



Residual motion of different posterior instrumentation and interbody fusion constructs

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Abstract

Purpose To elucidate residual motion of cortical screw (CS) and pedicle screw (PS) constructs with unilateral posterior lumbar interbody fusion (ul-PLIF), bilateral PLIF (bl-PLIF), facet-sparing transforaminal lumbar interbody fusion (fs-TLIF), and facet-resecting TLIF (fr-TLIF).

Methods A total of 35 human cadaver lumbar segments were instrumented with PS ($n = 18$) and CS ($n = 17$). Range of motion (ROM) and relative ROM changes were recorded in flexion/extension (FE), lateral bending (LB), axial rotation (AR), lateral shear (LS), anterior shear (AS), and axial compression (AC) in five instrumentational states: without interbody fusion (wo-IF), ul-PLIF, bl-PLIF, fs-TLIF, and fr-TLIF.

Results Whereas FE, LB, AR, and AC noticeably differed between the instrumentational states, AS and LS were less prominently affected. Compared to wo-IF, ul-PLIF caused a significant increase in ROM with PS (FE + 42%, LB + 24%, AR + 34%, and AC + 77%), however, such changes were non-significant with CS. ROM was similar between wo-IF and all other interbody fusion techniques. Insertion of a second PLIF (bl-PLIF) significantly decreased ROM with CS (FE -17%, LB -26%, AR -20%, AC -51%) and PS (FE - 23%, LB - 14%, AR - 20%, AC - 45%). Facet removal in TLIF significantly increased ROM with CS (FE + 6%, LB + 9%, AR + 17%, AC of + 23%) and PS (FE + 7%, AR + 12%, AC + 13%).

Conclusion bl-PLIF and TLIF show similarly low residual motion in both PS and CS constructs, but ul-PLIF results in increased motion. The fs-TLIF technique is able to further decrease motion compared to fr-TLIF in both the CS and PS constructs.

Keywords Interbody fusion · PLIF · TLIF · Unilateral · Facet-sparing

Introduction

Various interbody fusion techniques are available in the spinal surgical toolbox today, with posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF) being the most common [1, 2]. Both are usually

accompanied by posterior spinal instrumentation with pedicle screws (PSs) or cortical screws (CSs) [3]. CS, also known as cortical bone trajectory, is becoming more popular because it is less invasive and offers improved screw instrumentation strength [4] (Fig. 1).

The use of interbody fusion, especially PLIF and TLIF, has increased rapidly in the past few years [3]. The PLIF technique was first described in 1944 by Briggs and Milligan [5] and was later popularized by Cloward [6]. The use of interbody cages was later introduced by Brantigan and Steffee [7] in 1991, with superior fusion rates compared to bone grafts alone [8]. The standard PLIF techniques require insertion of two separate PLIF cages bilaterally, typically through bilateral laminotomies and, in some cases, partial resection of both facet joints to achieve adequate graft placement. During PLIF, the retraction of the thecal sac and nerve roots may endanger the nerve roots and the conus medullaris

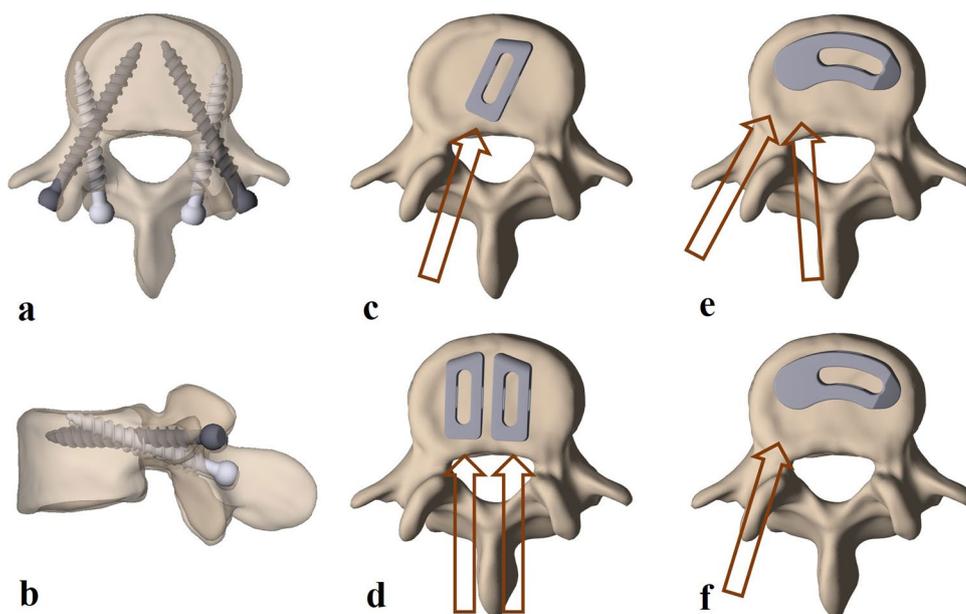
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Fig. 1 Schematic illustration of the different pedicle screw instrumentation and interbody fusion techniques. **a/b** Axial and lateral view of the cortical screw (CS, light gray) and pedicle screw (PS, dark gray). **c** Unilateral posterior lumbar interbody fusion (ul-PLIF). **d** Bilateral PLIF (bl-PLIF). **e** Facet-sparing transforaminal interbody fusion (fs-TLIF), either through the Kambin's triangle (lateral arrow) or mid-line approach (medial arrow). **f** Facet-resecting TLIF (fr-TLIF) through a left-sided facetectomy



