flexibility was evaluated following cyclic loading to 7.5 Nm for 2000 cycles in each direction studied with loading applied at approximately 2 Hz. The directions tested were flexion, extension, right and left lateral bending, right and left axial rotation for a total of 12,000 cycles. Three-dimensional specimen motion in response to the applied loads during flexibility tests was determined using the Optotrak 3020 system (Northern Digital, Waterloo, Ontario, Canada). This system

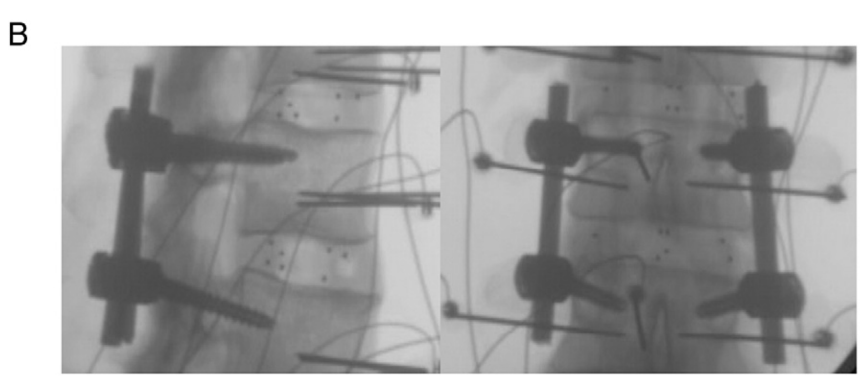

Fig. 1B. X-rays (lateral and A/P views) showing spines instrumented with bilateral PSR and SLIFT at L2–L3.

Table 1
Demographics and bone mineral density of specimens.

Number	Gender	Age (years)	DEXA (BMD g/cm2)	Group*
1	M	40	0.911	FF
2	F	50	0.797	PS
3	M	65	0.792	FF
4	F	61	0.900	PS
5	F	65	0.724	PS
6	F	39	1.067	FF
7	F	64	0.873	FF
8	F	48	0.938	FF
9	F	58	0.620	FF
10	F	54	0.807	FF
11	F	62	0.498	PS
12	M	55	0.787	PS
13	M	29	0.847	PS
14	M	63	0.732	PS
15	F	53	1.291	FF
Mean (SD)	All:	54.1(10.6)	0.842(0.178)	
	PS:	55.0(12.6)	0.755(0.129)	
	FF:	52.6(9.9)	0.912(0.200)	

* FF—FacetFuse facet screw; PS—pedicle screw.

measures stereophotogrammetrically the three-dimensional displacement of infrared-emitting markers rigidly attached in a non-collinear arrangement to each vertebra. Custom software converts the marker coordinates to angles about each of the anatomical axes in terms of the motion segment's own coordinate system (Crawford and Dickman, 1997; Crawford et al., 1999).

2.4. Data analysis

From the raw data, three parameters were generated from the quasistatic load-deformation data: angular range of motion (ROM), lax zone (LZ, zone of ligamentous laxity), and stiff zone (SZ, zone of ligamentous stretching). The LZ and SZ are components of the ROM and represent the low-stiffness and high-stiffness portions of the typically biphasic load-deformation curve, respectively (Crawford et al., 1998).

To mitigate the effect of interspecimen variability, raw values of motion for the instrumented conditions were normalized by dividing the data with the motion incurred in the respective intact conditions. Mean normalized LZ, SZ, and ROM for flexion, extension, lateral bending (average right and left) and axial rotation (average of right and left) were statistically analyzed using one-way analysis of variance (ANOVA) followed by Holm–Sidak pairwise tests to assess whether there were differences among means for values obtained in the TFPS, PSR, TFPS + SLIFT, and PSR + SLIFT instrumented conditions. Additionally, one-tailed paired Student's t-tests were used to determine whether stability parameters were significantly increased after fatigue for both groups. P-values less than 0.05 were considered statistically significant.

In addition to biomechanical assessments, specimens were disarticulated and assessed anatomically after completing tests to determine whether TFPS trajectories crossed facet joint planes and whether screw trajectories remained within the pedicles.

