Acta of Bioengineering and Biomechanics
Vol. 25, No. 3, 2023

Original paper
DOI: 10.37190/ABB-02315-2023-03

Biomechanical characterization of bilateral pedicle screw internal fixation combinations on lumbar vertebrae

WEIQI LI[1]*, PEIMING ZHANG[1], FEIHONG GAN[2]

[1] School of Health Science and Engineering, University of Shanghai for Science and Technology, Shanghai, China.
[2] The Affiliated Hospital of Stomatology, School of Stomatology, Zhejiang University School of Medicine and Key Laboratory of Oral Biomedical Research of Zhejiang Province, Hangzhou, Zhejiang, China.

Purpose: Pedicle screw fixation has been considered a suitable surgical intervention for addressing a diverse range of indications involving the lumbar spinal segments, but the impact of bilateral pedicle screw internal fixation combinations on the stability and flexibility of vertebral body motion has been limited. This study aimed to the effect of pedicle screw internal fixation on the mechanical characterization of lumbar multi-segmental vertebra under various loading conditions. *Methods*: Porcine lumbar multi-segmental vertebral samples were tested with three pedicle screw fixation groups including rigid fixation, mixed fixation and dynamic fixation under four loading conditions of flexion, posterior extension, left-side bend, and right-side bend at bending moments of 3 Nm, 4 Nm, 5 Nm and 6 Nm, respectively. The stability and flexibility of the segmental motion were statistically analysed. *Results*: The flexibility of joint activities increased using one-way dynamic pedicle screws with the range of motion for mixed fixation and dynamic fixation increased by 30% and 47% in left side bend and by 25% and 73% in right side bend, respectively. The range of motion for lumbar vertebra increased with higher moments. *Conclusions*: The flexibility of joint activities was improved using one-way dynamic pedicle screws and the mixed fixation was considered moderate providing larger flexibility in right and left side bend without compromising stabilization. The results of this study are useful for providing theoretical reference for clinical selection of surgical plans.

Key words: *lumbar vertebrae, pedicle screw, range of motion, mechanical loading*

1. Introduction

Lower back pain is a prevalent ailment affecting approximately 80% of the global population and is regarded as the second most common ailment [32]. The causes of lower back pain may result from a variety of factors, such as trauma, congenital diseases, tumours, infections and other degenerative conditions [29]. Additionally, a lumbar spine fracture may render the lumbar spine unstable, while surgical intervention for numerous conditions may compromise the stability of the lumbar spine [12]. Pedicle screw fixation has been reported as a suitable surgical intervention for addressing a diverse range of indications involving the lumbar spinal segments, including scoliosis, deformity, fractures, infection, or tumours [27], [36]. Immediate stability of pedicle screw-rod instrumentation can not only effectively reshape the vertebral body of the spine, but also indirectly restore the fractured part, so as to restore the proper physiological curvature of the spine and achieve the purpose of correcting kyphosis [24].

The pedicle fixation technique has been employed for the treatment of deformations, tumours, unstable fractures, tuberculosis and degenerative disorders of the spine [33]. Despite the increasing clinical usage of pedicle screws, various postoperative complications such as breakage, loosening, improper placement, spinal cord injury, nerve root injury, dural tears, pseudar-

* Corresponding author: Weiqi Li, School of Health Science and Engineering, University of Shanghai for Science and Technology, Shanghai, 200093, China, e-mail: liweiqi1010@163.com
Received: September 25th, 2023
Accepted for publication: October 27th, 2023

throsis and instrumentation infection have been reported [30]. Among these complications, breakage is the most common, and is frequently attributed to screw fracture caused by torsion or bending. Prior research indicates that screw breakage commonly occurs in the thread-shank region, with an incidence ranging from 2.6 to 60% [10]. Conventional rigid pedicle screws tend to provide excessive stability, resulting in increased stiffness within instrumented segments, concentration of stress on implants, and stress shielding within the interbody space [26]. Despite recent advancements in pedicle screw and connecting rod safety, including the use of novel shapes, hard materials and motorization, breakage remains a prevalent issue, with case reports continuing to emerge [25]. Accordingly, protecting pedicle screws and connecting rods against breakage remains an ongoing challenge.

The spine is capable of free movement in six directions, including forward flexion, backward extension, left bending, right bending, left rotation and right rotation [13]. It is crucial to ensure that the screw is securely attached to the spine to facilitate effective movement in three-dimensional space. Clinicians are concerned about the safety and practicality of pedicle screw fixation [8]. Therefore, the application of pedicle screw fixation has been the focus of several studies. The complications and results of pedicle screw plate stabilizations were investigated in lumbar fresh fractures and thoracolumbar fractures were treated using this approach [28]. Through previous studies on the internal fixation model of the posterior spine, pedicle screws can provide sufficient stability for the injured segment of the vertebral body [2], [3]. Recently, bilateral posterior fixation was analysed using finite element (FE) analysis to compare the stability of fusion constructs for the surgical treatment of degenerative lumbar disease [1]. With the increasing clinical application of lumbar posterior internal fixation, it is essential to conduct theoretical analysis and animal experimental studies on lumbar pedicle screw internal fixation under various loading conditions.

