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Lumbar vertebropexy after unilateral total facetectomy

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Abstract **BACKGROUND CONTEXT:** Posterior decompression with spinal instrumentation and fusion is associated with well-known complications. Alternatives that include decompression and restoration of native stability of the motion segment without fusion continue to be explored, however, an ideal solution has yet to be identified.

PURPOSE: The aim of this study was to test two different synthetic lumbar vertebral stabilization techniques that can be used after unilateral total facetectomy.

STUDY DESIGN: Biomechanical cadaveric study.

METHODS: Twelve spinal segments were biomechanically tested after unilateral total facetectomy and stabilized with a FiberTape cerclage. The cerclage was pulled through the superior and inferior spinous process (interspinous technique) or through the spinous process and around both laminae (spinolaminar technique). The specimens were tested after (1) unilateral total facetectomy, (2) interspinous vertebropexy and (3) spinolaminar vertebropexy. The segments were loaded in flexion-extension (FE), lateral shear (LS), lateral bending (LB), anterior shear (AS) and axial rotation (AR).

RESULTS: Unilateral facetectomy increased native ROM in FE by 10.6% (7.6%−12.6%), in LS by 25.8% (18.7%−28.4%), in LB 7.5% (4.6%−12.7%), in AS 39.4% (22.6%−49.2%), and in AR by 27.2% (15.8%−38.6%). Interspinous vertebropexy significantly reduced ROM after unilateral facetectomy: in FE by 73% (p=.001), in LS by 23% (p=.001), in LB by 13% (p=.003), in AS by 16% (p=.007), and in AR by 20% (p=.001). In FE and LS the ROM was lower than in the baseline/native condition. In AS and AR, the baseline ROM was not reached by 17% and 1%, respectively. Spinolaminar vertebropexy significantly reduced ROM after unilateral facetectomy: in FE by 74% (p=.001), in LS by 24% (p=.001), in LB by 13% (p=.003), in AS by 28% (p=.004), and in AR by 15 % (p=.001). Baseline ROM was not reached by 9% in AR.

CONCLUSION: Interspinous vertebropexy seems to sufficiently counteract destabilization after unilateral total facetectomy, and limits range of motion in flexion and extension while avoiding full segmental immobilization. Spinolaminar vertebropexy additionally restores native anteroposterior stability, allowing satisfactory control of shear forces after facetectomy.

CLINICAL SIGNIFICANCE: Lumbar vertebropexy seems promising to counteract the destabilizing effect of facetectomy by targeted stabilization.

Keywords: Facetectomy; Lumbar fusion; Lumbar spine; Semi-rigid; Spinal stabilization; Vertebropexy

FDA device/drug status: Not applicable.

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Introduction

Foraminal decompression surgery with unilateral removal of a facet joint [1,2] is usually combined with posterior spinal instrumentation and fusion (PSF). It is known that resection of important passive stabilizers like the supraspinous and interspinous ligaments, ligamentum flavum and posterior bony structures such as the facet joint can negatively affect segmental stability [3]. Biomechanical studies have shown that a unilateral resection of more than 50% of the facet joint results in a change in translational displacement and motion segment flexibility, indicating destabilization of the vertebral segment [4]. In addition, it is known that degenerative changes can lead to instability of a motion segment [5]. Therefore, facetectomy for decompression of the intervertebral foramen is usually combined with PSF or transforaminal lumbar interbody fusion (TLIF) [6,7]. However, PSF is associated with well-known complications such as adjacent segment degeneration (ASD), screw loosening, implant failure, and pseudoarthrosis [8−11]. In addition, it is associated with longer postoperative recovery, more surgically related complications, and higher costs than decompression alone [12]. An ideal surgical solution that includes decompression and restoration of native stability of the vertebral segment without fusion is still pending.

