



Spinous process resistance to different materials and looping techniques for interspinous lumbar vertebroplasty

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Abstract

Purpose Semi-rigid spinal stabilization has been explored as an alternative to spinal fusion, and early experience with spinal segment augmentation (“vertebroplasty”) is promising. The main technical challenge is to maintain the integrity of the spinous processes during loading. This study aimed to compare different looping materials and techniques with respect to their performance in maintaining spinous process integrity.

Methods One hundred and five thoracolumbar vertebrae were tested with various looping materials and techniques; the “Tunnel-only” double-loop technique was tested with a synthetic tape (FiberTape®), bovine tendon, and a hybrid tape option. Additionally, the performance of the synthetic tape was tested for other augmentation techniques such as the “Figure-of-eight” looping technique, a double-loop combination of tunneling and cortical wrapping, and a double-loop with “Cortical wrapping only”. Biomechanical testing was performed by uniaxial caudo-cranial distraction to failure.

Results The loads required to cause spinous process failure were lowest with the synthetic tape, followed by tendon and hybrid constructs by tendency (419 N vs. 487 N vs. 519 N) in the “Tunnel-only” double-loop technique. The comparison showed that the “Tunnel+cortical wrapping” technique required significantly higher forces to induce failure compared to other techniques, particularly the “Tunnel only” method ($p < 0.001$).

Conclusion The choice of the looping technique and material in lumbar interspinous vertebroplasty significantly affects the resistance of the spinous process to load. Techniques that incorporate cortical bone and use tendinous material demonstrate superior resistance to higher forces, compared to methods that involve passing synthetic tape through a hole solely within trabecular bone. Additionally, the role of trabecular bone density in the spinous process is relatively minor when cortical bone is utilized as an abutment for the loop.

Keywords Spinal stabilization · Semi-rigid · Vertebroplasty · Lumbar spine · Spinous process · Augmentation

Introduction

Spinal fusion is the most common surgical procedure in spine surgery for degenerative spine disorders [1]. Its use has increased in recent years with the availability of minimally

invasive techniques that are highly effective in restoring sagittal and coronal alignment [2–4]. Complications associated with spinal fusion, such as adjacent segment degeneration, screw loosening, pseudoarthrosis, cage migration, and subsidence can result in neurological compression and recurrent pain, often necessitating revision surgery [5]. Given the substantial proportion of patients needing revision surgery within a few years post-initial procedure [6], a novel technique, “Vertebroplasty” has been developed as an alternative surgical treatment. Based on the orthopedic principles of ligament reinforcement/augmentation, it has demonstrated encouraging biomechanical results when used after decompression surgery or unilateral total facetectomy; restoring native segmental stability and transitioning the segment into a semi-rigid state, especially notable in flexion-extension

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[7–9]. Furthermore, early short-term clinical outcomes indicate clinical potential [10].

Several techniques have been developed to augment the spinous processes of a spinal segment for vertebroplasty. One such technique involves drilling a hole into the spinous process to loop and tension the stabilizing material, such as tendon or synthetic tape. This approach aims to restore stability to the decompressed and destabilized spinal segment. It is similar to ligamentous augmentation techniques used in adult spinal deformity surgeries to reduce proximal junctional kyphosis and proximal junctional failure, thereby reducing stress at the upper instrumented vertebra [11, 12]. However, drilling a hole in the spinous process can increase the risk of spinous process fractures, particularly when considering long-term stability maintenance [13–15]. Understanding the biomechanical resistance of the spinous process to these augmentation techniques is crucial for refining them to achieve more reliable clinical outcomes.

The aim of this biomechanical study was twofold: (1) to determine the forces that cause a spinous process fracture, and (2) to compare various materials and augmentation techniques biomechanically. The ultimate goal is to identify an augmentation technique (vertebroplasty) that offers high resistance to distraction forces.