and may be technically challenging, especially in revision surgery. Thus, some authors have reported unilateral insertion of a single PLIF cage, with adequate clinical outcomes [9, 10].

To avoid these potential drawbacks of PLIF, Harms [11] described the TLIF technique, which involves the placement of a single, larger interbody cage through a unilateral facetectomy. However, unilateral resection of the facet may destabilize the instrumented segment, especially with torsional stress loadings [12]. Some authors have reported a facet-sparing TLIF approach for which increased construct stiffness is propagated [4, 13, 14].

Currently, PLIF and TLIF are considered the gold standard for circumferential fusion. However, until now, the different impact of these interbody fusion techniques on biomechanical characteristics has not been comprehensively investigated. We aimed to elucidate this gap and investigated the residual motion of CS and PS constructs of lumbar and lumbosacral segments accompanied by unilateral PLIF (ul-PLIF), bilateral PLIF (bl-PLIF), facet-sparing TLIF (fs-TLIF), and facet-resecting TLIF (fr-TLIF) (Fig. 1).

Methods

Specimen preparation

After ethical approval (BASEC Nr. 2017–00,874), we used 12 fresh-frozen human spine cadavers (Science Care, Phoenix, AZ, USA) with an average age of 59 years (range 50–68 years; 8 males and 4 females). The specimens were stored at -20°C until further dissection and biomechanical testing, which was performed after thawing them overnight

at a room temperature of 20°C . We removed the paraspinal muscles and connective tissues from all the specimens and divided them into L1/2, L3/4, and L5/S1 segments. Special attention was taken to not damage the intersegmental ligaments, facets, and disks.

Instrumentation

We planned all screws with optimal trajectory, screw diameter and length, half with the CS (5–6 mm diameter \times 40–50 mm length) and the other half with the PS trajectory (6–7 mm diameter \times 50–60 mm length) based on the computed tomography data. After 3D printing of the specimen-specific 2.7 mm drill-guides, the screws (cannulated poly-axial titanium alloy pedicle screws, Medacta International, Castel San Pietro, Switzerland) were inserted, and titanium rods were vertically attached to the screw heads. Bilateral laminotomy, removal of the supraspinous and interspinous ligaments, and the ligamentum flavum were carried out in each segment, representing a standard mid-line decompression procedure. The intervertebral disk was kept intact before applying the interbody fusion techniques described below.

We performed the biomechanical testing of all specimens in the following constant sequence of states: (a) without interbody fusion (wo-IF); (b) nucleotomy via median anulus fibrosus and nucleus pulposus resection and unilateral PLIF cage (width \times length: 12 mm \times 32 mm; MectalIF Posterior PEEK, Medacta International, Switzerland) insertion from the left; (c) insertion of a second PLIF cage from the right; (d) removal of both PLIF cages, gentle left foraminal extension of the anulus fibrosus resection if necessary and extraforaminal insertion of the TLIF cage (width \times

length: 14 mm × 34 mm; MectaLIF Transforaminal PEEK, Medacta International, Switzerland) from the left; and (e) resection of the left facet joint, leaving the TLIF cage in place (Fig. 2). Mean disk height and lordosis were 10 mm (range 8–14 mm) and 5° (range 1–8°) in L1/2 segments, 12 mm (range 8–15 mm) and 3° (–2–6°) in L3/4 segments, and 11 mm (range 8–14 mm) and 5° (range 3–9°) in L5/S1 segments. We determined the accurate PLIF and TLIF cage heights (8–15 mm) based on the CT scans and “intraoperative” situation. PLIF and TLIF cage lordosis of 5° was found appropriate for all tested segments. We distracted the segments with –100 N prior to all cage insertions and removals and compressed them with +200 N before tightening the vertical rods.

