



Endplate weakening during cage bed preparation significantly reduces endplate load capacity

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Received: 9 November 2023 / Revised: 17 April 2024 / Accepted: 19 April 2024
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Abstract

Purpose To analyze the effect of endplate weakness prior to PLIF or TLIF cage implantation and compare it to the opposite intact endplate of the same vertebral body. In addition, the influence of bone quality on endplate resistance was investigated.

Methods Twenty-two human lumbar vertebrae were tested in a ramp-to-failure test. One endplate of each vertebral body was tested intact and the other after weakening with a rasp (over an area of 200 mm²). Either a TLIF or PLIF cage was then placed and the compression load was applied across the cage until failure of the endplate. Failure was defined as the first local maximum of the force measurement. Bone quality was assessed by determining the Hounsfield units (HU) on CT images.

Results With an intact endplate and a TLIF cage, the median force to failure was 1276.3N (693.1–1980.6N). Endplate weakening reduced axial endplate resistance to failure by 15% (0–23%). With an intact endplate and a PLIF cage, the median force to failure was 1057.2N (701.2–1735.5N). Endplate weakening reduced axial endplate resistance to failure by 36.6% (7–47.9%). Bone quality correlated linearly with the force at which endplate failure occurred. Intact and weakened endplates showed a strong positive correlation: intact-TLIF: $r=0.964$, slope of the regression line (slope)=11.8, $p<0.001$; intact-PLIF: $r=0.909$, slope=11.2, $p=5.5E-05$; weakened-TLIF: $r=0.973$, slope=12.5, $p<0.001$; weakened-PLIF: $r=0.836$, slope=6, $p=0.003$.

Conclusion Weakening of the endplate during cage bed preparation significantly reduces the resistance of the endplate to subsidence to failure: endplate load capacity is reduced by 15% with TLIF and 37% with PLIF. Bone quality correlates with the force at which endplate failure occurs.

Keywords Endplate · Dorsal fusion · Cage · Subsidence · PLIF · TLIF · Biomechanical study

Introduction

The use of intervertebral cages as part of spinal fusion surgery has increased rapidly in recent years. In the United States alone, the rate of lumbar fusion has increased by 322.6% between 2011 and 2019 [1]. This is because they offer biological and mechanical advantages: the insertion

of bone grafts improves and accelerates bony fusion [2], they expand the intervertebral space and facilitate lordosis correction [3], and absorb axial compression forces, thereby reducing the forces on pedicle screws and rods, which should reduce the risk of implant failure [4]. Posterior lumbar interbody fusion (PLIF) is used for various degenerative spinal conditions including degenerative disc disease, spondylolisthesis, spinal stenosis, and transforaminal lumbar interbody fusion (TLIF), which is preferred for foraminal stenosis [5].

As the number of fusion surgeries has increased, so have the associated complications [6]. Cage subsidence can cause pain due to loss of intervertebral height with foraminal narrowing and subsequent nerve root impingement, instrumentation failure, pseudoarthrosis, early screw loosening, kyphotic deformity, and adjacent segment degeneration [7]. Known risk factors include low bone density, posterior cage positioning, limited implant contact area and poor endplate condition [8]. Weakening of the endplate during cage bed

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preparation can also cause subsidence [9]. Typically, the cage bed is carefully prepared with a rasp to achieve bleeding and eventual bony fusion, but if this is done too aggressively, the endplate may be unknowingly opened [10].

Biomechanical studies have shown that endplate morphology plays an important role: If only the edge of the cage rests on the endplate due to the concave shape of the lower and upper endplate geometry, subsidence may occur due to peak loads [11]; the center of the endplate should be avoided as an isolated contact area, as this region is the weakest while the posterolateral region is the strongest [12].

Despite knowledge of the importance of cage positioning and the influence of endplate weakening, the biomechanical effect of endplate weakening has not been quantified yet.

The aim of this study was to analyze the effect of endplate weakening by PLIF and TLIF cages and to compare it to the other intact endplate of the same vertebral body. In addition, the influence of bone quality on endplate resistance was investigated. The hypotheses of the present study are that (1) endplate weakening significantly affects endplate load capacity and that (2) bone quality affects endplate resistance.