Materials and methods

Dissection and preparation

The study was approved by the responsible investigational review board. One hundred eight spinous processes originating from eighteen fresh frozen cadavers (Science Care, Phoenix, AZ, USA) were included. Three spinous processes had to be excluded leaving 105 spinous processes (18 TH12, 18 L1, 18 L2, 18 L3, 18 L4, 15 L5) for the tests. The average age was 70 years (38–98) with an average BMI of 36 kg/m² (15–55). Eight specimens were female and ten were male. To exclude any bony defects, computed tomography (CT) scans (NAEOTOM Alpha, Siemens Healthineers, Erlangen, Germany) were performed, after thawing. The specimens were carefully dissected, ensuring that all bony structures remained intact. Following the dissection, the spinous processes were separated at the pars interarticularis from the rest of the vertebrae using an oscillating saw. Subsequently, the facet joint capsules were incised using a scalpel, with the aim of preserving the inferior articular processes (IAP) of the facet joint on both sides while maintaining their connection to the spinous process.

In the samples assigned to a testing group that required an augmentation technique involving a hole through the bone, a 5 mm hole was drilled into the spinous processes. The hole

was positioned between the center and the upper third of the cranial border of the spinous process. A small metal rod was slid through the hole in the spinous process, ensuring a consistent distance of 5 mm between the center of the hole in the spinous process and the potting material during the potting process (Fig. 1A). The pars interarticularis and IAPs of the vertebral bodies were potted into appropriate boxes using Polymethyl methacrylate (PMMA; SCS-Beracryl D 28 Powder and SCS-Veracryl D 28 Liquid, Suter Kunststoff-AG, Frauenbrunnen, Switzerland). Subsequently, the metal rod was removed, and the tip of the spinous process was potted in a separate box to guarantee stable conditions for testing (Fig. 1B). The prepared specimen was then securely mounted in the testing machine (Fig. 1C).

Looping materials and looping techniques for interspinous vertebroplasty

Twelve spines with a total of 72 spinous processes were divided into three groups, each containing 24 spinous processes, to evaluate different materials using the original interspinous technique (Fig. 2). This technique was described in prior biomechanical studies and also in a clinical study [7–10] and consists of a double-loop construct with looping material being guided through a hole in the spinous process (“Tunnel only– Double loop”). Three distinct materials were tested: (1) FiberTape (Arthrex, Naples, Florida) (Fig. 2A), (2) bovine tendon, augmented at the ends with Fiberwire No. 2 (Arthrex) (Fig. 2B), and (3) a hybrid method where the bovine tendon was reinforced with FiberTape (Fig. 2C). For material (3), special attention was paid to ensure that the tendon was positioned internally and that the FiberTape did not make contact with the spinous process’s hole.

Further, six spines with 33 spinous processes (three spinous processes had to be excluded) were used to evaluate three newly established looping techniques with FiberTape. These constructs were compared to the original interspinous technique (“Tunnel only– Double loop”, Fig. 3A) and to each other: (i) “Figure-of-eight (8)– Single loop” (Fig. 3B), (ii) “Tunnel+cortical wrapping– Double loop” (Fig. 3C), and (iii) “Cortical wrapping only– Double loop” (Fig. 3D).

The loops were guided through the spinous process’s hole and/or wrapped around the cortical surface of the process and cranially attached to the testing machine using a hook (Fig. 1C).

Biomechanical experiments

A uniaxial distraction load was applied to the spinous process with a universal testing machine (Zwick/Roell, Zwick GmbH, Ulm, Germany) through the loop-hook connection