With this in mind, a new approach, a ligamentous reinforcement of vertebral bodies called "vertebropexy" [13], was developed based on orthopedic principles of semi-rigid fixation of joints. The aim of the technique is to achieve selective stabilization of the spine using allografts, autografts or synthetic grafts in order to restore sufficient stability, for example, as needed after iatrogenic instability caused by resection of ligamentous or bony structures of the spine. The procedure does not aim at completely immobilizing the segment, but rather at achieving stability in flexion-extension and during anterior-posterior (AP) shear movements. This distinguishes vertebropexy from previous wiring techniques used for cervical fixation, which aimed for absolute stability but were abandoned due to unsatisfactory results [14]. In addition, unlike other attempts at stabilization with an artificial ligament [15], the pedicles remain intact, so if stabilization fails, fusion is still possible without having to move to a more cranial vertebra. The biomechanical goal of selective stabilization has already been validated in cadaveric experiments [13] and in clinical use [16]. The aim of the present biomechanical study was to answer the question whether (1) synthetic semi-rigid stabilization of the spine (by vertebropexy) restores native segmental stability after unilateral total facetectomy and (2) simultaneously limits anteroposterior shear forces.

Materials and methods

Dissection, preparation and storage

The study was approved by the responsible investigational review board. Twelve fresh-frozen lumbar segments (Th12-L1: 4, L2−L3: 4, L4−L5: 4) from five human cadavers were procured from Science Care (Phoenix, AZ, USA). The median age was 75 years (range 43−94 years), two were male and three were female. Computed tomography scans (CT; SOMATOM Edge Plus, Siemens Healthcare GmbH, Erlangen, Germany) were performed to exclude specimens with fractures, tumors, spondylophyte formation, and any signs of bony defects. The cadavers were stored in plastic bags at -20°C until thawed overnight. After thawing, the cadavers were each separated into the vertebral segments Th12-L1, L2−L3, and L4−5. The specimens were cleaned of connective tissue and paraspinal musculature, leaving the intervertebral ligaments, disks, and facet joint capsule intact. After preparation, the segments were mounted on a testing machine (Fig. 1) using custom 3D-printed clamps [17].

The segments were previously tested in another study [18]. Specifically, the segments were tested in the native state and after the following surgical procedures: (1) after microsurgical decompression by unilateral laminotomy, (2) after interspinous vertebropexy, and (3) after spinolaminar vertebropexy. The native range of motion obtained in the previous study was used as the baseline for this study.

Description of the stepwise surgical decompression and techniques of the semi-rigid fixation

Unilateral total facetectomy and interspinous semi-rigid fixation

To simulate a realistic clinical scenario, microsurgical decompression was performed by unilateral laminotomy [18] prior to unilateral facetectomy (as in foraminotomy) for lumbar radiculopathy caused by nerve compression within the foramen. A chisel was used to unilaterally remove the inferior articular process of the cranial vertebral body to destabilize the facet joint.

For interspinous semi-rigid fixation, the technique of interspinous vertebropexy was followed and adapted by using a FiberTape Cerclage (Arthrex, Naples, Florida) instead of the allograft (18, Calek et al., submitted data): Both spinous processes were prepared by drilling a 3.2 mm hole through the center of the spinous process (Fig. 2). A

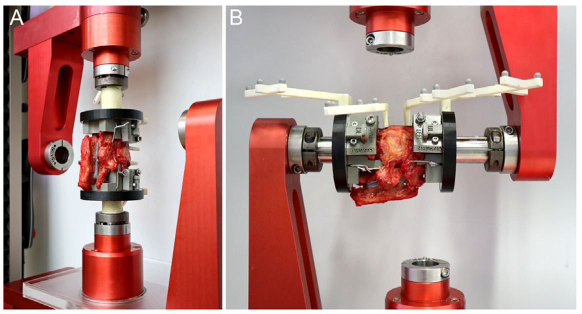

Fig. 1. The setup used for biomechanical testing (A+B) used to test spinal segments. Postero-lateral view (A) and lateral view (B).