From previous biomechanical testing of the lumbar spine, the failure of internal fixation systems varies depending on the type of system used [39]. Screw size, pedicle fill, bone density, bone structures and insertion technique are important factors for influencing internal fixation stability [22]. However, the effect of different pedicle screw internal fixation combinations on the stability and flexibility of vertebral body motion has not been adequately understood. While lumbar pedicle screw internal fixation has been shown to achieve effective fixation [15], it may restrict the mobility of the fixed segment and result in excessive mobility of the adjacent segment, which can increase the risk of degeneration in the adjacent segment. Therefore, the ability to attain immobilization effect whilst preserving the typical mobility of lumbar joints is of paramount importance.

Various integrated systems such as the Dynesys system, DPSFD fixation system, and CDHorizon universal screw system are currently available for the treatment of lumbar degenerative disease [37]. Effective utilization of these systems largely depends on the management of spinal activities to maintain the stability of the spinal cord and the range of motion (ROM) of the joint, thereby preventing internal fixation failure.

The aim of this study was to investigate the biomechanical properties of lumbar vertebral body under internal fixation with different pedicle screw combinations by measuring the range of motion of the lumbar spine joints. The range of motion of porcine lumbar multi-segmental vertebral specimens were tested under various loading conditions: flexion, posterior extension, left-side bend and right-side bend at four bending moments. The effects of different pedicle screw internal fixation combinations including universal screws, one-way dynamic screws and universal screws, and one-way dynamic screws with slight movement fixation on the stability and flexibility of the vertebral body were statistically analysed.

2. Materials and methods

2.1. Sample preparation

Fresh porcine lumbar multi-segmental vertebral specimens were obtained from a local slaughter. Following arrival in the laboratory, the samples with structural abnormalities or obvious degeneration were excluded using X-ray imaging and visual inspection. Twenty-one specimens were collected for mechanical testing after the surrounding muscles of the vertebral body were carefully removed. Discs, ligaments, facet joints and vertebrae were kept intact. The multi-segment samples were wrapped in tissue paper and soaked in Ringer’s solution and then stored at –40 °C in a freezer in double heat-sealed plastic bags [18], [19]. When Multi-segment specimens of pig lumbar vertebrae were required for testing, samples were taken out from the freezer and left in Ringer’s solution for 12 h ahead of dissection at room temperature. From previous studies, freeze-thaw treatment does not change the mechanical properties of biological tissue. During the dissection, the intervertebral discs, ligaments (anterior and posterior longitudinal), joint capsules, facet joints, and vertebrae were preserved intact to ensure the accuracy and stability of experimental results [5], [17], [34]. For mechanical experiments, the test samples were prepared by embedding and fixing the specimens onto a specialized device using self-curing denture powder materials. The test samples were divided into three groups based on pedicle screw internal fixation combinations to investigate the effects of pedicle screw internal fixation combinations on the mechanical characterization of lumbar multi-segmental vertebra, including rigid fixation with universal screws (Group A: universal screws on both sides), mixed fixation with one-way dynamic screws and universal screws (Group B: universal screws on the left and one-way dynamic screws on the right), and dynamic fixation with one-way dynamic screws in a slight movement (Group C: one-way dynamic screws on both sides).

2.2. Experimental setup

The spinal specimens fixed with pedicle screws were placed in the Instron Universal testing machine (Fig. 1) [20]. Prior to the data collection procedure for each testing, an samples were subjected to flexion, posterior extension, left-side bend and right-side bend under couple moments of 3 Nm, 4 Nm, 5 Nm and 6 Nm, respectively, with the compressive rate of 10 mm/min. The horizontal distance between the indenter and the central axis of each specimen was measured using a vernier upper indenter was lowered onto the specimen until a preload of 0.1 N was observed. The flexion and extension experiment with the moment of couple force 5 Nm was initially applied to reduce the influence of the viscoelasticity of the intervertebral disk and stabilize the samples. For mechanical testing, all calliper and the moment of a couple force was calculated by the force multiplied by the perpendicular distance to the force from the turning point ($M = F * d$). Testing parameters were inputted before pre-conditioning force was applied and changes to specimen geometry were then automatically accounted for. Between each test, the samples were sprayed with Ringer's solution to keep hydrated and reduce the tissue degeneration.