Materials and methods

The study was approved by the local ethics committee. Twenty-two lumbar vertebrae (three L1, five L2, five L3, five L4, four L5) obtained from five fresh-frozen human specimens (Science Care, Phoenix, AZ, USA) were tested in this study. The median age was 55.4 years (range 36–75, two males and three females). Computed tomography (CT) scans (SOMATOM Edge Plus, Siemens Healthcare GmbH) showed no bony defects or deformities. The lumbar vertebrae

were isolated, taking care not to damage the endplates. Any remnants of the disc were sharply removed. First, one of the two endplates was biomechanically tested by immobilizing the vertebral bodies in customized 3D-printed clamps in a testing machine (Fig. 1A) [13]. The vertebrae were then released from the clamps and inverted to test the other endplate. To ensure a stable fixation, the vertebral bodies were cast in appropriate boxes using polymethylmethacrylate (PMMA; Fig. 1B, E) to test the second endplates. The boxes were made of polylactic acid (PLA). Two different fixation techniques (clamps and potting) were used for practical and financial reasons.

Biomechanical experiments

One endplate of each vertebral body was tested in the intact state and the other in the weakened state. The endplates were weakened with a shaver commonly used to prepare the disc space prior to cage insertion. Cortical bone was removed over an area of 200 mm², corresponding to the head of the shaver, until cancellous bone was visible in the area where the cage was to be placed. Either a PLIF (PLIF; MectaLIF Posterior; Fig. 1B) or a TLIF cage (TLIF; MectaLIF Transforaminal; Fig. 1C) was then placed on the intact or weakened endplate. Allocation was randomised. Care was taken to ensure that there were equal numbers of vertebrae in the PLIF and TLIF groups. The rationale for using a unilateral PLIF (uPLIF) cage in our study was to be able to draw more appropriate conclusions regarding bilateral PLIF (bPLIF) cages (than vice versa) without underestimating the force acting on the endplate when using a single cage. Subsequently, uniaxial compression load was applied to the cage using a static testing machine (Zwick/Roell Allroundline

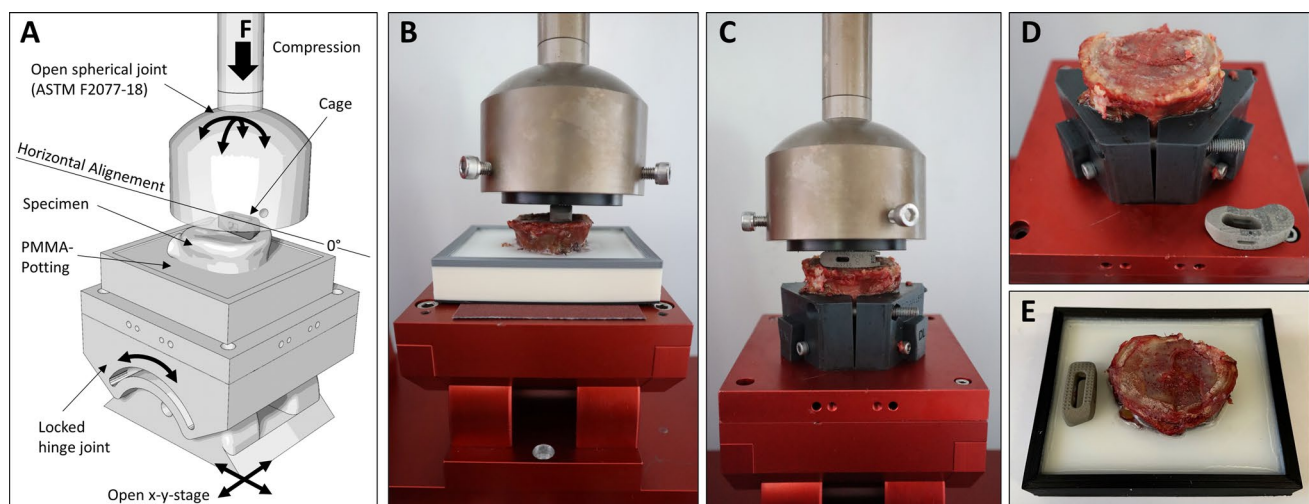


Fig. 1 Illustration of a lumbar vertebra undergoing a “ramp to failure” test (A). PLIF cage (B) and TLIF cage (C) mounted in the testing machine. Lumbar vertebra with endplate fracture after compression loading using a TLIF cage (D) and a PLIF cage (E)