Table 2
Sequence of conditions tested.

Group 1 (facet screws — TFPS)	Group 2 (pedicle screws — PSR)
1. Intact condition	1. Intact condition
2. After 4.5 × 35 mm bilateral TFPS at L1–L2 (or L2–L3).	2. After 5.0 × 35 mm bilateral pedicle screws and rods at L1 and L2 (or L2 and L3) (PSR).
3. After 5.5 × 35 mm bilateral TFPS and SLIFT at L1–L2 (or L2–L3) (TFPS + SLIF).	3. After adding SLIF at L1 and L2 (or L2 and L3) with PSR in place (PSR + SLIF).
4. After 12,000 cycles of fatigue (TFPS + SLIF — post-fatigue).	4. After 12,000 cycles of fatigue (PSR + SLIF — post-fatigue).

3. Results

The ranges of motion (ROM) at L1–L2 and L2–L3 for the intact specimens (Table 3) were similar to what has been reported in the literature (Lazaro et al., 2010) Intact motion was not different between Groups 1 and 2 in any direction of motion ($p > 0.5$). Analysis of normalized values of ROM (Fig. 4) showed that with an intact disc in place, fixation with TFPS resulted in equivalent stability compared to PSR during flexion, lateral bending and axial rotation ($p > 0.11$), while mobility was significantly less with TFPS than PSR during extension ($p < 0.001$). There were no significant differences between TFPS and PSR in any direction of loading with SLIFT in place ($p > 0.11$).

Based on paired tests comparing normalized values of ROM pre- and post-fatigue ROM, there were no significant increases in mobility during flexion ($p = 0.2$), extension ($p = 0.17$) or lateral bending ($p = 0.08$) with PSR + SLIFT in place, but there was an increase in mobility during axial rotation ($p = 0.029$, Fig. 4, Table 4). Similarly, cyclic loading in all directions of movement did not affect mobility during flexion ($p = 0.09$) or extension ($p = 0.07$) with TFPS + SLIFT (Fig. 4, Table 4). However, cyclic loading caused a significant increase in mobility during both lateral bending ($p = 0.04$) and axial rotation ($p = 0.04$) with TFPS + SLIFT. The increases in motion were most likely due to changes in SZ, which increased significantly during extension and axial rotation with TFPS + SLIFT ($p < 0.04$, Table 4), and during axial rotation with PSR + SLIFT ($p < 0.05$, Table 4). Although the mean post-fatigue mobilities were greater with TFPS + SLIFT vs. PSR + SLIFT (Fig. 4), based on one-way ANOVA, these differences were not statistically significant during any direction of movement ($p > 0.21$). However, there were considerable variability among specimens, as indicated by the large standard deviations (error bars in Fig. 4).

While visually observing the anatomy of the upper lumbar spine following testing and disarticulation, there appeared to be relative narrowing of lamina at L1–L2 compared to L2–L3 in all cases. There were no penetrations of the pedicle screws into the canals. In specimens with TFPS screws inserted at L1–L2, the facet screw did not cross the joint in an angle sufficient to provide direct compression across the facet joint in 6 of 10 cases (60%). In TFPS specimens with screws inserted at L2–L3, the facet screw did not traverse the facet joint in 1 of 6 specimens (16%). It was found that after drilling and tapping, the transfacet pedicle screw was within the facet joint in all specimens. Although the screw did not cross the facet joint in a perpendicular angle, the wide washer on the screw head was able to cover the facet joint and create compression. The areas of the facet joint surfaces were not measured. However, measurements made on disarticulated specimens after testing using digital calipers showed that facet screws were inserted at a mean distance of 4.25(SD 2.63) mm from the edge of the articulation at L1–L2 and 1.21(SD 2.31) mm at L2–L3. There were no signs of the washers having cut into the bone following disarticulation and testing.