Prior to mechanical experiments, optical markers (mark points) were securely affixed to the anterior surface of each segment of the lumbar spine samples. During the loading process of the experiment, the movement of the mark point along with the lumbar spine for each sample were assessed using a Canon EOS camera with dedicated macro lens to accurately collect the spatial position data and trajectory of the lumbar spine movement. The range of motion (ROM) of each specimen was subsequently measured and calculated using the angle measurement function in Image J. Range of motion means the extent or limit to which a part of the body can be moved around a joint or a fixed point. In this study, it refers to the angle (θ) between the new position of the moving bone and the initial position when the moving bone of the joint moves closer to or away from the fixed bone. The range of motion of each segment (Fig. 2). The lumbar

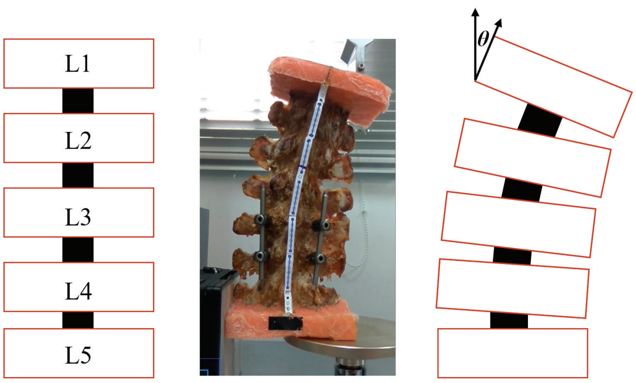

Fig. 2. Measurement of the range of motion for each segmental vertebral specimen

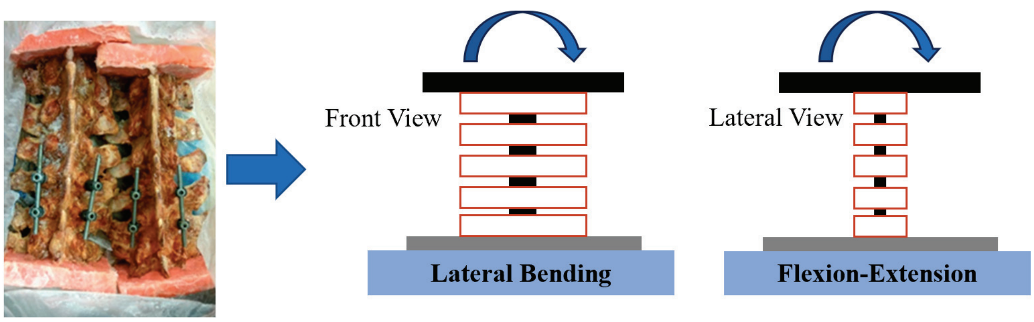

Fig. 1. Experimental setup for the compressive mechanical testing of porcine lumbar multi-segmental vertebral specimens

overall range of motion is equal to the sum of the spine comprises five distinct sections, which are generally classified as the L1–L5 vertebrae. To achieve smooth end faces, a self-solidifying dental base acrylic resin liquid and dental base acrylic resin powder were utilized to embed each spine, cranially at L1 and caudally at L5. The primary function of the lumbar vertebrae is to support the weight of the torso and protect the end of the spinal cord.

2.3. Data analysis

Sigmaplot Version 14.0 (Systat Software Inc., London, UK) was used to perform regression analysis for the curve fit of range of motion against bending moment. The relationship between vertebral specimens tested from different pedicle screw internal fixation combination groups and loading conditions were analysed by a one-way analysis of variance method (ANOVA). In the event that the normality test (Shapiro–Wilk) yielded a significance level ($p < 0.05$), a Kruskal–Wallis analysis of variance on ranks was employed. If ANOVA indicated a statistically significant difference ($p < 0.05$), pairwise comparisons among testing groups were conducted using a Student–Newman–Keuls Method (SNK) to identify significant differences when $p < 0.05$.

3. Results

The relationship between pedicle screw internal fixation combination group and loading condition and the range of motion, respectively, at all four couple moments being investigated, were displayed in Figs. 3a, b. The ROM for all tested samples showed an increasing trend with higher bending moment. The trend of ROM can be characterized by a linear curve fit across all moments tested (Eq. (1)).

$$R = D + AB, \quad (1)$$

where R is the ROM, A is the gradient of the slope, B is the testing moment and D is the intercept; D and A are empirically derived constants by the least-squares fit method summarised in Table 1.

Table 1. Statistical details derived from mean ROM against moment plot of Fig. 3 for three pedicle screw internal fixation combinations and four loading conditions. A and D are the constants from the curve fits. R^2 is the squared correlation coefficient indicating the goodness of regression line fit of data

	Range of motion linear fit parameter		
	A	D	R^2
Group A	1.69	5.76	0.98
Group B	1.58	8.39	0.94
Group C	3.72	–2.26	0.83
Left side bend	2.31	6.21	0.53
Right side bend	2.55	6.08	0.72
Flexion	2.31	1.75	0.89
Posterior extension	1.85	2.42	0.77

For specimens tested using various pedicle screw internal fixation combinations, the ROM of group C showed significant lower ($p < 0.05$) than that of group B at moment of 3 Nm while there was no significant difference between group A and group B. For other tested moments of 4, 5 and 6 Nm, a similar trend of ROM was