10kN and testXpert III software; Fig. 1A). The test setup was performed in accordance with the ASTM F2077-18 (Test Methods for Intervertebral Body Fusion Devices) standard for compression test configuration [14]. The endplate was loaded through an open spherical joint to ensure that the force was applied uniformly across the cage. In addition, the vertebra was mounted on an x-y stage that allowed translational motion orthogonal to the loading direction (Fig. 1A). Prior to biomechanical testing, the posterior bony structures were removed using an oscillating saw to ensure that the compression force was applied to the cage in isolation. A Xforce HP 10kN load cell with an accuracy of $\pm 0.5\%$ for force measurements above 100N, manufactured by the same company as the testing machine, was used.

Biomechanical testing protocol

Each vertebral body was tested twice in a ramp-to-failure test: (1) the intact endplate on one side, and (2) the weakened endplate on the other side. Eleven of the 22 lumbar vertebrae were assigned to the PLIF group and eleven to the TLIF group.

The cages were preloaded with $\pm 20\text{N}$ in the compression plane. Compression was applied at a velocity of 5 mm/min according to the specifications of the ASTM 2077-18 test standard. The force was recorded until 5 mm displacement were reached (Fig. 1D–E).

Data evaluation and statistical analysis

The force at which failure occurred, indicating sintering of the cage and therefore fracture of the endplate, was defined as the first local maximum of the force measurement (Fig. 2). The maximum compressive force that resulted in failure of the intact endplate was compared with the force that resulted in failure of the weakened endplate using paired nonparametric comparisons (Wilcoxon signed-rank test). Probability density functions were fitted onto the failure force results for different cage configurations (uPLIF, bPLIF, and TLIF) in order to compare the distributions of forces measured for the intact and the weakened endplates. In addition, bone quality was assessed for each vertebra from the CT images in Hounsfield units (HU) according to Schreiber et al. [15]. The average HU value resulting from three elliptical regions of interest within the vertebral body on axial slices (below the superior endplate, in the middle of the vertebral body, and above the inferior endplate) was set as the reference value for the status of the vertebral (trabecular) bone. Variable tube voltage used during CT acquisition was taken into account by adapting the HU according to the results of Afifi et al. [16].

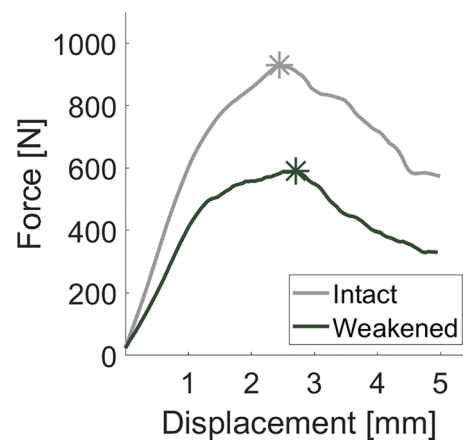


Fig. 2 Example curves of an intact and weakened endplate with the first local maximum (“asterisk”) of the force measurement and subsequent cage subsidence

Intraclass correlation coefficient (ICC) (Model: two-way mixed effect; Definition: absolute agreement, Type: single measurement) was: 0.996 [0.991,0.998]. Linear regression analysis was then used to investigate the resulting average HU value as a factor influencing endplate resistance to force through linear regression analysis. The significance level α was set to 0.05 and the values are specified as median (25th–75th percentile).

Results

Failure force in intact and weakened endplates

With a TLIF cage, the median force at failure was 1276.3N (693.1–1980.6N) with an intact endplate. With a weakened endplate, the force at which failure occurred was significantly reduced by a median of 15% (0–23%, $p = 0.04$; Fig. 3). The weakened endplates resisted a median force of 1149N for TLIF cages.