4. Discussion

The sagittal orientation of the facets and shorter lamina in the upper lumbar spine create anatomic technical difficulties in placing TFPS in the upper lumbar spine, and for this reason it has been reported that TFPS may not be able to provide equivalent fixation to PSR in the upper lumbar spine (Su et al., 2009). Based on our data involving L1–L2 and L2–L3 motion segments, the immediate stability obtained with TFPS with washers was actually superior to that with PSR during extension with an intact disc in place and equivalent to PSR during all other directions of motion. This was in spite of the slightly smaller diameter transfacet screw used (4.5 mm) vs. the 5.0 mm diameter pedicle screw. A possible reason for this could be the relatively small size pedicle screw that was used compared to what is normally used at this level. With SLIFT in place, and with equal sized screws (5 × 35 mm), TFPS and PSR performed equivalent in all directions of motion. This agrees with reported

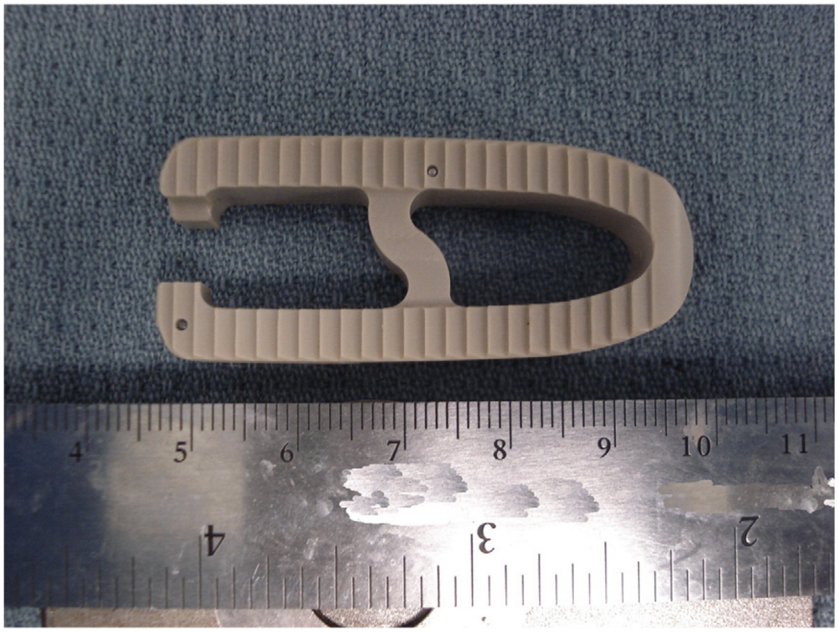

Fig. 2. Lateral interbody cage with ruler alongside for scale reference.

equivalency between transfacet and standard pedicle screws (both similarly and non-similarly sized) in terms of immediate stability, as reported by others (Ferrara et al., 2003; Kretzer et al., 2013; Reinhold et al., 2006).

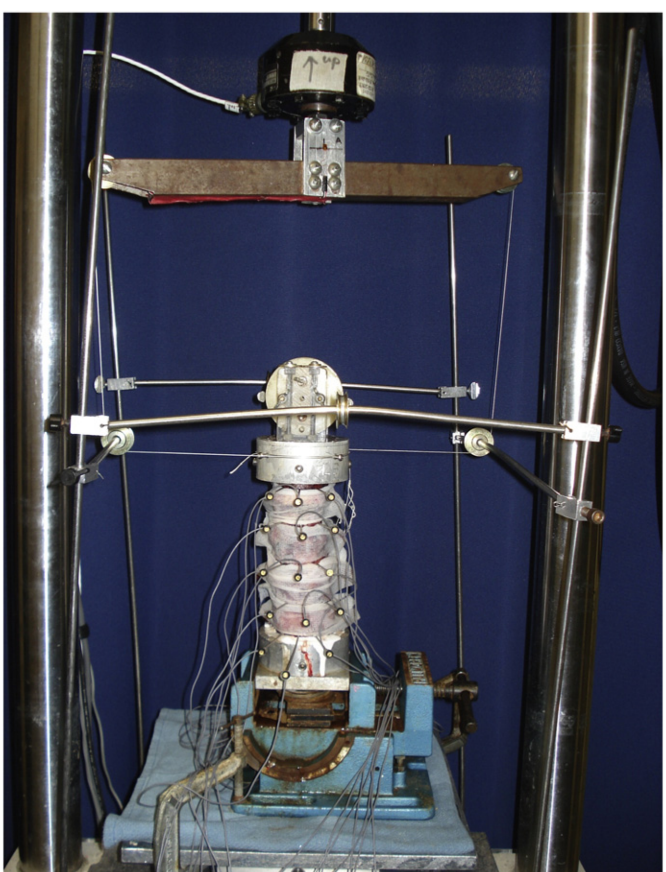

Fig. 3. Apparatus used with a system of cables and pulleys imparting non-destructive, non-constraining torques in conjunction with a standard servohydraulic test system.