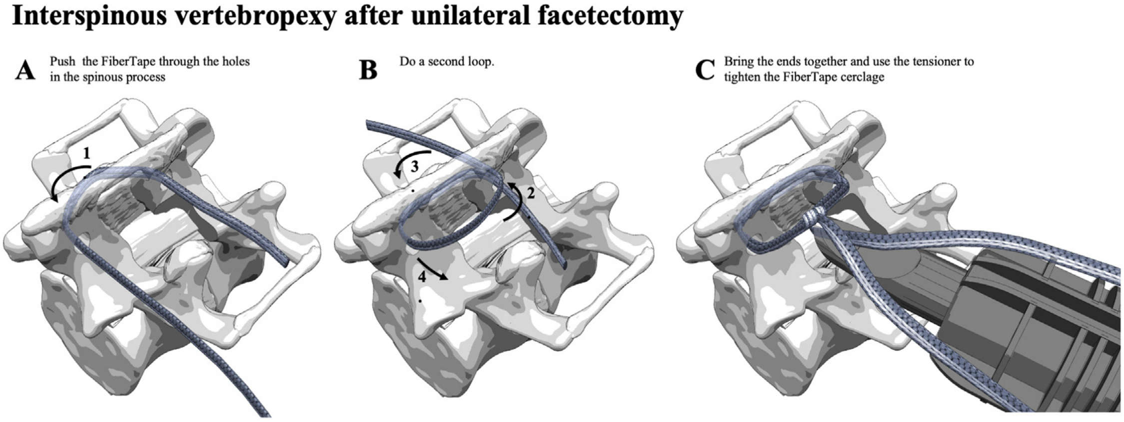

Fig. 2. Schematic illustrations of the interspinous vertebropexy after unilateral facetectomy.

FiberTape cerclage was pulled through the holes using a double loop technique (Fig. 2). An extension force of 5 Nm was applied using the testing machine to simulate physiological extension of the lumbar spine (in prone position). The cerclage was then tightened in a standardized manner using the corresponding tensioner with a force of approximately 180N each time (second mark on the tensioner). The cerclage was then secured with five knots.

Semi-rigid fixation was performed using a FiberTape Cerclage as an alternative to tendons (original concept of vertebropexy), as these may not be widely available and are expensive. We believe that the FiberTape cerclage comes closest to the original concept. Other alternatives, such as wiring systems, are significantly more rigid and bulky and may be perceived as intrusive by patients. In addition, they may increase the risk of iatrogenically induced spinal stenosis.

Spinolaminar semi-rigid fixation

A FiberTape cerclage was passed through the preexisting hole in the spinous process of the caudal vertebral body and then guided cranially anterior to the lamina of the proximal vertebral body. The cerclage was looped and passed again through the spinous process of the distal vertebra. The same technique was used on the opposite side (Fig. 3). Finally, the FiberTape cerclage was secured with five knots.

Biomechanical experiments and testing protocol

Force-controlled displacements were measured after the application of a predefined load to the cranial vertebra with the caudal vertebra fixed to a semi-constrained test apparatus (Zwick/Roell Allroundline 10 kN, Germany) (Fig. 1). Each specimen was tested native and after (1) unilateral total facetectomy, (2) interspinous fixation and (3) spinolaminar fixation. After each surgical step, the segments were loaded in flexion-extension (FE), lateral shear (LS), lateral bending (LB), anteroposterior shear (AS), and axial rotation (AR) (in the order listed). A customized mounting apparatus for the clamped specimens was used [17], consisting of high-precision fitting rings, pins, and a mechanism to compress the connection with a defined load prior to tightening.

FE and LB were tested at a speed of 1°/sec, achieving a torque of ± 10 Nm. For AR, the load was applied at a speed of 0.5°/sec. AS and LS were measured at a speed of 0.5 mm/sec, with 200 N applied in each direction [19]. To test the synthetic fixation of lumbar vertebral body segments at extreme loads, slightly higher loads than in the physiological range were intentionally chosen. After completion of five preconditioning cycles, the range of motion (ROM) of the sixth cycle was recorded. Infrared-emitting markers were attached to each vertebra to measure ROM (Fusion Track 500, Atracsys, Puidoux, Switzerland). Additional markers were attached to the 3D-printed mounting clamps to ensure proper fit of the clamps. During testing, specimens were kept fresh by spraying with phosphate-buffered saline.

Segmental ROM after unilateral facetectomy was compared with segmental ROM after (1) interspinous synthetic vertebropexy, and (2) spinolaminar synthetic vertebropexy. Furthermore, the two vertebropexies were compared with each other.