Biomechanical evaluation

A previously established biomechanical setup and test protocol was used for this study [15]. The cranial and caudal vertebrae of each segment were mounted with 3D-printed clamps [16]. The test apparatus (Zwick/Roell Allroundline 10 kN, ZwickRoell GmbH & Co. KG, Germany) applied predefined loads to the cranial vertebra, while the caudal vertebra was fixed to the semi-constrained test rig (Fig. 2A). This allowed pure bending/rotational moment around the z-axis and pure shear/compression forces along the z-axis, but coupled motion in the x–y-plane was possible. The range of motion (ROM) was recorded with a motion capturing system (Fusion Track 500, Atracsys, Puidoux, Switzerland) after five preconditioning cycles were completed. Six ROM directions were tested: flexion–extension (FE), lateral bending (LB), axial rotation (AR), anterior shear (AS), lateral shear (LS), and compression–decompression (AC). In each direction, commonly used loading parameters were applied that simulate physiological conditions [15, 17]. Angular motions (FE, LB,

AR) were performed with a velocity of 1°/sec, attaining a torque of ±7.5 Nm. AS and LS were measured at 0.5 mm/sec until 150 N was attained in each direction. AC was measured at 0.1 mm/sec until +400 N compression and –150 N distraction were reached [17].

Statistics

We performed the statistical analysis with MATLAB (Matlab 2019a, MathWorks, Massachusetts, USA). We used non-parametric statistical testing: Mann–Whitney *U* test and the Wilcoxon signed rank test for unmatched and matched data, respectively. In the manuscript, we report medians along with the 25th and 75th percentiles in parentheses. Due to multiple comparisons, the Bonferroni correction of *p* values was applied. Statistical significance was set at $\alpha < 0.05$.

Results

A total of 18 CS and 17 PS-instrumented segments were biomechanically tested and are presented here. One PS-instrumented segment had to be excluded, due to a vertebral body fracture segment. The different constructs noticeably differed in residual motion in FE, LB, AR, and AC, but AS and LS were less affected. Interbody fusion also similarly affected the CS and PS constructs, but larger differences in LB were observed in CS constructs when compared to wo-IF. Detailed information on absolute and relative ROM changes including data distribution are illustrated in Fig. 3 and Table 1 with *p* values in Table 2. The below reported changes in relative motion did not differ between L5/S1 and the upper lumbar segments of L1/2 and L3/4.

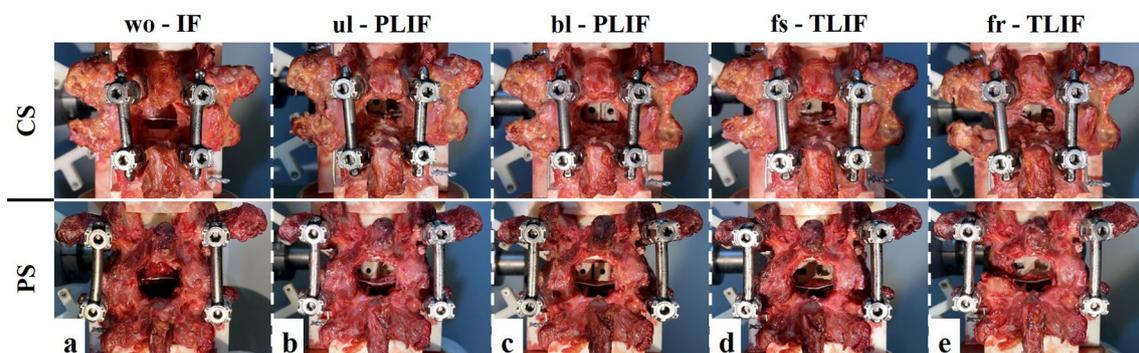


Fig. 2 Instrumentation following the cortical screw (CS; superior row) and pedicle screw (PS; inferior row) technique with different interbody fusion techniques: **a** Posterior instrumentation without interbody fusion (wo-IF). **b** Unilateral posterior lumbar interbody

fusion (ul-PLIF). **c** Bilateral PLIF (bl-PLIF). **d** Facet-sparing transforaminal interbody fusion (fs-TLIF). **e** Facet-resecting TLIF (fr-TLIF) through a left sided facetectomy