Kretzer et al. investigated the kinematic responses of a stand-alone lateral lumbar interbody cage compared with supplemental posterior fixation using either facet or pedicle screws after lateral discectomy(Kretzer et al., 2013), and found no statistically significant differences between two different types of bilateral facet screws, and bilateral pedicle screws at L2–L3 and L4–L5. However, only the acute ROM results were reported (i.e. immediate stability) without further investigating the long term fatigue behavior.

Ferrara et al. compared the biomechanical effects of short-term and long-term cyclic loading on L1–L2 and L3–L4 motion segments instrumented with either TFPS or PSR (Ferrara et al., 2003). They found that stiffness and ROM were unchanged following cyclic loading, and observed no differences between the two fixation systems tested. This is in contrast to our findings of significant changes following cyclic loading, for both supplemental fixation methods. The reasons are most likely related to differences in screw sizes and test methods. Their cyclic loading tests were performed with a maximum load of 6 Nm in only one direction of movement (flexion), whereas we performed cyclic loading with a slightly greater maximum load (7.5 Nm) and in a total of six directions of movement (flexion, extension, right and left lateral bending, and right and left axial rotation). Although, as pointed out by Ferrara et al. (2003), flexural bending is considered the most common direction of movement in the lumbar spine, given the surgical approach involved with a laterally delivered interbody cage, we felt it was important to include cyclic loading in both lateral bending and axial rotation. Furthermore, the pedicle screws used by Ferrara et al. (2003) were

Table 3

Mean (one standard deviation) angular range of motion for intact and instrumented configurations. (TFPS — transfacet pedicle screws, PSR — pedicle screws and rods, SLIF — sagittal lateral interbody fixation).

	Flexion–extension	Lateral bending	Axial rotation
Intact	7.8 (2.3)	4.3 (1.1)	1.5 (0.7)
4.5 × 35 TFPS	1.2(0.5)	2.2 (1.2)	0.7 (0.3)
5.0 × 35 PSR	2.2 (0.9)	1.8 (0.8)	1.0 (0.4)
5.0 × 35 TFPS + SLIF	1.8 (1.5)	2.6 (2.2)	1.1 (0.9)
5.0 × 35 PSR + SLIF	1.7 (1.0)	1.6 (0.8)	1.0 (0.6)
5.0 × 35 TFPS + SLIF (post-fatigue)	3.1 (3.1)	3.8 (3.4)	1.7 (1.5)
5.0 × 35 PSR + SLIF (post-fatigue)	1.8 (1.0)	1.7 (0.9)	1.0(0.6)

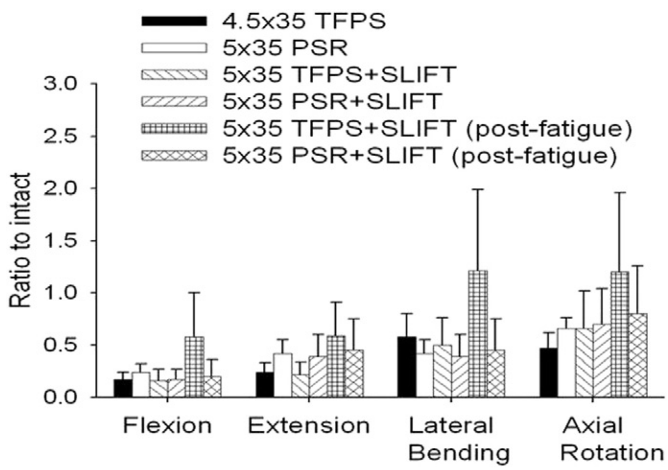

Fig. 4. Mean normalized ROM for instrumented configurations with facet screws (TFPS) or pedicle screw rods (PSR), with and without SLIFT, before and after cyclic loading. Values for lateral bending and axial rotation are average right/left. Error bars show standard deviation.