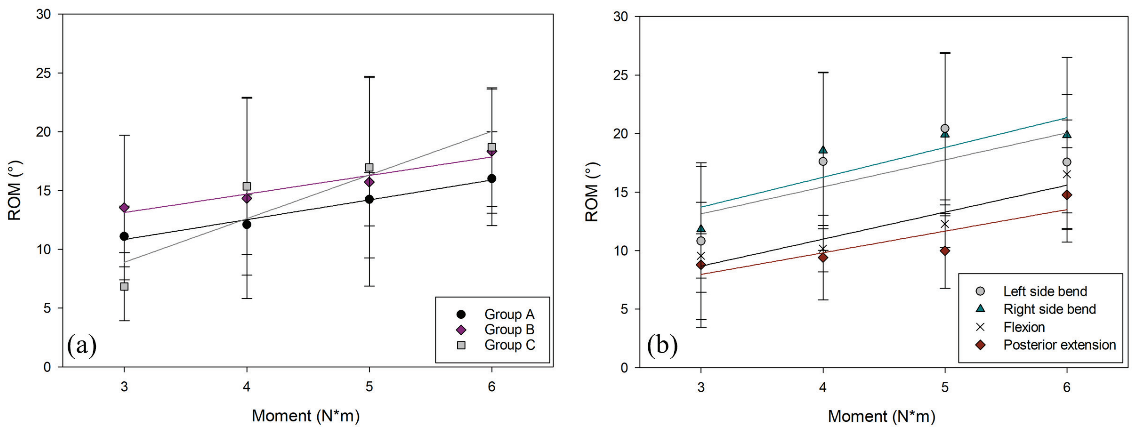

Fig. 3. Variation of ROM with the bending moment of lumbar multi-segmental vertebra for (a) three pedicle screw internal fixation combinations (Group A: universal screws on both sides, Group B: universal screws on the left and one-way dynamic screws on the right and Group C: one-way dynamic screws on both sides) and (b) four loading conditions of left side bend, right side bend, flexion and posterior extension. Linear regression displayed by Eq. (1) was fitted across all moments tested. Error bars represent 95% confidence intervals

found with no significant difference ($p > 0.05$) between pedicle screw internal fixation groups. Group A showed a lowest mean value of 14.3° in ROM over all tested moments indicating universal screws on both sides could provide a relatively stable loading environment. Group C showed the highest mean value of 17.1° in ROM, followed by the specimens from the group B with 16.1°.

For different loading conditions, the specimens tested under left-side bend and right-side bend exhibited the similar trend in mean ROM across the tested moments with no significant difference found between them ($p > 0.05$) 17.2° and 17.6° over tested moments, respectively. There was also no significant difference between specimens tested under flexion and posterior extension, with 12.1° and 10.7°, respectively. For specimens tested at moment of 4 and 5 Nm, the ROM of lumbar vertebra specimens tested under left-side bend and right-side bend loading conditions showed significant greater ($p < 0.05$) than flexion and posterior extension loading conditions, which indicated that left and right side bend has a greater impact on the flexibility of joint activities.

The ROM of the adjacent-segment intervertebral discs between L1 and L5 was analysed (Fig. 4). In general, L2–L3 showed the smallest value of 3.1° in ROM, followed by the L3–L4 with 4.5° while L1–L2 and L4–L5 had the greater range of motion of 5.8° and 6.2°, respectively. From the specimens tested from various pedicle screw internal fixation groups shown in Fig. 4a, specimens with universal screws on both sides showed significantly lower ($p < 0.05$) ROM compared to group B and group C for L1–L2, L3–L4 and L4–L5. For specimens from L2–L3 lumbar vertebral, no significant difference ($p > 0.05$) of ROM was found between group A and group B. Generally, one-way dynamic screws improved the flexibility of joint activities. The joint range of motion of each segment for group B was considered moderate with both stability and flexibility.

From specimens tested under varying loading conditions shown in Fig. 4b, samples with left side bend and right side bend exhibited significantly higher ($p < 0.05$) ROM across all intervertebral discs tested. No significant difference was found between flexion and posterior extension, however, for L2–L3, a significant difference of ROM was considered between them. For all adjacent-segment intervertebral discs between L1 and L5, left side bend and right side bend showed a similar trend with no significant difference considered, which indicated that the impact of different pedicle screw internal fixation combinations on them were similar.