With a PLIF cage, the median force at failure was 1057.2N (701.2–1735.5N) with an intact endplate. With a weakened endplate, the force at which failure occurred was significantly reduced by a median of 36.6% (7–47.9%, $p = 0.007$; Fig. 3). The weakened endplates resisted a median force of 1101.7N for PLIF cages.

Bone quality correlated linearly with the force at which endplate failure occurred (Fig. 4). Both, intact and weakened endplates showed a strong positive correlation: intact—TLIF: $r = 0.964$, slope of the regression line (slope) = 11.8, $p < 0.001$; intact—PLIF: $r = 0.909$, slope = 11.2, $p = 5.5E - 05$; weakened—TLIF: $r = 0.973$, slope = 12.5, $p < 0.001$; weakened—PLIF: $r = 0.836$, slope = 6, $p = 0.003$.

Fig. 3 Absolute and relative compression resistance in intact and weakened endplates with TLIF and PLIF cages (* $p < 0.05$; ** $p < 0.01$)

Endplate resistance to compression

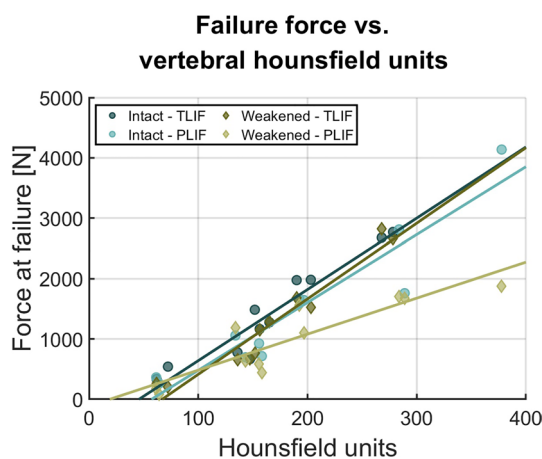
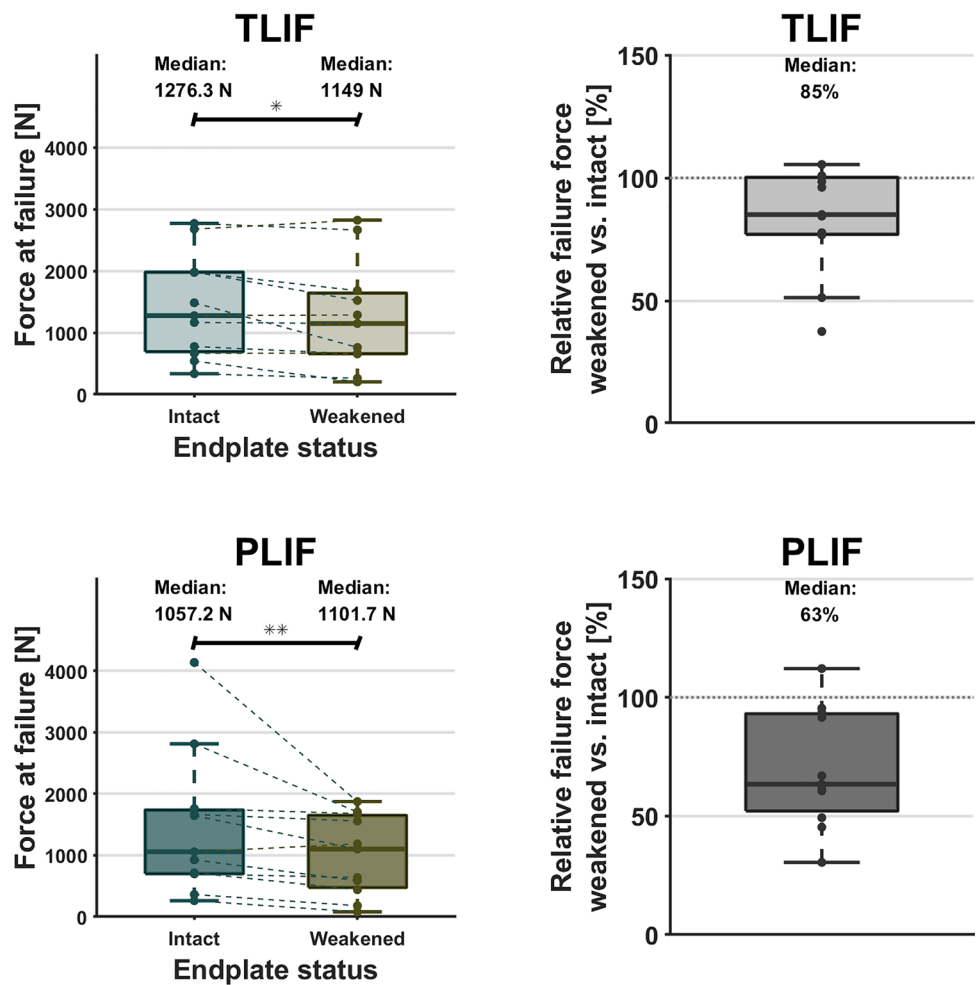