Data analysis

The statistical evaluation was performed using MATLAB (Matlab 2020b, MathWorks, Massachusetts, USA). The difference in range of motion (ROM) relative to the native condition is reported with the median and interquartile range. The Wilcoxon signed rank test was used for the statistical comparison of matched relative ROM values. The alpha level of significance was set at 0.05 and p-values were corrected according to Bonferroni to adjust for multiple comparisons.

Results

Biomechanical effect of unilateral total facetectomy

Unilateral facetectomy increased native ROM in all loading cases (Fig. 4): in FE by 10.6% (7.6%−12.6%), in

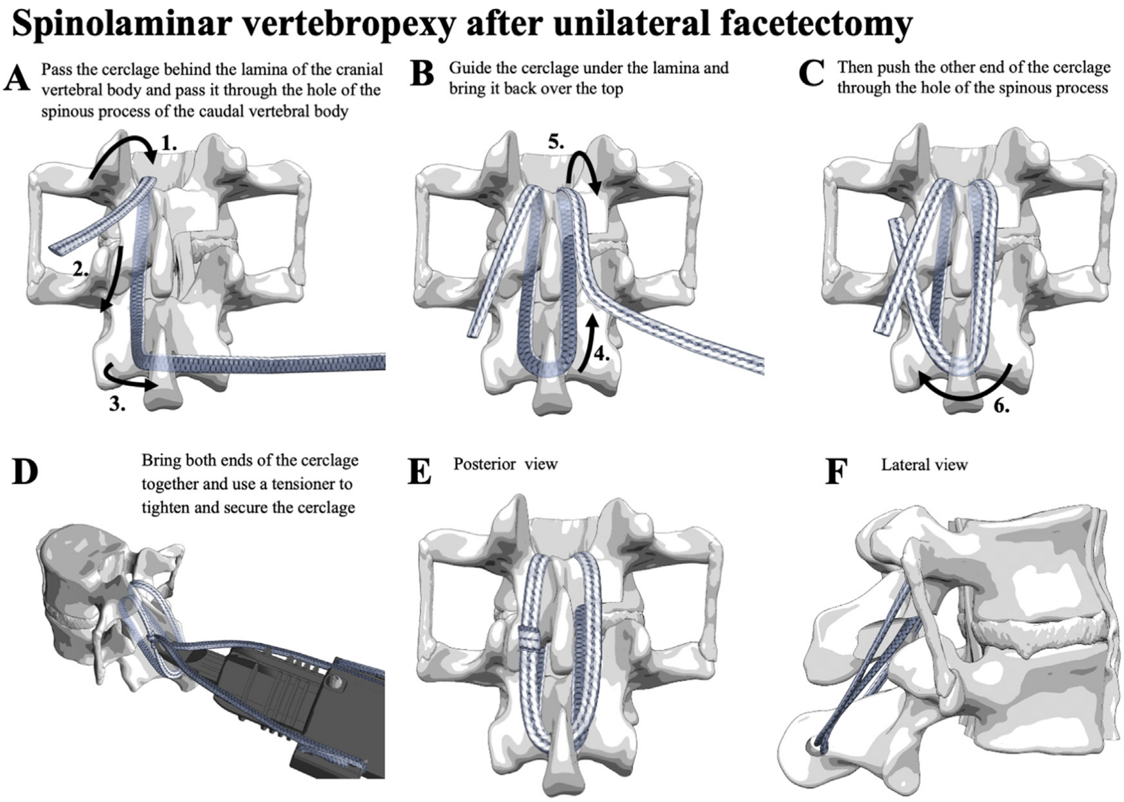

Fig. 3. Schematic illustrations of the spinolaminar vertebropexy after unilateral facetectomy.

LS by 25.8% (18.7%−28.4%), in LB 7.5% (4.6%−12.7%), in AS 39.4% (22.6%−49.2%), and in AR by 27.2% (15.8% −38.6%).

