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Abstract: BACKGROUND While convergent placement of pedicle screws in the axial plane is known to be more advantageous biomechanically, surgeons intuitively aim toward a parallel placement of screws in the sagittal plane. It is however not clear whether parallel placement of screws in the sagittal plane is biomechanically superior to a non-parallel construct. The hypothesis of this study is that sagittal non-parallel pedicle screws do not have an inferior initial pull-out strength compared to parallel placed screws. **METHODS** The established lumbar calf spine model was used for determination of pull-out strength in parallel and non-parallel intersegmental pedicle screw constructs. Each of six lumbar calf spines (L1-L6) was divided into three levels: L1/L2, L3/L4 and L5/L6. Each segment was randomly instrumented with pedicle screws (6/45 mm) with either the standard technique of sagittal parallel or non-parallel screw placement, respectively, under fluoroscopic control. CT was used to verify the intrapedicular positioning of all screws. The maximum pull-out forces and type of failure were registered and compared between the groups. **RESULTS** The pull-out forces were 5,394 N (range 4,221 N to 8,342 N) for the sagittal non-parallel screws and 5,263 N (range 3,589 N to 7,554 N) for the sagittal-parallel screws ($p = 0.838$). Interlevel comparisons also showed no statistically significant differences between the groups with no relevant difference in failure mode. **CONCLUSION** Non-parallel pedicle screws in the sagittal plane have at least equal initial fixation strength compared to parallel pedicle screws in the setting of the here performed cadaveric calf spine experiments.

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Abstract

Background While convergent placement of pedicle screws in the axial plane is known to be more advantageous biomechanically, surgeons intuitively aim toward a parallel placement of screws in the sagittal plane. It is however not clear whether parallel placement of screws in the sagittal plane is biomechanically superior to a non-parallel construct. The hypothesis of this study is that sagittal non-parallel pedicle screws do not have an inferior initial pull-out strength compared to parallel placed screws.

Methods The established lumbar calf spine model was used for determination of pull-out strength in parallel and non-parallel intersegmental pedicle screw constructs. Each of six lumbar calf spines (L1-L6) was divided into three levels: L1/L2, L3/L4 and L5/L6. Each segment was randomly instrumented with pedicle screws (6/45 mm) with either the standard technique of sagittal parallel or non-parallel screw placement, respectively, under fluoroscopic control. CT was used to verify the intrapedicular positioning of all screws. The maximum pull-out forces and type of failure were registered and compared between the groups.

Results The pull-out forces were 5,394 N (range 4,221 N to 8,342 N) for the sagittal non-parallel screws and 5,263 N

(range 3,589 N to 7,554 N) for the sagittal-parallel screws ($p=0.838$). Interlevel comparisons also showed no statistically significant differences between the groups with no relevant difference in failure mode.

Conclusion Non-parallel pedicle screws in the sagittal plane have at least equal initial fixation strength compared to parallel pedicle screws in the setting of the here performed cadaveric calf spine experiments.

Keywords Biomechanical comparison · Sagittal non-parallel · Pedicle screw · Pull-out force

Introduction

Posterior pedicle screw instrumentation has become the most frequently used surgical technique in the treatment of spinal disorders. However, pull-out of the screws can be a concern and is a major contributor to instrumentation failure in osteoporotic spines [5, 7, 14]. Technical options to minimize potential screw fixation failure by loosening and pull-out are: use of pedicle screws with an outer cylindrical and inner conical configuration with a V-shaped thread [10], cannulated pedicle screws with polymethylmethacrylate augmentation [2, 14] and expansive pedicle screws [10, 11]. Intraoperatively, not only can the choice of the implant affect the mechanical stability of the pedicle screw-rod construct, but also the placement and alignment of the screws themselves. “Hubbing” should be avoided during insertion [12]. Cortical violation decreases pull-out forces, particularly if the lateral cortex of the pedicle is affected [4]. If the screws are redirected after breach of the lateral wall, their maximal insertion torque, seating torque, screw loosening force and axial pull-out strength are largely decreased [15]. Redirection should be avoided if possible, but is often performed if the surgeon is not satisfied with the parallelism of the screws in the lateral

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fluoroscopic image. Although it is known that convergence of the screws in the axial plane increases the biomechanical stability [1, 6], the optimal placement of the screws in the sagittal plane is not clear. However, the surgeon intuitively tends to aim for radiographic parallelism of the screws in the sagittal plane. The hypothesis of this study is that sagittal non-parallel pedicle screws do not have inferior initial pull-out strength compared to parallel placed screws. If so, this would add to the reasoning for not redirecting sagittal non-parallel screws.