The mean ROM of showed an increasing trend from group A to group C while for specimens tested with flexion the lowest ROM was found in group C (Fig. 5). Compared with group A where no significant differences of ROM were found between four loading conditions, vertebral specimens tested with left side bend exhibited a significantly higher value ($p < 0.05$) than specimens from posterior extension in group B and vertebral specimens tested with right and left side bend exhibited a significantly higher value than other two loading conditions in group C. The flexibility of joint activities was increased using one-way dynamic pedicle screws with the ROM of mixed fixation and dynamic fixation increased by 30 and 47% in left side bend and by 25 and 73% in right side bend, respec-

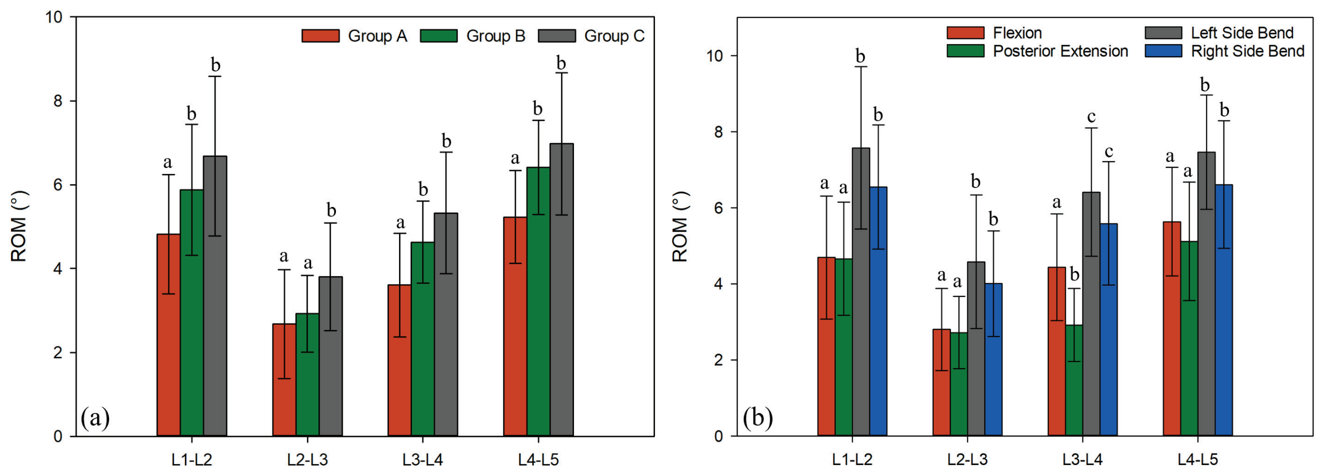

Fig. 4. Grouped vertical bars of ROM (mean ± 95% confidence intervals) for L1–L5 lumbar multi-segmental vertebra tested from (a) three pedicle screw internal fixation combinations (Group A: universal screws on both sides, Group B: universal screws on the left and one-way dynamic screws on the right and Group C: one-way dynamic screws on both sides) and (b) four loading conditions of left side bend, right side bend, flexion and posterior extension. In adjacent-segment intervertebral discs, ROM not sharing a letter are considered to be significantly different (Tukey HSD)

tively. No significant differences were found between three combination fixations in flexion and posterior extension.

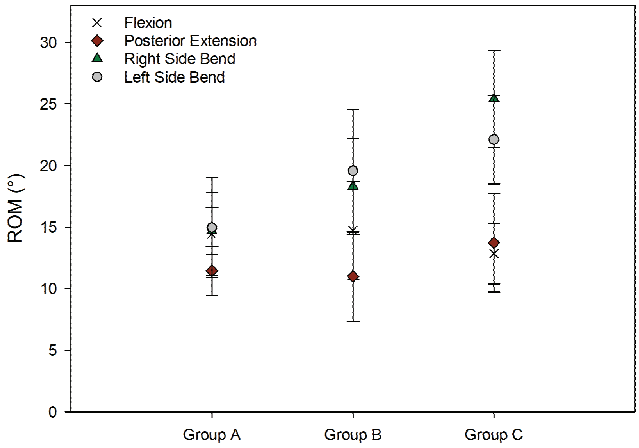

Fig. 5. Mean range of motion (ROM) of three pedicle screw internal fixation combinations (Group A: universal screws on both sides, Group B: universal screws on the left and one-way dynamic screws on the right and Group C: one-way dynamic screws on both sides) at four loading conditions. Error bars represent 95% confidence intervals

4. Discussion

This study has demonstrated the effect of pedicle screw internal fixation combinations on the mechanical properties of lumbar vertebra under various loading conditions by measuring the range of motion in compression. It has provided analysis essential to compare internal fixation groups for lumbar multi-segmental vertebra capable of predicting the corresponding flexibility of joint activities. Experiments of different pedicle screw internal fixation combinations were not performed on the same sample, which minimized the experimental error. The ROM was dependent on the bending moment, increasing with higher moments. Many other studies used the similar curve fit method to define material properties including bovine articular cartilage [7], [21]. The variation between the universal screws and one-way dynamic screws on mechanical properties of porcine lumbar vertebral specimens was statistically analysed across all loading conditions. Through the mechanical experiments, one-way dynamic screws effectively improved the flexibility of the vertebral body. The experimental results could provide a basis for clinicians to choose the best fixation method according to the actual situation of patients.