6.5×40 mm, compared to 5×35 mm used in our study, suggesting that appropriately sized pedicle screws that fill up the pedicle may be less susceptible to screw loosening. Another difference between studies is that the facet screws used by Ferrara et al. (2003) lacked the large retaining washers that were used with the TFPS used in our study. Based on our data, it seems feasible that the washers contribute to improved stability with TFPS. The TFPS did not traverse the facet joint in a perpendicular fashion, but the large size (12 mm) washers utilized in our study provided indirect compression.

Mahar et al. (2006) have also shown equivalency between transfacet fixation and standard PSR. Using L4–L5 motion segments, where capture of the facet joints is much easier than at L1–L2 or L2–L3, they studied the performance of slightly wider diameter pedicle screws (5.5 mm versus 5 mm diameter) and adjustable length 4.5 mm diameter facet screws. Like the wide washer present on TFPS in the current study, their device incorporated a collar at the head of the screw to distribute load.

Others have studied the effects of pedicle screw angle and cyclic loading, reporting that straight screw insertion results in a more stable construct (Kim et al., 2011). Pedicle screw insertion angle was not considered in our study.

Zheng et al. (2010) performed an *in vitro* biomechanical study involving non-osteoporotic lumbar motion segments (including T12-L1 through L5-S1) instrumented with facet or pedicle screws augmenting a filled mesh bag serving as an interbody device (implanted using a TLIF approach). Using loading methods similar to ours, they measured immediate stability and reported greater stability with the facet screws than pedicle screws during axial rotation, and equivalent stability during flexion–extension and lateral bending. In our study we also found a greater mean stability with TFPS vs. PSR during axial rotation (Fig. 4), but without statistical significance ($p = 0.219$). Zheng et al. (2010) also reported no significant difference in the performance of facet screws vs. pedicle screws with TLIF in place regarding cage subsidence following cyclic in flexion–extension. We did not consider cage subsidence in the present study, but this would be an interesting focus of study.

Reinhold et al. (2006) investigated the effects of BMD and in vitro performance of PSR following cyclic loading and found high correlations between BMD and the number of cycles at failure. Our specimens were non-osteoporotic and we did not load the spine segments to failure, nor did we consider effects of load-bearing areas, as Reinhold et al. However, given Reinhold's findings, future studies involving comparisons between transfacet screws and standard pedicle screws using cyclic loading in osteoporotic spines would be of interest.

Table 4
P-values from paired Student's t-tests comparing normalized values from pre- and post-fatigue tests.

	TFPS + SLIFT	PSR + SLIFT
ROM		
Flexion	0.091	0.200
Extension	0.072	0.173
Lateral bending	**0.044**	0.076
Axial rotation	**0.036**	**0.029**
LZ		
Flexion–extension	0.100	0.134
Lateral bending	0.091	0.192
Axial rotation	0.205	0.139
SZ		
Flexion	0.078	0.430
Extension	**0.033**	0.667
Lateral bending	0.546	0.591
Axial rotation	**0.023**	**0.042**

Significant values $p < 0.05$ are shown in bold.

5. Conclusions

With an intact disc, TFPS with washers can provide equivalent, if not better immediate stability than PSR at L1–L2 and L2–L3. However, due to the anatomic limitations of the upper lumbar spine and orientation of the facets, it is difficult to obtain direct compression of the facet joint with TFPS fixation. PSR seems to be less susceptible to loosening and may be preferred over TFPS as augmenting posterior fixation during fusion with SLIFT in the upper lumbar spine.