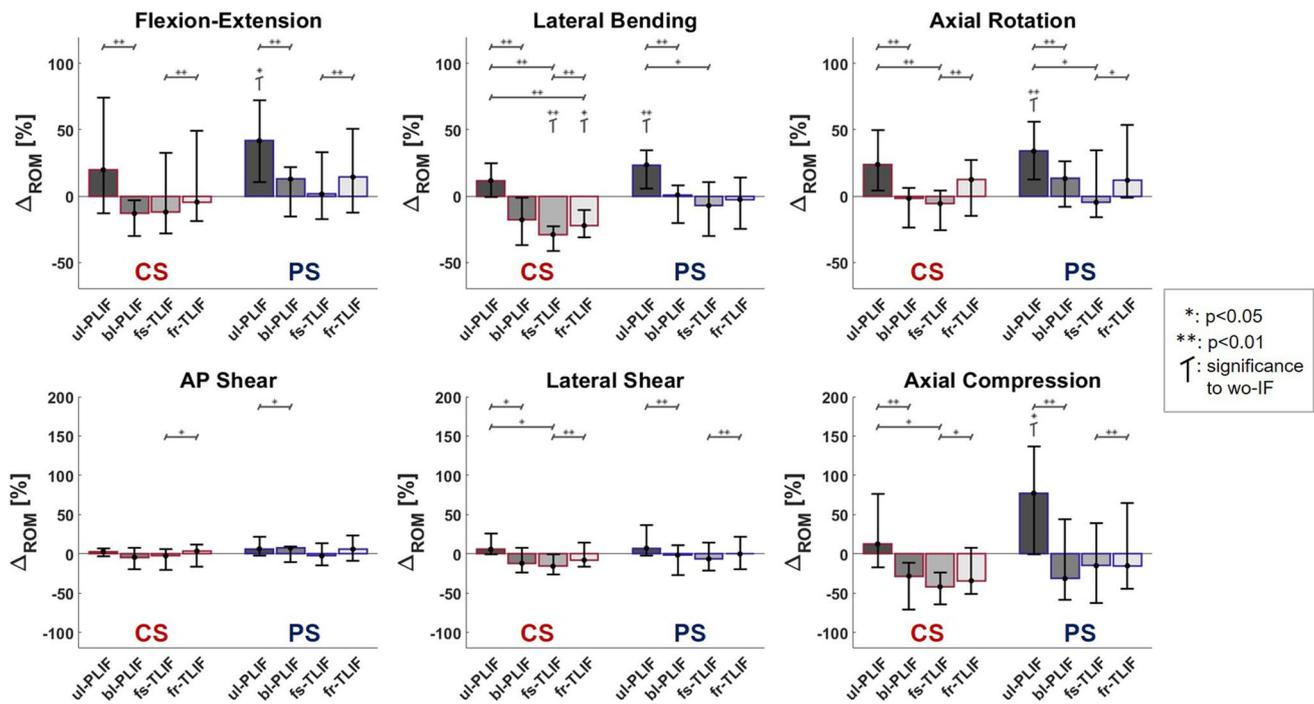


Fig. 3 Change of residual range of motion (ROM) after different interbody fusion (IF) techniques in relation to posterolateral instrumentation without interbody fusion (wo-IF). Change is calculated as $\Delta ROM (\%) = (1 - [ROM_{IF} / ROM_{wo-IF}]) * 100$. The medians of the single differences are shown, along with the 25th and 75th percentiles. Bars below 0 indicate less motion with than without IF. Asterisks (*)

indicate statistical significance. CS cortical screw, PS pedicle screw, wo-IF without interbody fusion, ul-PLIF unilateral posterior lumbar interbody fusion, bl-PLIF bilateral posterior lumbar interbody fusion, fs-TLIF facet-sparing transforaminal interbody fusion, fr-TLIF facet-resecting transforaminal interbody fusion

PLIF versus TLIF

In comparison to wo-IF, ul-PLIF tended to increase the ROM, which was significant in FE with a median relative ROM change of +42% (median absolute ROM change = +0.4°), LB +24% (+0.3°), AR +34% (+0.4°), and AC +77% (+0.2 mm) in PS-instrumented segments (all $p < 0.05$) but was not statistically significant in the CS-instrumented segments in any loading direction. In contrast, the ROM was similar and not significantly different between wo-IF and bl-PLIF in any loading direction, regardless of CS or PS instrumentation. Both fs-TLIF and fr-TLIF were also not significantly different from wo-IF in any loading direction in PS-instrumented segments. However, a significant decrease in ROM was found in LB in CS-instrumented segments both with fs-TLIF of -29% (-0.6 mm) and fr-TLIF of -22% (-0.5 mm). While ul-PLIF was inferior to TLIF in multiple loading directions in CS and PS constructs, bl-PLIF was similar and non-statistically different from both fs-TLIF and fr-TLIF.

ul-PLIF versus bl-PLIF

Insertion of a second PLIF cage reduced the ROM in all loading directions in both the CS and PS-instrumented segments, which was statistically significant, except AS in the CS-instrumented segments. In CS-instrumented segments, the largest relative ROM reductions with a second PLIF cage compared to a unilateral PLIF were found in AC of -51% (-0.2 mm), followed by LB -26% (-0.5°), AR -20% (-0.2°), FE -17% (-0.2°) LS -11% (-0.2 mm), and AS -4% (-0.1 mm). In terms of relative ROM, AC was also most affected by insertion of a second PLIF cage in PS-instrumented segments with significant relative ROM reductions of -45% (-0.2 mm), followed by FE -23% (-0.3 mm), AR -20% (-0.2°), and LB -14% (-0.4°).

fr-TLIF versus fs-TLIF

fr-TLIF was superior to fs-TLIF in both the CS and PS-instrumented segments. Removal of the facet led to a significant increase in all loading directions in CS-instrumented