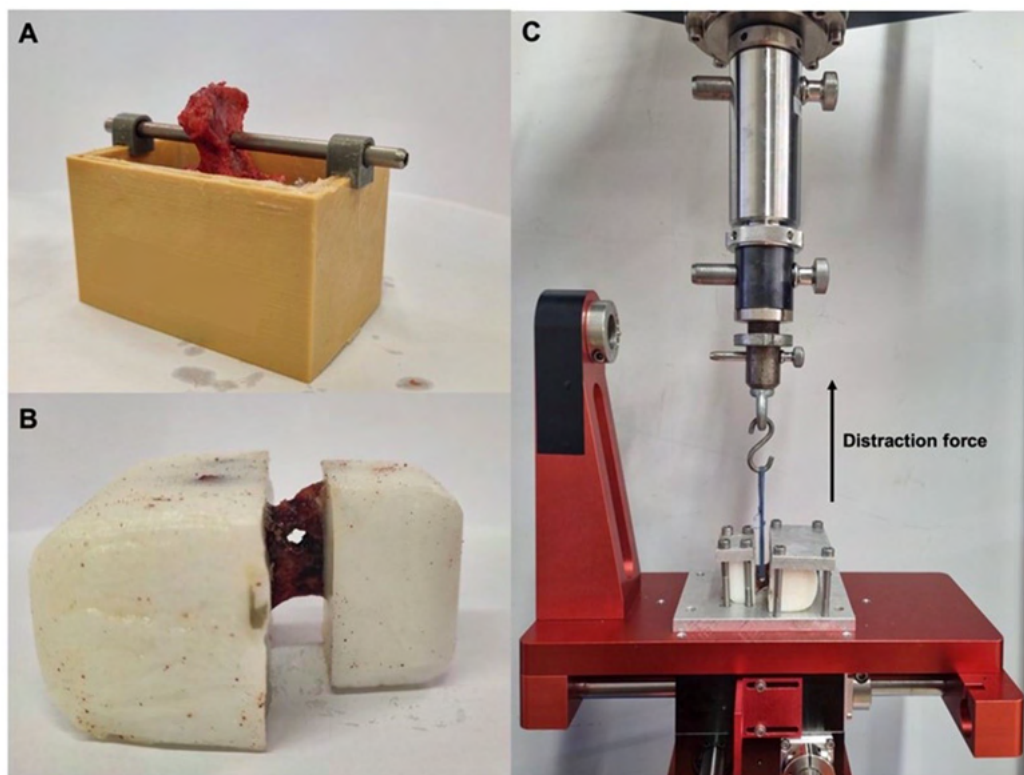


Fig. 1 The setup for biomechanical testing: (A) potting of the spinous process with a metal rod slid through the hole to ensure a distance of 5 mm from the potting material. (B) Potted specimen. (C) Specimen mounted in the testing machine

Varying looping material

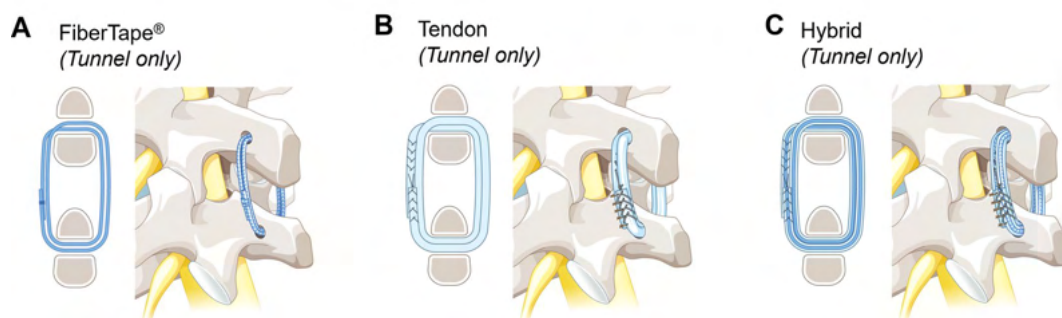


Fig. 2 Schematic representation of the investigated looping materials (with the original “Tunnel only– Double loop” technique): (A) FiberTape, (B) Tendon, (C) Hybrid

(Fig. 1C). For this purpose, the Xforce HP 10 kN load cell, which has a measurement accuracy of $\pm 0.5\%$ for force measurements above 100 N and is produced by the same manufacturer as the testing machine, was utilized.

Each specimen underwent a ramp-to-failure test to assess its performance under these conditions. The spinous processes were initially subjected to a preload of ± 5 N in the distraction plane. The distraction load was methodically applied at a constant rate of 0.2 mm/second. This force was progressively increased until a failure event occurred, which

could be either fracture of the spinous process or failure of the loop. The recording of the force was promptly ceased when a decrease of 50% from the maximum force was observed. Subsequently, an analysis was conducted to compare the maximum distraction forces achieved using different looping techniques.

CT scans were used to determine the trabecular bone quality in the spinous process in PACS (picture archiving and communication system). A two-dimensional image slice was obtained along the midsagittal plane of each vertebra,