Fig. 4 Influence of bone quality (measured in Hounsfield Units) on endplate resistance force

Discussion

The most important finding of the study is that endplate weakening significantly reduced endplate resistance to subsidence of the endplates, which may promote cage migration or subsidence. The effect was even more pronounced when a uPLIF cage was used (70% (median)–36.6%) compared to TLIF cage (83.1% (median)–15%).

Lumbar interbody fusion techniques have evolved rapidly over the past few decades, leading to an expansion of indications [17]. Among these, PLIF and TLIF are the most commonly used techniques [18, 19]. They provide solid fusion and allow for neural decompression, provide an additional fusion interface with a higher fusion rate than bone graft alone [20], restore the intervertebral height and help restore alignment [21]. From a biomechanical point of view, the interbody fusion device is designed to support the anterior column and transmit compressive forces [22, 23]. However, failure to achieve bony fusion may result in cage migration

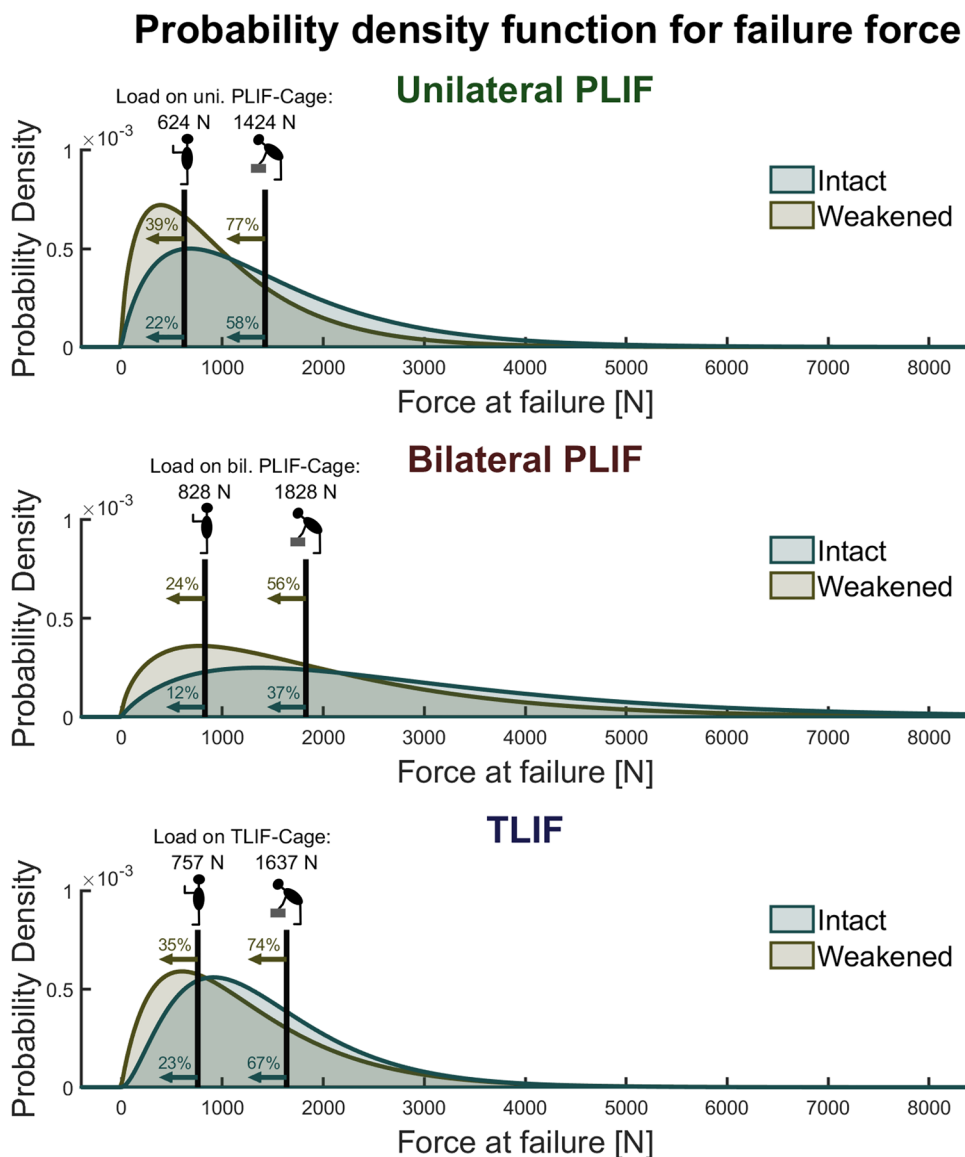
or subsidence. Cage subsidence rates reported in the literature range from 0 to 65% [21, 24–27], with implant contact area, endplate condition, and bone mineral density appearing to play an important role [8, 28].