Materials and methods

The established calf spine model for screw pull-out testing [3, 9] was selected to answer the research question asked here. Six lumbar spines (L1–L6) from calves (age, 4–5 months; mean weight, 117 ± 12 kg) were divided into three levels, L1/L2, L3/L4 and L5/L6, so that 18 segments were available for testing. Randomly, nine samples were selected for sagittal-parallel screw placement (“P”) and nine for sagittal non-parallel (= sagittal open and closed angle) (“N”) screw placement (Figs. 1, 2 and 3) so that for each lumbar level, six segments were available in the P and six in the N group.

The holes were drilled with a 3-mm drill under fluoroscopic imaging aiming at intersegmental parallelism in the sagittal plane for the P group. For the N group, the aim was to drill the holes in 30° convergence on one side (sagittal closed angle) and in 30° divergence (sagittal open angle) on the contralateral side (Figs. 2 and 3 and Table 1). Convergence of at least 60° was desired in the axial plain (Table 1) in both the N and P groups. Attention was paid not to violate the pedicle during drilling. Subsequently, 6/45-mm pedicle screws were inserted and connected with a 6-mm rod. Computer tomography was used to exclude intraosseous pathologies such as hematomas and to assure intrapedicular placement of all screws before biomechanical testing (Fig. 4).

Pull-out testing was performed with a universal testing machine (Zwick-Roell, Zwick GmbH, Ulm, Germany). The segments were fixed with a steel rod (16 mm) connected to the testing machine and inserted through the spinal canal (Fig. 5) to avoid the influence of polymer resin fixation on pull-out strength [13]. Each end of the two rods was connected to a high-tension steel cable to allow both sides to be independent of each other (Fig. 5). Pull-out testing was initiated with a preload of 100 N and a constant displacement rate of 1 mm/s. The maximum pull-out force was quantified, and the type of failure was documented by two observers. Two types of failure were distinguished: screw pull-out versus vertebral/pedicle fracture, respectively.

Statistical analyses

Descriptive statistics were used to report means, standard deviations and ranges of data, where adequate. Intergroup comparison of insertion angles and pull-out forces was done using two-tailed Student’s *t*-test assuming parametric data, with a *p*-value of <0.05 defined as statistically significant.

Results

The maximal pull-out force was similar with 5,394 N (range 4,221 N to 8,342 N) in the N group compared to 5,263 N (range 3,589 N to 7,554 N) in the P group ($p=0.838$), with no relevant differences if individual segments were compared (Table 2).

The mean maximum pull-out forces per calf differed from 4,108 N to 7,377 N with each lumbar calf spine, providing three segments for testing. Each lumbar calf spine with its three segments was randomized to receive either a sagittal-parallel construct for L1/2, then a sagittal non-parallel construct for L3/4 and finally again a sagittal-parallel construct for L5/6 (P-N-P),

Fig. 1 Fluoroscopic lateral and axial images of a vertebral segment, instrumented with the standard sagittal parallel screw technique

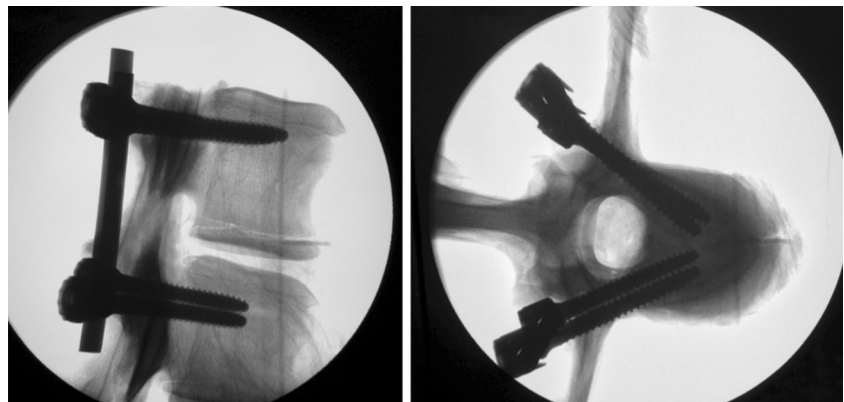
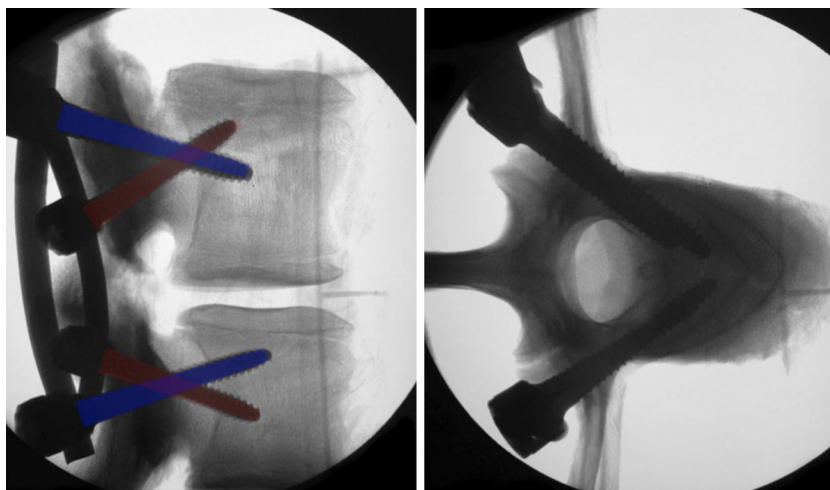