Table 1 Absolute range of motion (°) without interbody fusion and absolute (Δ [°]) and relative (%) change with different interbody fusion techniques

		FE (°)			LB (°)			AR (°)			AS (mm)			LS (mm)			AC (mm)		
		25 th /75 th			Median			25 th /75 th			Median			25 th /75 th			Median		
		Median	25 th	75 th	Median	25 th	75 th	Median	25 th	75 th	Median	25 th	75 th	Median	25 th	75 th	Median	25 th	75 th
CS	wo-IF	[°]	1.1	0.9/1.4	2.5	1.8/3.0	1.4	0.9/1.9	1.1	0.9/1.4	1.3	0.9/2.1	0.3	0.2/0.5					
	ul-PLIF	Δ [°]	1.4	0.8/2.1	2.8	2.0/3.3	1.6	1.1/2.0	1.1	0.9/1.4	1.3	1.1/2.1	0.4	0.2/0.7					
		[%]	0.2	-0.1/0.5	0.2	0.0/0.4	0.3	0.0/0.4	0.0	-0.1/0.1	0.1	0.0/0.2	0.1	-0.1/0.1					
		[°]	20	-13/74	12	-1/25	24	4/50	3	-3/7	6	-1/26	13	-17/76					
	bl-PLIF	Δ [°]	0.8	0.7/1.5	1.8	1.6/2.5	1.2	1.0/1.6	1.1	0.8/1.4	1.2	0.8/2.0	0.2	0.1/0.4					
		[%]	-0.1	-0.3/-0.1	-0.4	-1.0/-0.3	0.0	-0.7/0.0	0.0	-0.3/0.0	-0.1	-0.5/-0.1	-0.1	-0.3/-0.1					
		[°]	-13	-30/-3	-18	-37/-1	-2	-24/6	-4	-19/8	-12	-24/8	-28	-71/-11					
	fs-TLIF	Δ [°]	1.1	0.7/1.5	1.6	1.1-2.0	1.2	0.8/1.9	1.1	0.8/1.5	1.1	0.8/2.0	0.2	0.2/0.2					
		[%]	-0.1	-0.3/0.1	-0.6	-0.9/-0.6	-0.1	-0.4/0.0	0.0	-0.3/0.1	-0.2	-0.4/-0.1	-0.2	-0.2/-0.1					
		[°]	-12	-28/33	-29	-41/-23	-6	-26/4	-2	-20/6	-16	-26/0	-42	-64/-23					
fr-TLIF	Δ [°]	1.2	0.8/1.5	1.7	1.2/2.2	1.4	1.1/2.2	1.1	0.9/1.6	1.2	0.9/2.2	0.2	0.2/0.4						
	[%]	0.0	-0.2/0.1	-0.5	-0.6/-0.4	0.2	-0.3/0.3	0.0	-0.3/0.1	-0.1	-0.3/0.1	-0.1	-0.2/-0.1						
	[°]	-5	-19/49	-22	-31/-10	12	-15/27	4	-17/12	-8	-17/14	-34	-51/8						
PS	wo-IF	[°]	1.1	0.8/1.8	1.7	1.4/1.9	1.1	0.8/1.3	1.0	0.8/1.5	1.1	0.8/1.4	0.3	0.3/0.5					
	ul-PLIF	Δ [°]	1.7	1.0/2.3	1.8	1.5/2.4	1.4	1.1/1.7	1.0	0.9/1.6	1.1	0.9/1.6	0.5	0.3/0.8					
		[%]	0.4	0.1/0.8	0.3	0.1/0.5	0.4	0.2/0.4	0.1	0.0/0.2	0.1	0.0/0.4	0.2	0.0/0.4					
		[°]	42	11/72	24	6/34	34	12/56	6	-3/22	7	-2/37	77	0/137					
	bl-PLIF	Δ [°]	1.2	0.8/1.8	1.4	1.2/2.0	1.2	0.9/1.3	1.0	0.8/1.5	0.9	0.7/1.3	0.3	0.1/0.5					
		[%]	0.1	-0.1/0.3	0.0	-0.4/0.1	0.2	0.0/0.2	0.1	-0.1/0.1	0.0	-0.3/0.2	-0.1	-0.1/0.1					
		[°]	13	-15/22	1	-20/8	13	-8/26	7	-11/10	-1	-27/11	-31	-58/44					
	fs-TLIF	Δ [°]	1.2	1.0/1.7	1.6	0.9/1.9	1.2	0.9/1.4	0.9	0.8/1.5	0.8	0.7/1.5	0.3	0.2/0.5					
		[%]	0.0	-0.2/0.3	-0.1	-0.4/0.2	-0.1	-0.2/0.4	0.0	-0.1/0.1	0.0	-0.2/0.2	0.0	-0.2/0.1					
		[°]	2	-17/33	-7	-30/11	-5	-16/34	-3	-15/14	-6	-22/15	-15	-62/39					
fr-TLIF	Δ [°]	1.5	1.0/1.9	1.6	1.0/2.1	1.2	1.0/1.6	0.9	0.8/1.7	0.9	0.7/1.7	0.4	0.2/0.6						
	[%]	0.1	-0.1/0.5	0.0	-0.3/0.2	0.1	0.0/0.5	0.1	0.0/0.2	0.0	-0.1/0.4	0.0	-0.2/0.3						
	[°]	14	-13/51	-3	-25/14	12	-1/54	6	-9/24	0	-20/22	-15	-44/65						