The contact area between the cage and the endplate depends on the morphology of the endplate (i.e., highly concave or irregularly shaped endplates reduce the contact area), and on the shape and size of the cage. The smaller the surface contact area, the higher the stress on the endplate [29–31]. Banana-shaped and anatomically contoured cages increase the contact surface compared to rectangular cages and therefore theoretically have a lower tendency to subside [11]. This may explain why the failure load of the uPLIF was slightly lower than that of the TLIF in the present study. Due to the concavity of the endplates, the PLIF cage often only came into contact with the bone at the edges, causing force peaks in these areas and resulting in fractures.

Violation of the endplates during cage bed preparation appears to have a relevant biomechanical effect: the exposure of cancellous bone reduced the failure force by 15% for the TLIF and 37% for the PLIF, respectively. To compare the distributions of forces measured for the intact and the weakened endplates, and to better assess the potential clinical implications of the experimental results, probability density functions were fitted to the failure force results for each cage configuration (uPLIF, bPLIF, and TLIF; Fig. 5).

Preload and percentage of external load transfer through the cage were obtained from previously published biomechanical experiments involving axially compressed spinal segments with load cell instrumented vertebral cages [32]. Specifically, an average preload of up to 328N was measured (uPLIF 224N; bPLIF 328N; TLIF 317N), and up to 50% (uPLIF 40%; bPLIF 50%; TLIF 44%) of the external compressive load was transmitted through the cage to the

Fig. 5 Illustration of the probability density functions of the intact and weakened endplate for three different cage configurations. For all three cage configurations, the cage loads in the upright position and during physical activity (such as lifting an object) are evident, as are the areas under the probability density function curves: the probability of endplate fracture is higher in the weakened state than in the intact state for all configurations



ventral column of the spine, thus affecting the endplates. It was therefore possible to determine the likely loading of each cage configuration during upright standing (about 1000N acting on the spine) and during more vigorous daily activities (about 3000N on the spine) and to link it to the cage-specific failure forces of intact and weakened endplates [33, 34]. During upright standing, likely 624N, 828N, and 757N are going through the uPLIF, the bPLIF, and the TLIF, respectively. During more vigorous activities, the uPLIF, bPLIF and TLIF are subjected to 1424N, 1828N, and 1637N, respectively. Consequently, 12% (bPLIF) to 23% (TLIF) of intact endplates would fail during upright standing, whereas up to 39% (uPLIF) of the weakened endplates could fail under such loads (Fig. 5).