Effect of synthetic vertebropexies after unilateral total facetectomy

Interspinous vertebropexy significantly reduced ROM in all loading cases after unilateral facetectomy (Fig. 4): in FE by 73% (p=.001), in LS by 23% (p=.001), in LB by 13% (p=.003), in AS by 16% (p=.007), and in AR by 20 % (p=.001). Interspinous fixation resulted in lower ROM than baseline for FE and LS. Baseline ROM was not achieved for AS (by 17%) and for AR (by 1%).

Spinolaminar vertebropexy significantly reduced ROM in all loading cases after unilateral facetectomy: in FE by 74% (p=.001), in LS by 24% (p=.001), in LB by 13% (p=.003), in AS by 28% (p=.004), and in AR by 15 % (p=.001). Spinolaminar fixation did not reach native baseline ROM by 9% in AR.

Comparison of interspinous and spinolaminar vertebropexy

The effect of the two techniques was comparable (Fig. 4): FE 30.3% versus 29.1%, p=.157 (median; relative ROM after interspinous versus spinolaminar synthetic vertebropexy; native =100%); LS 97% versus 96.1%, p=1; LB 93.3% versus 93.3%, p=1; AS 117.3% versus 100.3%, p=.192; and AR 101.4 versus 108.7%, p=.037.

Discussion

The main findings of the present study are that both vertebropexy techniques (interspinous and spinolaminar) decreased vertebral segment ROM after unilateral total facetectomy. In FE, LS, and LB the segment was transferred beyond the native state to a more stable state, without complete immobilization of the segment. Aligned with the goal of vertebropexy [13], the greatest effect was seen in flexion-extension. The spinolaminar fixation technique furthermore restored the native segmental stability after unilateral total facetectomy and anteroposterior shear forces could be reduced, especially with the spinolaminar technique.

Lumbar foraminal stenosis is a common condition that occurs in the context of degenerative processes caused by spondylolisthesis, hypertrophy of the upper facets, decreased disc height, and osteophyte formation. In addition to these bony stenoses, foraminal stenosis can also affect young patients without relevant degenerative changes. The underlying cause is a foraminal disc herniation that constricts the exiting nerve. In both cases, there are several surgical treatment options to relieve the compression of the exiting nerve root, including foraminotomy, facetectomy, partial pediculotomy, usually combined with posterior spinal fusion [1,6,20].