ROM range of motion, 25th/75th 25. percentile and 75. Percentile, FE flexion/extension, LB lateral bending, AR axial rotation, AS anteroposterior shear, LS lateral shear, AC axial compression, CS cortical screw, PS pedicle screw, wo-IF without interbody fusion, ul-PLIF unilateral posterior lumbar interbody fusion, bl-PLIF bilateral posterior lumbar interbody fusion, fs-TLIF facet-sparing transforaminal interbody fusion, fr-TLIF facet-resecting transforaminal interbody fusion

Table 2 Cross-tabulation of *p* values

	ul - PLIF			bl - PLIF			fs - TLIF			fr - TLIF		
	FE	LB	AR	FE	LB	AR	FE	LB	AR	FE	LB	AR
	AS	LS	AC	AS	LS	AC	AS	LS	AC	AC	LS	AC
CS												
wo - IF	0.190	0.124	0.055	0.451	0.171	1.000	1.000	0.010	0.628	1.000	0.015	0.994
	1.000	0.154	0.736	1.000	0.858	0.111	1.000	0.079	0.233	1.000	1.000	1.000
ul - PLIF	[Redacted]			0.002	0.001	0.003	0.672	0.001	0.007	1.000	0.002	1.000
				0.168	0.011	0.001	1.000	0.034	0.017	1.000	0.467	0.512
bl - PLIF	[Redacted]			[Redacted]			1.000	0.424	1.000	1.000	1.000	0.349
							1.000	1.000	1.000	0.316	1.000	1.000
fs - TLIF	[Redacted]			[Redacted]			[Redacted]			0.008	0.002	0.002
										0.015	0.001	0.034
PS												
wo - IF	0.017	0.009	0.007	1.000	1.000	0.910	1.000	1.000	1.000	0.336	1.000	0.098
	0.098	0.177	0.026	1.000	1.000	1.000	1.000	1.000	1.000	0.910	1.000	1.000
ul - PLIF	[Redacted]			0.002	0.004	0.004	0.893	0.022	0.039	1.000	0.147	1.000
				0.034	0.003	0.002	0.130	0.130	0.677	1.000	1.000	1.000
bl - PLIF	[Redacted]			[Redacted]			1.000	1.000	1.000	1.000	1.000	0.677
							1.000	1.000	1.000	1.000	1.000	1.000
fs - TLIF	[Redacted]			[Redacted]			[Redacted]			0.010	0.147	0.016
										0.237	0.008	0.002

ROM range of motion, 25th–75th 25. percentile and 75. Percentile, Gray background indicates statistical significance, with black font standing for increase and white font for decrease in ROM when comparing row versus column. FE flexion/extension, LB lateral bending, AR axial rotation, AS anteroposterior shear, LS lateral shear, AC axial compression, CS cortical screw, PS pedicle screw, wo-IF without interbody fusion, ul-PLIF unilateral posterior lumbar interbody fusion, bl-PLIF bilateral posterior lumbar interbody fusion, fs-TLIF facet-sparing transforaminal interbody fusion, fr-TLIF facet-resecting transforaminal interbody fusion

segments and in all loading directions except for LB and AS in PS-instrumented segments. In CS instrumentations, facet removal led to the most prominent ROM changes in relation to fs-TLIF in AC of +23% (+0.1 mm), followed by AR +17% (+0.3 mm), LS +10% (+0.1 mm), LB 9% (+0.1°), FE +6% (+0.1°), and AS +6% (+0.1 mm). In the PS group, a relative ROM increase of fr-TLIF compared to fs-TLIF was observed in AC +13% (+0.1 mm), AR +12% (+0.1 mm), FE +7% (+0.1°), and LS +6% (+0.1 mm).

Discussion

This biomechanical study provides a comprehensive insight into residual motion with different posterior interbody fusion techniques in combination with CS and PS instrumentation. The main findings are that bilateral PLIF and TLIF provide a similar decrease in residual motion, but ul-PLIF is inferior to the traditional bl-PLIF in both PS and CS instrumentations. In contrast, the fs-TLIF technique provides more ROM reduction than the standard fr-TLIF technique and is a viable option in combination with CS and PS instrumentation.