Considering the subsidence rates from clinical studies, the mean incidence of subsidence with bPLIF is 15.8% (10–65.1%) [21, 25, 35, 36], whereas the mean incidence of subsidence with TLIF is approximately 25.3% (0–51.2%) [8, 9, 21, 27, 37–44]. This clinically reported difference between TLIF and bPLIF subsidence is consistent with the experimentally determined distributions of endplate failure: both indicate a higher probability of failure with TLIF than with bPLIF (Fig. 5). In addition, the average clinically observed subsidence is within the range of endplates predicted to fail during standing (12–24% for bPLIF and 23–35% TLIF cages). This suggests that subsidence occurring in the early postoperative period may be induced by exposure to comparatively low spinal loads experienced during upright posture or non-impact activities.

Biomechanically, bone quality correlated positively with the absolute resistance force of the endplate: the higher the mean intracorporal HU values, the more axial compression force had to be applied until a fracture occurred in both the intact and weakened states. An increase of 10 HU in the mean intracorporal HU of an intact vertebral body resulted in an increase of 100N in the failure force (slope of the regression lines is approximately 10, Fig. 4). While this appears to be unchanged in a weakened vertebral body with the use of a TLIF cage, endplate weakening appears to be more detrimental with the use of a PLIF cage (Fig. 4). Reasons for this phenomenon could be the different positioning area for TLIF and PLIF, with a more “peripheral” placement of TLIF and the slightly larger contact area of TLIF.

This biomechanical understanding can guide clinical practice: in osteoporotic spines, where there is a higher risk of screw loosening and cage subsidence [9], bone density should be optimized preoperatively whenever possible [45], cages with large footprints should be preferred over small cages, and great care should be taken to preserve the endplates.

Some authors claim that neither fusion rates nor clinical outcomes are affected by cage subsidence [46], however,

many of the advantages that come with a cage, as mentioned above, are lost with subsidence.

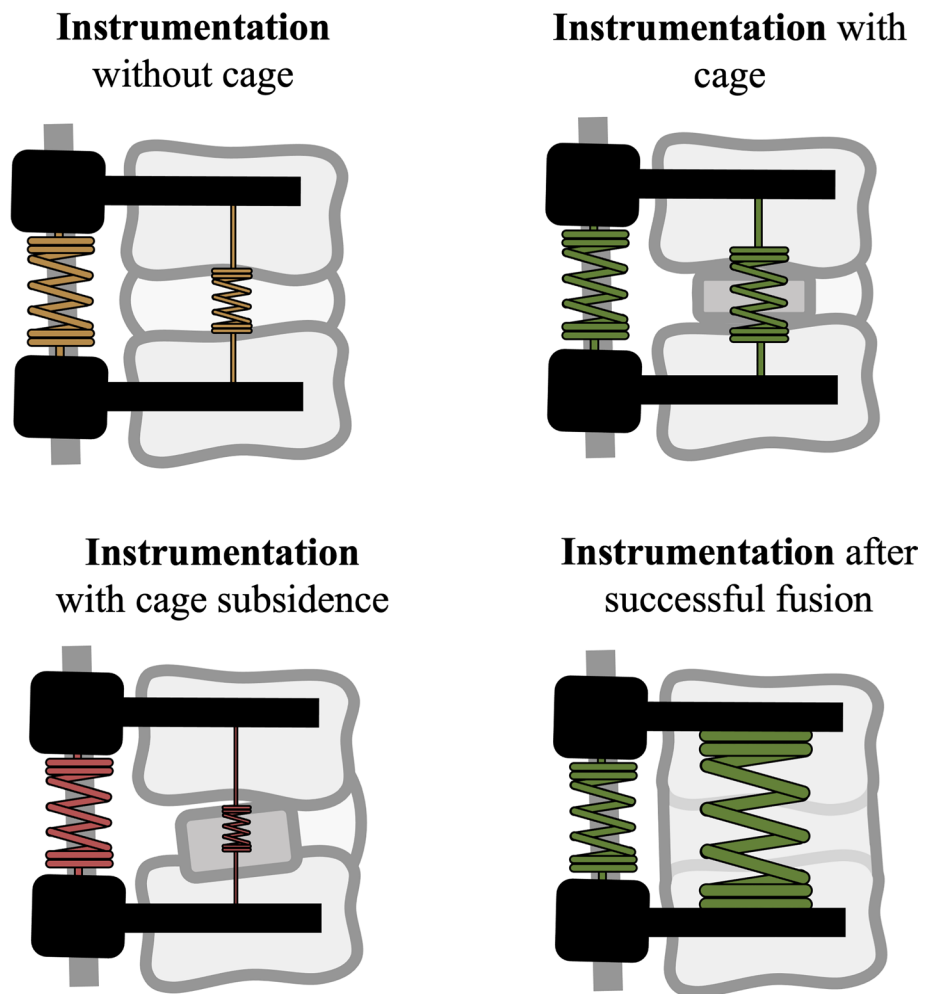
Overall, we believe that endplate preparation should be performed with caution, as cortical bone compromise is associated with significant loss of resistance to axial compression (Fig. 6). In addition, ventral force transmission is further compromised by the previous disc dissection required for cage insertion [47]. This results in increased stress at the screw-bone interface. Park et al. [9] demonstrated a correlation between cage positioning, endplate injury, single cage use, and cage migration. Cage migration did not result in subsidence in all cases. However, the rate of non-fusion and screw loosening was significantly higher in patients with cage subsidence. Understanding these biomechanical relationships can be used to improve clinical decision-making.