Varying looping technique

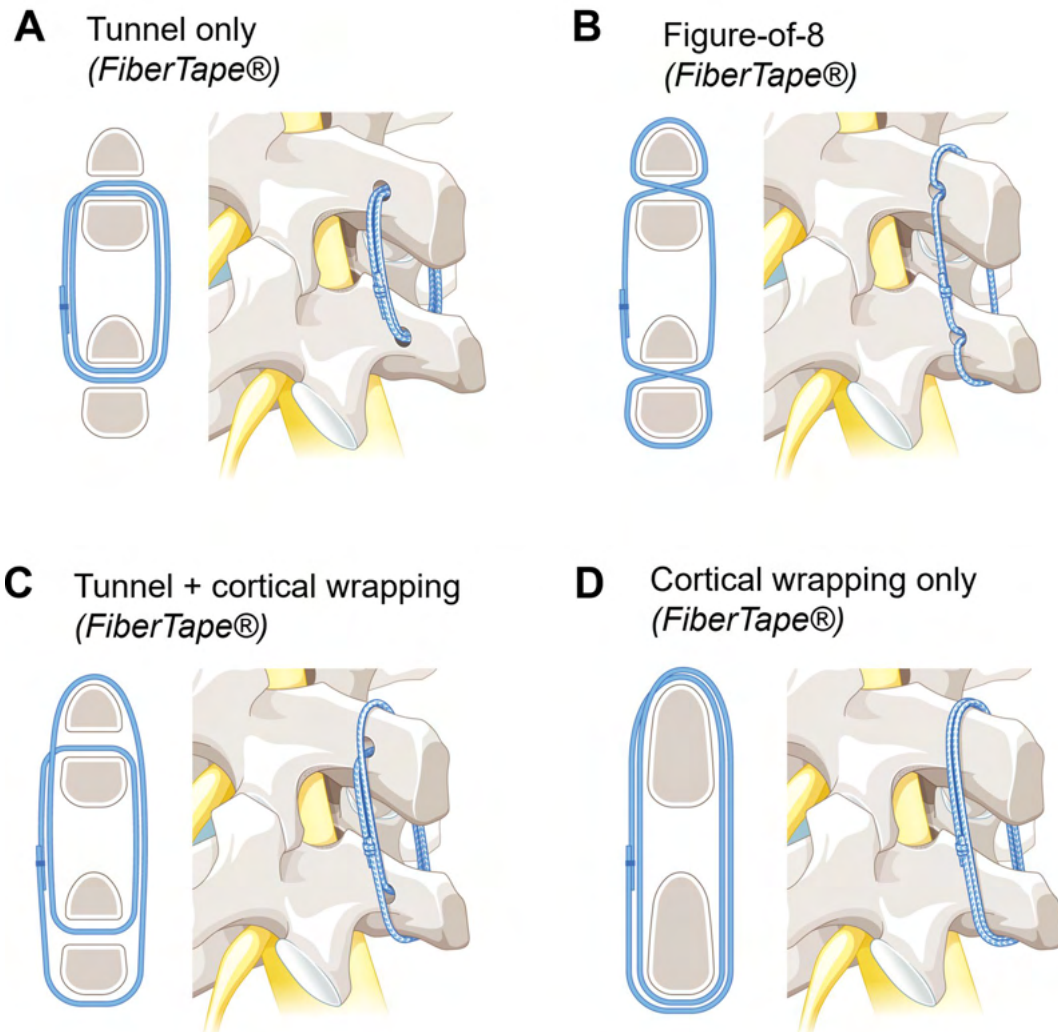


Fig. 3 Schematic representation of the investigated looping techniques (using FiberTape material): (A) original interspinous technique or “Tunnel only– Double loop”, (B) “Figure-of-eight (8)– Single loop”,

and the average Hounsfield Units (HU) was obtained within a circular area with a minimum diameter of 5 mm. The circle covered only trabecular bone. This factor’s influence on the spinous process’s resistance to the applied force was thoroughly investigated.

Statistical analysis

The statistical analysis was performed with MATLAB (Matlab 2020b, MathWorks, Massachusetts, USA). For each tested looping material/technique combination, the median (25th -75th percentile) of the maximal resistance force was computed. Kruskal-Wallis tests and Bonferroni-corrected

(C) “Tunnel+cortical wrapping– Double loop”, (D) “Cortical wrapping only– Double loop”

pairwise comparisons were performed to determine whether there were differences in failure force when using different looping materials or different looping techniques. The correlation between force and average HU in the spinous process trabecular bone was computed. The significance level α was set at 0.05.