The range of motion of porcine lumbar multi-segmental vertebra increased with higher bending moment. It is worth highlighting that the significant linear trend was considered for group A and group B with coefficient of determination R^2 of 0.98 and 0.94, respectively, while the ROM of group C increased largely between 3 and 4 Nm, which might indicate for this bending moment range the impact of micro-movement fixation with one-way dynamic screws on the flexibility of the vertebral body is significant. In comparison with a study where the whole porcine was tested at bending moments of 1–7.5 Nm [38], the ROMs of the porcine lumbar multi-segmental vertebra reported in this paper were lower at comparable loading conditions. Despite comparisons being limited by the potential discrepancies in the types of experimental conditions and testing protocols, the general trends of the results were found to be similar with the L2–L3 and L3–L4 segments showing lower value.

The rigid fixation has been considered adverse stress-shielding effects for the interbody due to excessive stabilization [16]. The mean range of motion in this study increased from group A to group C with rigid fixation with universal screws exhibiting least flexibility. In comparison with universal screws on both sides, one-way dynamic screws enhanced mobility and might provide a favourable loading environment among vertebral bodies, endplates, and lumbar discs, which was consistent to simulation results of lumbar vertebrae [9]. The mechanical characterization of bovine spine lumbar segments with various pedicle screw internal fixation combinations was previously investigated, indicating a 6.2% increase in extension and 5.6% increase in flexion for dynamic pedicle screw device when compared to rigid fixation [31]. The corresponding results in this study were higher at similar testing protocols, which may be due to the tested sample size or specimen species. From previous research, following loads caused changes in the range of motion under various postures [4]. The effect of following loads could be investigated in future studies on biomechanical properties of lumbar vertebral body under internal fixation with different pedicle screw combinations.

Due to the ethical reasons and difficulties in obtaining human vertebra specimens, animal samples are often adopted for use in the characterization of pedicle screw fixation including sheep [40], cow [41] and pig [42]. The discrepancies for the mechanical properties between human and animal vertebra tissue has been controversial. Based on literature, it was observed that fresh human tissue demonstrated comparatively softer mechanical properties when compared to human autopsy findings, indicating that data obtained from animal brain tissue might yield closer results [14]. Further, the porcine tissue was considered a suitable model for comparative studies due to similarities in pedicle width and bone mineral density to the human vertebrae [11]. Based on this similarity, the mechanical properties of porcine lumbar multi-segmental vertebral specimens tested in this study may be used to characterize the feasibility of pedicle screw fixation for potential comparative human study.

Previous studies have extensively investigated the biomechanical characterization of pedicle screw fixation systems through single vertebrae biomechanical testing and finite element analysis [6], [35]. However, limited research exists regarding experimental analysis of the stability and flexibility of these systems. The biomechanical properties of lumbar pedicle screw fixation were evaluated by three-dimensional numerical simulation, showing that the fixation systems were more stable in flexion and extension, which is consistent with the results contained in the present study that the ROMs of lumbar vertebra specimens tested under flexion and posterior extension loading conditions were significantly lower [23]. Despite the similar trend was found, the finite element model ignored the influence of muscle and nerve tissue, resulting in a lack of objectivity and comprehensiveness in reflecting the biomechanical properties of the interaction between the pedicle screw system and the human body. The mechanical properties of mixed fixation with one-way dynamic screws and universal screws were intermediate in the comparison, which might overcome the issue of uniaxial malalignment between the rod and fixed angle screw head. Hence, the utilization of mixed fixation holds promise as a viable alternative for conservative treatment of spinal stenosis or chronic low-back pain. The consideration of the desired stability of the surgical segment becomes clinically significant in determining the appropriate choice of fixation system.

5. Conclusions

The effect of pedicle screw internal fixation combinations on the mechanical characterization of lumbar multi-segmental vertebra is multi-factorial. The range of motion for lumbar vertebra was dependent on the bending moment, increasing with higher moments. No significant differences were found between three combination fixations in flexion and posterior extension. The mixed fixation was considered moderate providing larger range of motion in right and left side bend without compromising stabilization. Rigid fixation with universal screws focused on patients who require strong stability, while the flexibility could be increased using one-way dynamic pedicle screws. These findings could provide essential information from the aspect of biomechanics for surgical planning.

Authors' contributions

The preparation of the research program (WL, PZ). The execution of research (WL, FG). The statistical analysis (all authors). The interpretation of data (WL, PZ). Preparation of the manuscript (WL). Obtain financing (WL).

Funding

This study was supported by the National Natural Science Foundation of China (Grant No. 12302417) and Shanghai Pujiang Program (23PJ1409200).

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval

All guidelines were following in so far as is applicable to a study where animal tissues were otherwise destined for the food-chain. No live animals were handled or euthanized specifically for this study.

Competing interests

The authors declare that there is no conflict of interest.

References

[1] AMBATI D.V., WRIGHT E.K., LEHMAN R.A., KANG D.G., WAGNER S.C., DMITRIEV A.E., *Bilateral pedicle screw fixation provides superior biomechanical stability in transforaminal lumbar interbody fusion: a finite element study*, The Spine Journal, 2015, 15, 1812–1822, DOI: 10.1016/j.spinee.2014.06.015.