This *in vitro* biomechanical study has several limitations. Firstly, an isolated axial compression force was applied to the vertebral body. This is a simplified model that does not represent the complex movement of the spine. However, we know that the axial compression force is the main loading direction for all loading cases, therefore it is an appropriate study scenario. Secondly, the endplates were weakened with a shaver until cancellous bone was visible. It is possible that in some cases a little more substance was removed than in others. However, since the endplate in the cage area was completely removed during shaving, the effect of a little more or less depth should be negligible compared to the effect of a missing endplate. Thirdly, the degrees of freedom in our setup always allowed the cage to align perfectly with the endplate. *In vivo*, it is possible that a cage is loaded more unilaterally and collapses more quickly. However, in another study, it was found that under high loads, the cage is mostly loaded relatively evenly (anterior vs posterior load distribution) [32]. Fourthly, HU are widely used to assess bone quality, but the absolute values vary between scanners and they are notoriously difficult to compare between studies. However, within this study only relative comparisons between the samples were drawn, which are justifiable from our point of view, as the imaging parameters were the same. Lastly, we have tried to position the cages in the same area of the endplate, but small variations may have been unavoidable.

Conclusion

Weakening of the endplate during cage bed preparation significantly reduces the resistance of the endplate to subsidence to failure: endplate load capacity is reduced by 15% with TLIF and 37% with PLIF. Bone quality correlates with the force at which endplate failure occurs.

Fig. 6 Illustrative visualization of lumbar vertebral body segments without and with a cage, with cage subsidence and after successful bony fusion. Compared to the intervertebral disc, an inserted cage increases the stiffness of the construct and thus the force transmission to the underlying screws. With bony fusion, the stiffness is further increased. If cage subsidence is present, the cage cannot transmit interbody forces and the stiffness of the anterior column decreases



Acknowledgements Imaging was performed with support of the Swiss Center for Musculoskeletal Imaging, SCMI, Balgrist Campus AG, Zurich.

Author contributions AKC: data collection, design of the study, results interpretation, manuscript writing and editing; FC: conception and manuscript editing; MS: technical support and data collection; MRF: data analysis and manuscript editing; MF: manuscript editing; JW: conception, design of the study, results interpretation and manuscript editing;

Funding Open access funding provided by University of Zurich. The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

Data availability None.

Declarations

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

Ethical approval Kantonale Ethikkommission Zurich had given the approval for the study. (Basec No. KEK-ZH-Nr. 2022–00104).

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