Results

Comparison of looping material for the “Tunnel only– Double loop” technique: FiberTape, tendon, and hybrid

In eight out of 72 samples, failure occurred at the loop rather than in the bone. The causes of failure included tendon rupture and/or fixation slippage. Comparing FiberTape, tendon, and hybrid materials, the results showed that the maximum forces required to cause failure of the spinous process ($n=64$) tended to be lowest with FiberTape (Fig. 4A; Table 1 in Supplementary Information).

Bone density influenced the resistance of the spinous process when using FiberTape or the hybrid method. A higher HU value corresponded to an increased absolute force required to fracture the spinous process: FiberTape: $\rho=0.57$, $p<0.001$; hybrid: $\rho=0.642$, $p<0.05$. However, when a tendon was used, bone density had no significant impact on resistance: tendon: $\rho=0.429$, $p=0.08$ (Fig. 4B).

Comparison of looping techniques utilizing FiberTape: “Tunnel only”, “Figure-of-eight”, “Tunnel + cortical wrapping”, and “Cortical wrapping only”

The comparison between “Tunnel only” (original interspinous technique), “Figure-of-eight”, “Tunnel + cortical wrapping”, and “Cortical wrapping only” showed that the maximum forces required to induce failure of the spinous

process or the loop itself were higher for the “Tunnel + cortical wrapping” and “Cortical wrapping only” compared to the other techniques with significantly higher forces compared to the “Tunnel only” condition: $p<0.001$ (Fig. 5A; Table 2 in Supplementary Information).

Bone density did not influence the resistance of the spinous process when using the “Figure-of-eight” ($\rho=0.01$, $p=0.98$), “Tunnel + cortical wrapping” ($\rho=-0.07$, $p=0.83$), and “Cortical wrapping only” ($\rho=-0.04$, $p=0.91$) (Fig. 5B). This suggests that bone density does not significantly affect the resistance force of the spinous process when at least a segment of the loop is wrapped around the cortical bone of the spinous process (Fig. 1).

Discussion

Semirigid segmental augmentation techniques (concept of vertebroplasty [9]) have been developed to provide a novel stabilization technique for spinal segments in addition to spinal fusion. This is crucial because degenerative conditions of the lumbar spine are among the most common spinal pathologies leading to surgery. Spinal fusion minimizes segmental mobility and results in load redistribution that places more stress on adjacent segments [16]. As a result, patients are informed that 20–36.1% of all patients will require revision surgery within the first five to 15 years after the index procedure [6, 17, 18]. These numbers may have decreased somewhat with the advent of minimally invasive techniques in recent years that preserve the posterior ligament and do

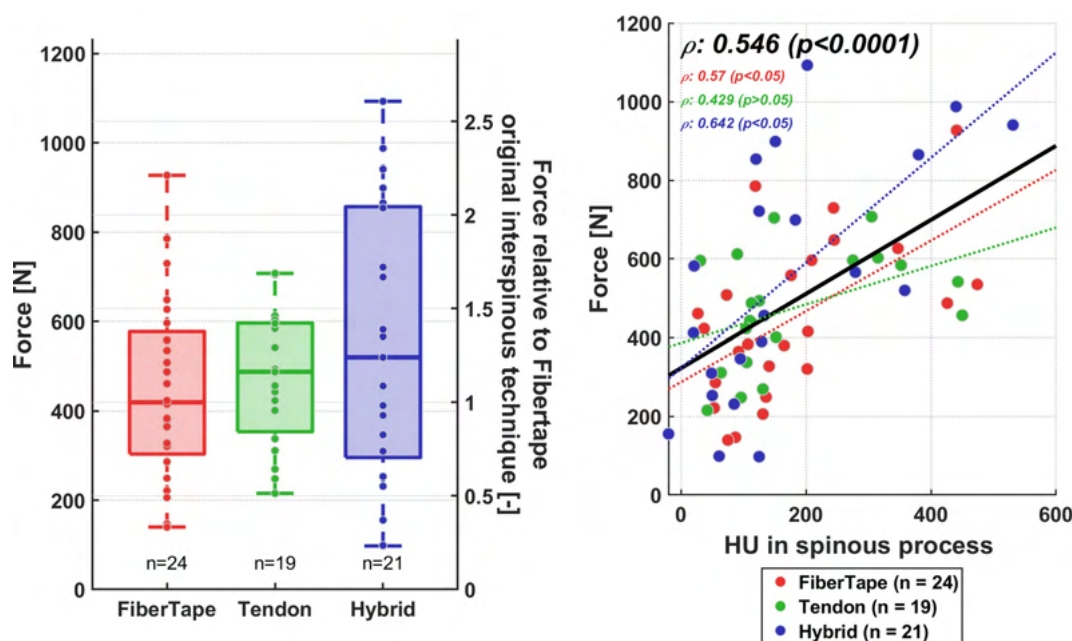


Fig. 4 Comparison of looping material: Absolute resistance to failure of the construct (A) and the influence of bone density on the resistance force (B). Only specimens with a fracture of the spinous process were considered