The scientific literature on biomechanical effect of interbody fusion on segmental motion presents diverging results. For example, Harris et al. [18] reported a flexibility increase of 300% in AR following stand-alone TLIF in comparison to the intact, uninstrumented spine. Further, the study reported that a circumferential fusion with TLIF and pedicle screws did only reapproximate the flexibility to the intact, uninstrumented segment, but still an increased ROM in AR of 144% was found, with FE and LB only being decreased by 19% and 14%, respectively [18]. This stands in striking contrast to the findings of Godzik et al. [19, 20], who reported a significant motion decrease of 80% in FE and LB directions and 60% in AR when comparing PLIF and pedicle screw fixation to intact, uninstrumented segments.

When comparing interbody fusion with pedicle screw fixation to pedicle screw fixation alone, the literature also provides heterogenous findings. Whereas Godzik et al. [19] found a trend to motion decrease with the use of interbody fusion, the results of Ntilikina et al. [21] show a non-significant trend toward motion increase in FE, LB, and AR in comparison to pedicle screw instrumentation alone. Our study confirms that neither bl-PLIF nor TLIF lead to

noticeable reduction of residual motion in most of the loading directions in both PS and CS instrumentations.

The posterior access route to interbody cage insertion does necessarily mean a destabilizing harm to the segment because of the focal resection of anulus fibrosus and discectomy as well as partial or full facetectomy. Further, the implanted cage may not fully replace the stabilizing properties of the intervertebral disk but also partially act as a fulcrum in FE and LB motions. This trade-off should be bared in mind in each individual case.

Anterior column support with interbody cages has been recommended to avoid pseudarthrosis and implant failure [1, 22]. In a finite-element model, interbody fusion has further shown to provide anterior column support and reduce stress on the pedicle screw-bone and screw-rod interfaces [23]. This effect has also been shown in clinical investigations, which showed a 60% reduction of early pedicle screw loosening with the use of TLIF [24]. However, regardless of the architectural structure of the spinal instrumentation construct, the mission of the interbody cage is only in part to decrease motion but to temporarily hold the disk height, until bony fusion through the impacted bone material has advanced.

PLIF versus TLIF

In our study, PLIF and TLIF were biomechanically not different, as long as PLIF was performed bilaterally. In contrast, Sim et al. [25] found higher immediate stability in lateral bending with PLIF compared to TLIF and attributed their findings to the larger interbody footprint provided by two laterally placed PLIF cages and to the destabilizing effect of the facetectomy performed with TLIF [25]. The RCT by Yang et al. [26] has shown no difference in clinical outcomes after PLIF versus TLIF for isthmic spondylolisthesis, but PLIF required more operative time and resulted in more blood loss than TLIF. The systematic review performed by Makanji et al. [27] did not find any substantial differences between PLIF and TLIF in terms of clinical outcome, with fusion rates of 94.7% and 93.3%, respectively. However, posterolateral instrumentation without interbody fusion was less successful than with interbody fusion. A recent meta-analysis comparing TLIF and PLIF found a lower complication rate, less blood loss, shorter operating time, and slightly better patient-reported outcomes with the TLIF technique in the treatment of lumbar spondylolisthesis [28].

In our opinion, the main advantage of TLIF over PLIF is the unilateral approach to the disk space, which leads to less nerve root and spinal cord retraction and therefore might also explain the lower complication rates reported. However, the choice of implant and technique is only one factor for successful fusion. In our opinion, restoring disk height and sagittal alignment, indirect neural decompression, and, most

importantly, meticulous interbody bone grafting are crucial to achieve solid fusions and desirable clinical outcomes with either interbody fusion technique.

ul-PLIF versus bl-PLIF

In the face of substantial scarring, some surgeons may attempt to use only one PLIF cage intraoperatively to avoid any harm to the dura or contralateral nerve root. In a finite-element model, Zagra et al. [29] found a tendency toward higher stiffness with bl-PLIF than ul-PLIF, but ul-PLIF was comparable to TLIF in their analysis. However, the authors have shown adequate clinical results with ul-PLIF and concluded ul-PLIF as viable and safe [29]. In our study, we found substantially higher levels of residual motion with ul-PLIF compared to bl-PLIF in both CS and PS, especially in AC, FE, LB, and AR. We speculate that the focal resection of anulus fibrosus and discectomy does heavily destabilize the segment, and insertion of a single PLIF does not adequately compensate for this damage, which especially manifests in AC motion. The results of our biomechanical study support the findings of Cho et al. [30], who reported 7.7 times increased pseudarthrosis rates 1 year postoperatively with ul-PLIF compared to bl-PLIF. However, others have shown adequate clinical outcomes with the use of only one PLIF cage without radiographic signs of pseudarthrosis [10]. Based on our results, caution is advised regarding the use of ul-PLIF. In our opinion, ul-PLIF should only be considered if the operative situs does neither allow insertion of a second PLIF nor change of procedure to TLIF.