[2] AN H.S., SINGH K., VACCARO A.R., WANG G., YOSHIDA H., ECK J., MCGRADY L., LIM T.-H., *Biomechanical evaluation of contemporary posterior spinal internal fixation configurations in an unstable burst-fracture calf spine model: special references of hook configurations and pedicle screws*, Spine, 2004, 29, 257–262.

[3] BURTON D., MCIFF T., FOX T., LARK R., ASHER M.A., GLATTES R.C., *Biomechanical analysis of posterior fixation techniques in a 360 arthrodesis model*, Spine, 2005, 30, 2765–2771.

[4] CAI X.-Y., YUCHI C.-X., DU C.-F., MO Z.-J., *The effect of follower load on the range of motion, facet joint force, and in-*

tradiscal pressure of the cervical spine: a finite element study, Med. Biol. Eng. Comput., 2020, 58, 1695–1705, DOI: 10.1007/s11517-020-02189-7.

[5] Chan R.W., Titze I.R., *Effect of postmortem changes and freezing on the viscoelastic properties of vocal fold tissues*, Annals of Biomedical Engineering, 2003, 31, 482–491, DOI: 10.1114/1.1561287.

[6] Chen S.-H., Lin S.-C., Tsai W.-C., Wang C.-W., Chao S.-H., *Biomechanical comparison of unilateral and bilateral pedicle screws fixation for transforaminal lumbar interbody fusion after decompressive surgery – a finite element analysis*, BMC Musculoskeletal Disorders, 2012, 13, 72, DOI: 10.1186/1471-2474-13-72.

[7] Crolla J.P., Lawless B.M., Cederlund A.A., Aspden R.M., Espino D.M., *Analysis of hydration and subchondral bone density on the viscoelastic properties of bovine articular cartilage*, BMC Musculoskeletal Disorders, 2022, 23, 228, DOI: 10.1186/s12891-022-05169-0.

[8] Gautschi O.P., Schatlo B., Schaller K., Tessitore E., *Clinically relevant complications related to pedicle screw placement in thoracolumbar surgery and their management: a literature review of 35,630 pedicle screws*, Neurosurgical Focus, 2011, 31, E8, DOI: 10.3171/2011.7.FOCUS11168.

[9] Goto K., Tajima N., Chosa E., Totoribe K., Kuroki H., Arizumi Y., Arai T., *Mechanical analysis of the lumbar vertebrae in a three-dimensional finite element method model in which intradiscal pressure in the nucleus pulposus was used to establish the model*, Journal of Orthopaedic Science, 2002, 7, 243–246.

[10] Griza S., de Andrade C.E.C., Batista W.W., Tentardini E.K., Strohaecker T.R., *Case study of Ti6Al4V pedicle screw failures due to geometric and microstructural aspects*, Engineering Failure Analysis, 2012, 25, 133–143.

[11] Harper R.A., Pfeiffer F.M., Choma T.J., *The minipig as a potential model for pedicle screw fixation: morphometry and mechanics*, Journal of Orthopaedic Surgery and Research, 2019, 14, 246, DOI: 10.1186/s13018-019-1292-9.

[12] Heary R.F., Kumar S., *Decision-making in burst fractures of the thoracolumbar and lumbar spine*, Indian Journal of Orthopaedics, 2007, 41, 268.

[13] Heliövaara M., Mäkelä M., Knekt P., Impivaara O., Aromaa A., *Determinants of sciatica and low-back pain*, Spine, 1991, 16, 608–614.

[14] Hohmann E., Keough N., Glatt V., Tetsworth K., Putz R., Imhoff A., *The mechanical properties of fresh versus fresh/frozen and preserved (Thiel and Formalin) long head of biceps tendons: A cadaveric investigation*, Annals of Anatomy, 2019, 221, 186–191, DOI: 10.1016/j.aanat.2018.05.002.

[15] Huang W., Luo T., *Efficacy analysis of pedicle screw internal fixation of fractured vertebrae in the treatment of thoracolumbar fractures*, Experimental and Therapeutic Medicine, 2013, 5, 678–682.

[16] Ito M., Fay L.A., Ito Y., Yuan M.R., Edwards T.W., Yuan H.A., *The Effect of Pulsed Electromagnetic Fields on Instrumented Posterolateral Spinal Fusion and Device-Related Stress Shielding1996 Program Committee*, Spine, 1997, 22, 382–388.

[17] Li W., Shepherd D.E.T., Espino D.M., *Frequency dependent viscoelastic properties of porcine brain tissue*, Journal of the Mechanical Behavior of Biomedical Materials, 2020, 102, 103460, DOI: 10.1016/j.jmbbm.2019.103460.

[18] Li W., Shepherd D.E.T., Espino D.M., *Dynamic mechanical characterization and viscoelastic modeling of bovine brain tissue*, Journal of the Mechanical Behavior of Biomedical Materials, 2021, 114, 104204, DOI: 10.1016/j.jmbbm.2020.104204.