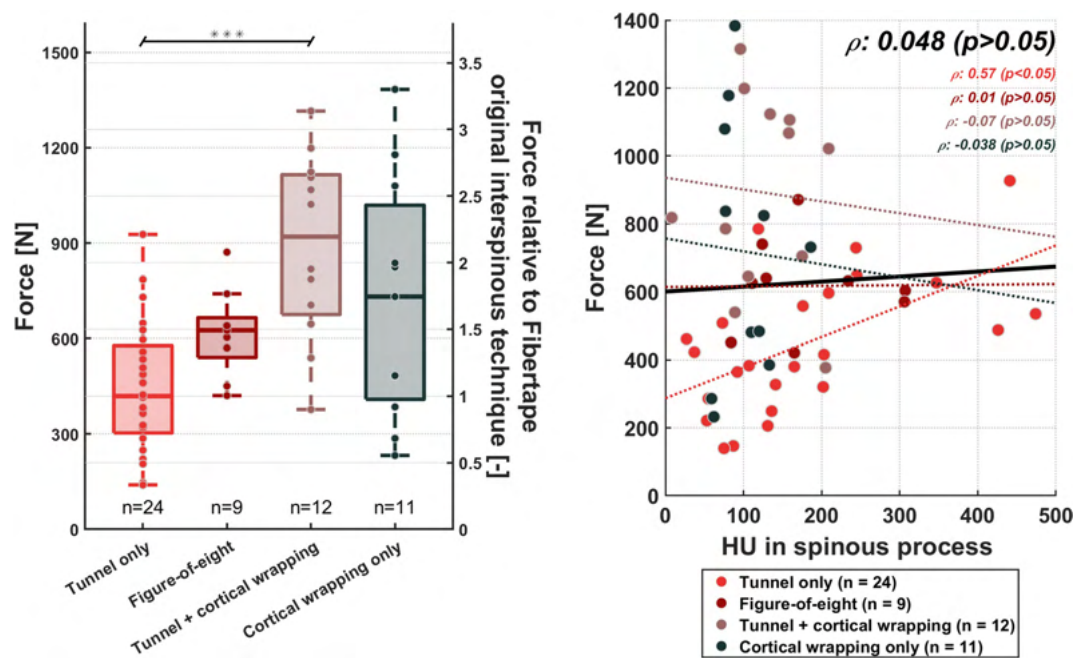


Fig. 5 Comparison of looping techniques: Absolute resistance to failure of the construct (A) and the influence of bone density on the resistance force (B). Only specimens with a fracture of the spinous process were considered

not detach the paraspinal muscles. Nevertheless, the biomechanical drawbacks persist, which is why the technique of vertebroplasty has been developed.

Interspinous vertebroplasty [7, 9] relies on the resistance of the spinous process to mechanical forces. With increasing biomechanical testing and results from various vertebroplasty techniques (interspinous, interlaminar, spinolaminar) and their clinical applications [10], it has become clear that the mechanical resistance of the spinous process is crucial to the performance of these techniques. This is particularly important when combined with decompressive laminotomies. Previous biomechanical studies have shown that an intact lumbar spinous process can tolerate distraction forces between 291 and 707 N before fracturing, whereas this tolerance is reduced to 85–453 N after a laminotomy [19]. Therefore, this biomechanical study aimed to compare different techniques and materials for interspinous vertebroplasty to identify the optimal configuration. The three main findings were:

1. Looping techniques involving cortical bone are superior.
2. Allograft materials perform better than synthetic tape (FiberTape).
3. Bone density is only relevant in the techniques that rely solely on trabecular bone (“Tunnel only, double loop”).