fs-TLIF versus fr-TLIF

In the first description of minimally invasive interbody fusion in 1989 by Schreiber and Leu [31], a facet-sparing approach running laterally to the facet through Kambin's triangle was described [32]. Today, fs-TLIF is increasingly reported, especially for minimally invasive interbody fusion [14, 33]. Preserving the facet in interbody fusion along with cross-link augmentation has also been recommended by Matsukawa et al. [4] as a countermeasure against increased torsional motion provided by CS constructs. The present study confirmed a reduction of residual motion with fs-TLIF compared to fr-TLIF in both CS and PS constructs, which are most prominent in AC (+23% and +13%) and AR (+17% and +12%) for CS and PS constructs, respectively. We believe fs-TLIF might indeed be advantageous, especially in constructs in which a large residual ROM is expected with screw instrumentation only. In our experience, an fs-TLIF with an extraforaminal approach through the Kambin's triangle can also be chosen in open surgery, especially in the upper lumbar spine, due to the more medial lying facet joints. However, in the lower lumbar spine, fs-TLIF is easily

possible after midline decompression with insertion of the TLIF cage through a PLIF approach and aggressive rotation of the TLIF cage once positioned in the interbody space.

CS and interbody fusion

In this study, we had included posterior instrumentation with both PS and CS. The CS technique has gained popularity, because its trajectory beginning at the lateral part of the pars interarticularis reduces paraspinous muscle dissection and spares the superior facet joints and has further shown increased insertion torque and pull-out-strength [4, 34–36]. However, some authors have reported decreased construct stiffness due to the more medial running screw heads and decreased resistance to shear forces [37, 38]. Matsukawa et al. [4] have therefore recommended anterior column support with interbody fusion to overcome this potential drawback of CS in construct stability.

In this study, we have found significant reductions of residual motion with fs-TLIF and fr-TLIF in LB in the CS constructs. The reported findings support the routine use of TLIF in CS construct to decrease residual motion and increase construct stiffness. The largest clinical study to date on circumferential instrumentation with CS and TLIF by Marengo et al. [39] has also shown promising fusion rates of 94% after 1 year of follow-up.

Limitations

The biomechanical test setup in this study has some limitations. Most importantly, the reported ROM in FE, LB, AR, AS, LS, and AC is only rough simplifications of the complex motion and force patterns of a human spine *in vivo*. Also, the analyzed residual motions represent the immediate post-implantation motion in the postoperative short-term course, and the long-term outcome of these interbody fusion techniques was not investigated. Intuitively, the less residual motion provided with the instrumentation technique, the better the microenvironment to develop a solid bony fusion. Even though we speculate that a decrease in residual motion does have a beneficial clinical effect, we do not know to which extent the here reported differences impact the postoperative course in terms of patient satisfaction, rates of pseudarthrosis and implant loosening. In this study, we have reported both absolute and relative changes in ROM. In our opinion, the relative values are more informative because the reference ROMs, which were the instrumented segment without interbody fusion, were already low. Hence, the biomechanical effects of additional interbody fusion were also rather small with absolute differences ranging between 0–0.6° and 0–0.2 mm. However, relatively, these differences still have an essential and significant impact on residual motion.

The effect of the different interbody fusion techniques was measured on segments after bilateral laminotomy and resection of supra- and intraspinal ligaments, a common decompression technique that ensures adequate exposure of the disk space for interbody fusion. However, our results may not entirely translate to segments in which less invasive decompression techniques or minimal invasive interbody fusion were performed. With the insertion and subsequent removal of the PLIF cages from both sides, the posterior longitudinal ligament and anulus fibrosus were potentially harmed more extensively than with the direct fs-TLIF approach. This may have impaired the residual motion of the fs-TLIF construct, especially in the FE loading direction, according to a previous report that the posterior longitudinal ligament contributes 16% to flexion stability [15]. We also refrained from interbody bone grafting because we believe that this only minorly contributes to residual motion of the construct and, more importantly, is not standardizable in a biomechanical testing protocol.

Conclusion

The traditional PLIF and TLIF techniques lead to similarly low levels of residual motion in both CS and PS instrumentations. Caution is advised with the use of ul-PLIF, as it results in increased residual motion compared to bl-PLIF and TLIF and even increases motion in comparison to posterolateral instrumentation alone. In contrast, the fs-TLIF technique is able to decrease residual motion compared to the standard fr-TLIF technique in both the CS and PS constructs and presents a valuable option whenever surgically feasible.

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Declarations

Conflict of interest All authors state that they have no potential conflict of interest in relation to this study's content. MF is consultant for Medacta, but unrelated to the content of this manuscript.

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