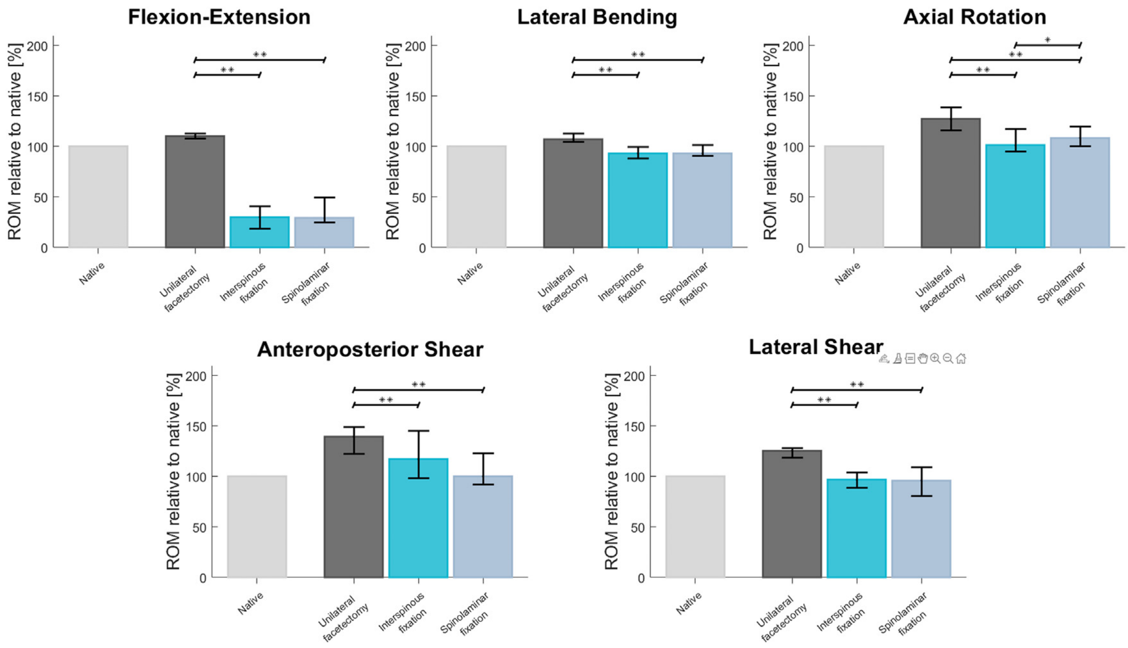

Fig. 4. Effect of unilateral facetectomy, interspinous and spinolaminar vertebropexy.

In the case of total facetectomy, fusion must be performed due to the resulting loss of stability, which may appear radical in young patients. Especially in light of the fact that pedicle screw instrumentation reduces the segment mobility to a minimum. The resulting redistribution of loads may lead to adverse mechanical consequences within the spine, which are associated with negative patient outcomes [21]. Overall, spinal fusion has a high complication rate [8−11], with one-third of patients requiring reoperation within 15 years [22].

While fusion surgery eliminates segmental mobility, facet joint surgery, which ranges from partial resection to total facetectomy [20,23], achieves the opposite. The facet joints are important for guiding vertebral motion and resisting compression, shear, rotation, and load bearing − they play a critical role in providing stability and strongly influence spinal kinematics [24]. Biomechanical studies demonstrated that a unilateral resection of the facet joint of more than 50% leads to a change in translational displacement and motion segment flexibility, indicating destabilization of the vertebral segment [4]. The increased segmental mobility may cause pain and advance the degenerative cascade [13,25,26].

Previous dynamic stabilization systems, such as Dynesys, a pedicle screw-based dynamic stabilization system, bear the major problem of screw loosening [27]. The large movements between the bone and screw interface are associated with loosening rates greater than 20% [28], making these systems inappropriate. The TOPS system, a mobile spinal implant designed to replace the posterior elements of a functional spinal unit, also contains pedicle screws and, despite satisfactory results in small cohorts [29,30], carries the aforementioned risk of screw loosening. In contrast, syndesmoplasty uses an artificial ligament whose free ends are inserted into the vertebral body through a hole in the pedicle, crossed within the vertebral body, and re-exited from the vertebral body through the opposite pedicle [15]. The authors report good clinical and radiographic results, but stabilization appears to be technically challenging and carries the risk of pedicle destruction and, if the ligament is avulsed, iatrogenic spinal stenosis. Another technique called "interspinous ligamentoplasty" uses a figure-of-eight technique to hold two to three spinous processes together [31]. It showed comparably good results in patients with degenerative spondylolisthesis. No disadvantages of semirigid fixation over dorsal fusion have been demonstrated [32]. However, from our point of view, the main problem with this technique is the inability to achieve semirigid stabilization. In a preliminary experimental study, we tested a number of stabilization techniques, including a figure-of-eight configuration, which produced less optimal results than the techniques presented here because it was impossible to apply sufficient tension to the ligament.

In summary, a good surgical alternative for affected patients is still pending, and a middle ground is being sought to neither destabilize nor fix too rigidly. The goal must be to restore at least native stability.

Synthetic vertebropexies may represent this solution; both techniques presented in this paper increased segment stability for all directions of motion after unilateral total facetectomy without totally abolishing segment mobility. In flexion-extension, the effect was most profound; the two techniques reduced ROM by almost 70% compared to the destabilized segment.

The stabilizing effect of the two synthetic vertebropexy techniques was comparable. However, one relevant difference was encountered between the two techniques: Native antero-posterior stability could be restored with the spinolaminar technique, whereas this was less achievable with the interspinous technique. The reason for this is presumably that fixation with the spinolaminar technique involves not only the cranio-caudal direction but also the antero-posterior direction (Fig. 3), and thus forces can be absorbed in this direction. Only in one direction of motion, AR, both techniques could not fully restore native stability. Native stability was missed by a few degrees: 1° for the interspinous technique and 9° for the spinolaminar technique. However, this study biomechanically tested an extreme condition, total unilateral facetectomy. This is certainly not always necessary, and it is expected that after more sparing resections that preserve parts of the joint, native stability can be restored in all directions of motion.