The first main finding was that biomechanical resistance to failure is significantly improved if the tape or tendon is wrapped around the spinous processes in a way that involves

cortical bone. Specifically, the double loop technique, where one loop of the construct is passed through a hole in the spinous process and the other loop is wrapped around the spinous process (“Tunnel+cortical wrapping”; Fig. 3C), withstood forces that were twice as high compared to the original technique (“Tunnel only”; Fig. 3A). This indicates that the distribution of forces is more optimal in this technique, resulting in spinous process fractures only occurring at higher forces. Additionally, bone density affects the resistance of the spinous process if the loop tunnels through the spinous process without wrapping over it. However, when parts of the loop are wrapped around the cortical bone of the spinous process, the trabecular bone density no longer significantly affects the resistance in this experimental setting. We believe that in cases where the loop surrounds the cortical bone, the quality of the cortical bone is much more important than the trabecular bone density, as the cortical bone’s integrity is not necessarily dependent on the condition of the trabecular bone.

The second main finding was that the material used in interspinous vertebroplasty affects biomechanical performance. In the original description of interspinous vertebroplasty, allografts were used to stabilize spinal segments [9]. Subsequently, synthetic materials were tested as alternatives [7, 8]. In this experimental setting, the tested synthetic band (FiberTape) created the lowest resistance forces for the original technique of interspinous vertebroplasty, likely due to a gigli saw effect.

The third finding was that bone density positively correlated with the absolute resistive force of the spinous process in techniques that relied mainly on trabecular bone (“Tunnel only, double loop”). Specifically, the higher the mean HU in the spinous process, the more axial distraction force was required to cause a fracture when materials were looped through a hole in the spinous process. However, this positive correlation ceased when parts of the loops were wrapped around the cortical bone of the spinous process.

Combining the main findings of this study, it appears that compared to the original description of the interspinous technique [9], the biomechanical performance of the spinous process can be improved by wrapping the material at least once around the cortical bone and by using tendons or similar materials.

This study does not investigate whether natural materials (allografts, xenografts, autografts) offer advantages over synthetic ligaments in terms of biological integration and stiffness, beyond the criterion of primary stability. While the initial rationale for using allografts (biologic material) was to promote more efficient scarring, thereby enhancing the effect of vertebroplasty, this benefit may be less pronounced with synthetic materials.

In contrast to the material, the choice of the looping technique appears to be crucial for creating a stable and lasting construct. This is particularly important given the unknowns about force transmission through passive structures during complex spinal movements in a living body. We recommend that the technique should at least loop around the spinous processes. The biomechanical advantage in terms of mechanical strength achieved by this method outweighs the minor disadvantage of potentially damaging the adjacent segment (tunneling through the interspinous ligaments).

This biomechanical study has several limitations. First, we studied the isolated failure case of bone pull-out. With the methods we use, we cannot make any statements about other failure possibilities, such as fracture of the spinous process due to bending moments. This will be addressed in a follow-up study. Second, a bovine tendon was used instead of an allograft, and one might argue that these are not suitable surrogates for human tendons. However, a previous biomechanical study [20] demonstrated that bovine tendons have similar stiffness and failure loads compared to human cadaveric tendons in *in vitro* studies. Third, looping techniques that wrap around the spinous process might weaken the interspinous ligament. However, since the procedure would require the creation of only a small passageway for the graft, we believe this is within acceptable limits. Fourth, a small sample size of cadaveric vertebrae has been biomechanically tested and clinical applicability remains to be confirmed.

Conclusion

The choice of the looping technique and material in lumbar interspinous vertebroplasty significantly affects the resistance of the spinous process to load. Techniques that incorporate cortical bone and use tendinous material demonstrate superior resistance to higher forces, compared to methods that involve passing synthetic tape through a hole solely within trabecular bone. Additionally, the role of trabecular bone density in the spinous process is relatively minor when cortical bone is utilized as an abutment for the loop.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00586-025-08724-0>.

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Declarations

Ethics approval Kantonale Ethikkommission Zürich had given the approval for the study. (Basec No. KEK-ZH-Nr. 2024–00382).

Competing interests The last author (MF) reports being a Consultant for Medacta, Arthrex, 25Segements, Zurimed and President of the Board of MovingSpine (Balgrist University Startup) and shareholder of Balgrist University Startups (Moving Spine AG and X23D). JW is a part-time employee and a shareholder of Moving Spine AG. MRF is a part-time employee of Moving Spine AG. All the other authors report no conflicts of interest.

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