Fig. 2 Fluoroscopic lateral and axial images of a vertebral segment, instrumented with the alternative sagittal non-parallel screw technique



or first a sagittal non-parallel construct for L1/2 followed by a sagittal-parallel construct for L2/3 and sagittal non-parallel construct for L5/6 (N-P-N). There was no difference within the lumbar calf spines with a P-N-P sequence ($5,321 \pm 1,790$ N) compared to an N-P-N sequence ($5,335 \pm 708$ N).

The reason for failure of fixation was fracture of the pedicle or the vertebra in five (56 %) cases with a sagittal-parallel screw construct with a pull-out force of $5,526 \pm 1,443$ N. In the other four (44 %) cases with a sagittal-parallel screw construct, the pedicle screws pulled out without an osseous fracture with a pull-out force of $4,935 \text{ N} \pm 871$ N. With sagittal non-parallel screws, a fracture of the pedicle or the vertebra occurred in six (67 %) cases (mean of maximum pull-out force $5,911 \text{ N} \pm 1,553$ N), and pull-out of pedicle screws occurred in three (33 %) cases (mean of maximum pull-out force $4,360 \pm 76$ N). In the sagittal non-parallel screw constructs, the sagittal closed angle side failed four times ($6,221 \pm 1,733$ N), and the sagittal open-angle side failed five times with a non-significantly lower force of $4,732 \pm 858$ N ($p=0.189$).

Discussion

While it is well known that convergence of the pedicle screws in the axial plane adds to the biomechanical stability of the

instrumentation construct, most surgeons aim at radiographic parallelism in the sagittal plane. Often, the screws are redirected if not parallel enough in the sagittal plane for the sake of radiological aesthetics. The aim of this in vitro biomechanical study was to investigate whether the pull-out strength of sagittal non-parallel screws is inferior, equal or superior to sagittal parallel screws. We were able to document the non-inferiority of the pull-out strength of sagittal non-parallel screws compared to parallel screws in a cadaveric calf lumbar spine model. This observation has an important intraoperative impact as it counteracts the surgeon's intuition to place the screws absolutely parallel in the sagittal plane. Some surgeons even redirect screws to achieve radiographic parallelism in the sagittal plane, even though it is well known that redirecting screws decreases the biomechanical stability [15]. One would expect that sagittal intersegmental divergence (sagittal open-angle positioning) of the screws would add to the biomechanical stability because of better bone quality near the endplates, but it was reported previously that pedicle screws placed straight forward have similar pull-out failure characteristics compared to screws placed in an upward trajectory [8]. This is in concordance with our observation of the non-inferiority of sagittal intersegmental closed angle screws achieving at

Fig. 3 Posterior view of instrumented vertebral segments with the standard sagittal parallel screw and the alternative sagittal non-parallel screw technique