All in all, the synthetic vertebropexies achieve passive stability, not only more "conservatively" than PSF, but also more targeted: they mainly restrict flexion-extension and, to a lesser extent, shear movements, while the other directions of movement are restored close to the native state.

Clinical implications

Lumbar vertebropexy seems promising to counteract the destabilizating effect of facetectomy by targeted stabilization and could therefore be an alternative to fusion, especially in young patients with foraminal stenosis. By not completely immobilizing the segment, complications such as ASD may be avoided or at least delayed. Moreover, the proposed technique is reversible, that is, stabilization can be reversed, and the option of conversion to dorsal fusion remains. Segmental stability is increased without complete immobilization, so the drawbacks of fusion should be avoided. Semi-rigid stabilization is particularly interesting for those cases in which the surgeon wishes to achieve more stability after decompression, for example in the case of preexisting low-grade spondylolisthesis, but wishes to avoid fusion (Meyerding grades I and II).

The results of the present study suggest that stabilization with lumbar vertebropexy after unilateral facetectomy may be sufficient in this regard, as it satisfactorily limits motion in flexion and extension. With spinolaminar fixation, native anteroposterior stability could be restored, suggesting that low-grade spondylolisthesis can be treated with this novel stabilization technique.

Limitations

This biomechanical study has some limitations. The main limitations of the biomechanical experimental setup have been described in detail elsewhere [18]: namely, the difficulty of approximating real ROM, since the human spine undergoes complex motion sequences in vivo, and that the ROM represented here must be expected to change over time due to scarring and degenerative changes. To simulate a prone position, an extension load of 5Nm was applied via the static testing machine. This force may vary in the clinical setting depending on the positioning of the patient and is not reliably measurable. However, the influence of positioning should not be underestimated, as changes in the force required to tighten the construct are expected depending on the degree of lordosis/kyphosis of the segment. For spinolaminar stabilization in unilateral pathology, the approach must be extended to the opposite side, which inevitably weakens the ligamentum flavum by creating a small passage for the graft. However, since fusion (TLIFs with pedicle screw instrumentation) is performed as an alternative to vertebropexy after unilateral facetectomy, which also requires bilateral exposure, we believe that this extension of the surgical approach is not negligible, but within acceptable limits. A further limitation of use of synthetic material for vertebropexy might be a cut-out effect with repetitive micromotions. However, we believe that the scarring process in vivo will counteract this potential limitation in clinical application.

Vertebropexy specifically restricts motion, with the greatest effect in flexion-extension. In contrast to fusion, the segments are not completely immobilized in other directions of motion, therefore the redistribution of load to adjacent segments may be smaller and the adverse mechanical consequences we face after fusion leading to ASD may be less common. However, previous lumbar stabilization techniques could not prevent ASD completely [33]. Therefore, clinical studies with long-term follow-up are needed to investigate whether the theories suggesting motion preservation will result in lower ASD rates with vertebropexy.

Conclusion

Interspinous vertebropexy seems to sufficiently counteract destabilization after unilateral total facetectomy, and limits range of motion in flexion and extension while avoiding full segmental immobilization. Spinolaminar vertebropexy additionally restores native anteroposterior stability, allowing satisfactory control of shear forces after facetectomy.

Authors' contribution

AKC: design of the study, data collection, results interpretation, manuscript writing and editing; JW: results interpretation and manuscript editing; MRF: data analysis and manuscript editing; MF: idea, conception, manuscript editing.

Declaration of Competing Interests

The last author (MF) reports being a Consultant for Incremed (Balgrist University Hospital Startup), Zimmer Biomet, Medacta, and 25 Segments (Balgrist University Hospital Startup). All the other authors report no conflicts of interest.

Acknowledgment

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Availability of data and material

None.

Ethics approval

Kantonale Ethikkommission Zürich had given the approval for the study. (Basec No. KEK-ZH-Nr. 2022-00715).

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