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References

Beaubien, B.P., et al., 2004. Posterior augmentation of an anterior lumbar interbody fusion: minimally invasive fixation versus pedicle screws in vitro. Spine (Phila Pa 1976) 29 (19), E406–E412.
Beutler, W.J., Peppelman Jr., W.C., 2003. Anterior lumbar fusion with paired BAK standard and paired BAK proximity cages: subsidence incidence, subsidence factors, and clinical outcome. Spine J. 3 (4), 289–293.
Chen, L., Tang, T., Yang, H., 2003. Complications associated with posterior lumbar interbody fusion using Bagby and Kuslich method for treatment of spondylolisthesis. Chin. Med. J. (Engl.) 116 (1), 99–103.
Crawford, N.R., Dickman, C.A., 1997. Construction of local vertebral coordinate systems using a digitizing probe. Technical note. Spine (Phila Pa 1976) 22 (5), 559–563.
Crawford, N.R., et al., 1995. An apparatus for applying pure nonconstraining moments to spine segments in vitro. Spine (Phila Pa 1976) 20 (19), 2097–2100.
Crawford, N.R., Peles, J.D., Dickman, C.A., 1998. The spinal lax zone and neutral zone: measurement techniques and parameter comparisons. J. Spinal Disord. 11 (5), 416–429.
Crawford, N.R., Yamaguchi, G.T., Dickman, C.A., 1999. A new technique for determining 3-D joint angles: the tilt/twist method. Clin. Biomech. 14 (3), 153–165.
Ferrara, L.A., et al., 2003. A biomechanical comparison of facet screw fixation and pedicle screw fixation: effects of short-term and long-term repetitive cycling. Spine (Phila Pa 1976) 28 (12), 1226–1234.
Fritzell, P., et al., 2002. Chronic low back pain and fusion: a comparison of three surgical techniques: a prospective multicenter randomized study from the Swedish lumbar spine study group. Spine (Phila Pa 1976) 27 (11), 1131–1141.
Kim, M.C., et al., 2011. Factors affecting the accurate placement of percutaneous pedicle screws during minimally invasive transforaminal lumbar interbody fusion. Eur. Spine J. 20 (10), 1635–1643.
King, D., 1948. Internal fixation for lumbosacral fusion. J. Bone Joint Surg. Am. 30A (3), 560–565.
Kretzer, R.M., et al., 2013. A comparative biomechanical analysis of stand alone versus facet screw and pedicle screw augmented lateral interbody arthrodesis: an

in vitro human cadaveric model. J. Spinal Disord. Tech. http://dx.doi.org/10.1097/BSD.0b013e3182868ef9 (published online ahead of print November 7, 2013).

Lazaro, B.C., et al., 2010. Biomechanics of a novel minimally invasive lumbar interspinous spacer: effects on kinematics, facet loads, and foramen height. Neurosurgery 66 (3 Suppl. Operative), 126–132 (discussion 132-3).

Mahar, A., et al., 2006. Biomechanical comparison of a novel percutaneous transfacet device and a traditional posterior system for single level fusion. J. Spinal Disord. Tech. 19 (8), 591–594.

Ozgur, B.M., et al., 2006. Extreme Lateral Interbody Fusion (XLIF): a novel surgical technique for anterior lumbar interbody fusion. Spine J. 6 (4), 435–443.

Panjabi, M.M., 1988. Biomechanical evaluation of spinal fixation devices: I. A conceptual framework. Spine (Phila Pa 1976) 13 (10), 1129–1134.

Phan, K., Thayaparan, G.K., Mobbs, R.J., 2015. Anterior lumbar interbody fusion versus transforaminal lumbar interbody fusion — systematic review and meta-analysis. Br. J. Neurosurg. 1–7.

Reinhold, M., et al., 2006. Influence of screw positioning in a new anterior spine fixator on implant loosening in osteoporotic vertebrae. Spine (Phila Pa 1976) 31 (4), 406–413.

Richter, M., Weidenfeld, M., Uckmann, F.P., 2015. Anterior lumbar interbody fusion. Indications, technique, advantages and disadvantages. Orthopade 44 (2), 154–161.

Su, B.W., et al., 2009. An anatomic and radiographic study of lumbar facets relevant to percutaneous transfacet fixation. Spine (Phila Pa 1976) 34 (11), E384–E390.

Zheng, X., et al., 2010. Biomechanical evaluation of an expandable meshed bag augmented with pedicle or facet screws for percutaneous lumbar interbody fusion. Spine J. 10 (11), 987–993.