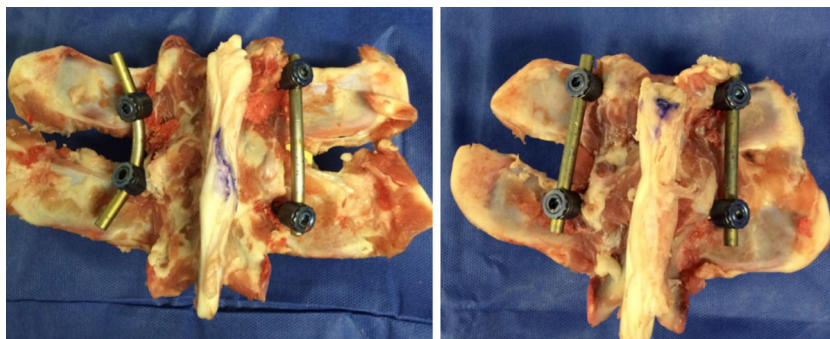
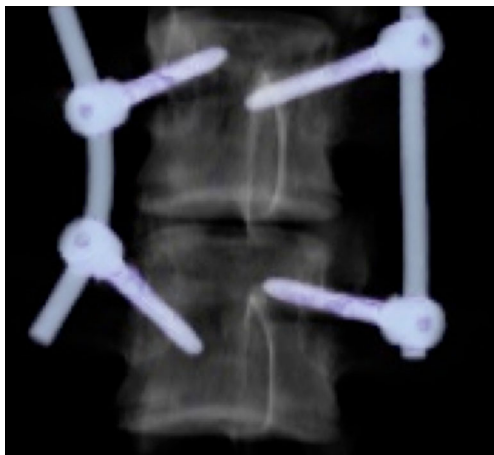


Table 1 Screw angles in the sagittal and axial plane in the sagittal-parallel (*P*) group and the sagittal non-parallel screw (*N*) group

	P group		N group		p
	Mean	SD	Mean	SD	
Sagittal view					
Screw angle in upper vertebra (°)	4	7	44	12	<0.005
Screw angle in lower vertebra (°)	5	5	44	8	<0.005
Intersegmental screw angle (°) (convergent/closed angle)	4	7	-39	6	<0.005
Intersegmental screw angle (°) (divergent/open angle)	6	6	46	9	<0.005
Axial view					
Screw angle in upper vertebra (°)	71	7	70	8	0.871
Screw angle in lower vertebra (°)	78	9	69	9	0.059

least the same pull-out strength as sagittal open-angle screws.

There are several aspects to consider before directly translating the results of this study to daily surgery. First, in the human spine, anatomical landmarks often limit the free choice of sagittal angulation of the screws. While intersegmental convergence (closed angle) of the screws is limited by the mechanical conflict of the head of the screw to the adjacent facet joint, intersegmental divergence (open angle) is limited by avoiding perforation of the endplates with the tips of the screws. Second, we used a calf spine model. While established in numerous previous studies on the pull-out strength of pedicle screws, the model has important limitations. The interspecies anatomy of the vertebrae is different, and the pedicles of the calf are significantly larger than human vertebral pedicles. However, the bone quality of different calf spines is more equal than those of cadaveric human spines of different ages. In this study, computer tomography was

**Fig. 4** Three-dimensional reconstruction of computer tomography images of a vertebral segment, instrumented with sagittal non-parallel screws**Fig. 5** Setup for biomechanical testing of pull-out strengths with a universal testing machine (Zwick-Roell, Zwick GmbH, Ulm, Germany). The segments are fixed with a steel rod (16 mm) connected to the testing machine and inserted through the spinal canal. Each end of the two rods is connected to a high-tension steel cable

used to rule out intraosseous pathologies such as hematomas that could influence the fixation strength of the screw and introduce bias. Further, the spinal segments were randomly assigned to the different groups in order to eliminate selection bias. Third, we assessed only primary stability by applying axial pull-out forces and cannot report on behavior of the different constructs with cyclic loading or angulated forces as this was not the research question of this study and is the subject of further research. Specifically, it was not the aim to

Table 2 Maximal pull-out forces of the sagittal-parallel (*P* group) and sagittal non-parallel screws (*N* group) in Newton

	P group		N group		p
	Mean	SD	Mean	SD	
Overall pull-out force	5,263	1,193	5,394	1,453	0.838
Level 1/2	5,559	1,728	5,376	922	
Level 3/4	5,495	484	5,670	2,317	
Level 5/6	4,735	1,357	5,135	1,419	

show the superiority but the non-inferiority of sagittally not perfectly parallel screws to counteract the surgeon's intuition of desiring radiographic parallelism in the sagittal plane.

Conclusion

Non-parallel pedicle screws in the sagittal plane have at least equal initial fixation strength compared to parallel pedicle screws in the setting of the here performed cadaveric calf spine experiments.

Presentation at conferences None.

Conflicts of interests None.

Source of funding Internal institutional resources.

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