[19] Li W., Shepherd D.E.T., Espino D.M., *Investigation of the Compressive Viscoelastic Properties of Brain Tissue Under Time and Frequency Dependent Loading Conditions*, Annals of Biomedical Engineering, 2021, DOI: 10.1007/s10439-021-02866-0.

[20] Liu C., Kamara A., Yan Y., *Investigation into the biomechanics of lumbar spine micro-dynamic pedicle screw*, BMC Musculoskeletal Disorders, 2018, 19, 231, DOI: 10.1186/s12891-018-2132-5.

[21] Mahmood H., Shepherd D.E.T., Espino D.M., *Surface damage of bovine articular cartilage-off-bone: the effect of variations in underlying substrate and frequency*, BMC Musculoskelet Disord, 2018, 19, 384, DOI: 10.1186/s12891-018-2305-2.

[22] McKinley T.O., McLain R.F., Yerby S.A., Sharkey N.A., Sarigul-Klijin N., Smith T.S., *Characteristics of pedicle screw loading: effect of surgical technique on intravertebral and intrapedicular bending moments*, Spine, 1999, 24, 18–24.

[23] Mu S., Wang J., Gong S., *Mechanical Analysis of Posterior Pedicle Screw System Placement and Internal Fixation in the Treatment of Lumbar Fractures*, Computational and Mathematical Methods in Medicine, 2022, e6497754, DOI: 10.1155/2022/6497754.

[24] Nayak A.N., Gutierrez S., Billys J.B., Santoni B.G., Castellvi A.E., *Biomechanics of lateral plate and pedicle screw constructs in lumbar spines instrumented at two levels with laterally placed interbody cages*, The Spine Journal, 2013, 13, 1331–1338.

[25] Ozer A.F., Oktenoglu T., Egemen E., Sasani M., Yilmaz A., Erbulut D.U., Yaman O., Suzer T., *Lumbar single-level dynamic stabilization with semi-rigid and full dynamic systems: a retrospective clinical and radiological analysis of 71 patients*, Clinics in Orthopedic Surgery, 2017, 9, 310.

[26] Park P., Garton H.J., Gala V.C., Hoff J.T., McGillicuddy J.E., *Adjacent segment disease after lumbar or lumbosacral fusion: review of the literature*, Spine, 2004, 29, 1938–1944.

[27] Perna A., Smakaj A., Vitiello R., Velluto C., Proietti L., Tamburrelli F.C., Maccauro G., *Posterior percutaneous pedicle screws fixation versus open surgical instrumented fusion for thoraco-lumbar spinal metastases palliative management: a systematic review and meta-analysis*, Frontiers in Oncology, 2022, 12, 884928.

[28] Roy-Camille R., Saillant G., Mazel C., *Internal fixation of the lumbar spine with pedicle screw plating*, Clinical Orthopaedics and Related Research®, 1986, 203, 7–17.

[29] Samini F., Gharedaghi M., Khajavi M., Samini M., *The etiologies of low back pain in patients with lumbar disk herniation*, Iranian Red Crescent Medical Journal, 2014, 16.

[30] Sanpera Jr I., Piza-Vallespir G., Burgos-Flores J., *Upper thoracic pedicle screws loss of fixation causing spinal cord injury*, Journal of Pediatric Orthopaedics, 2914, 34, e39.

[31] Scifert J.L., Sairyo K., Goel V.K., Grobler L.J., Grosland N.M., Spratt K.F., Chesmel K.D., *Stability Analysis of an Enhanced Load Sharing Posterior Fixation Device and Its Equivalent Conventional Device in a Calf Spine Model*, Spine, 1999, 24, 2206.

[32] Smedley J., Inskip H., Cooper C., Coggon D., *Natural history of low back pain: a longitudinal study in nurses*, Spine, 1998, 23, 2422–2426.

[33] Song M., Sun K., Li Z., Zong J., Tian X., Ma K., Wang S., *Stress distribution of different lumbar posterior pedicle screw insertion techniques: a combination study of finite element*

analysis and biomechanical test, Sci Rep., 2021, 11, 12968, DOI: 10.1038/s41598-021-90686-6.

[34] SZARKO M., MULDREW K., BERTRAM J.E.A., *Freeze-thaw treatment effects on the dynamic mechanical properties of articular cartilage*, BMC Musculoskeletal Disorders, 2010, 11, DOI: Artn 231 10.1186/1471-2474-11-231.

[35] TAI C.-L., CHEN W.-P., LIU M.-Y., LI Y.-D., TSAI T.-T., LAI P.-L., HSIEH M.-K., *Biomechanical comparison of pedicle screw fixation strength among three different screw trajectories using single vertebrae and one-level functional spinal unit*, Frontiers in Bioengineering and Biotechnology, 2022, 10.

[36] TSCHUGG A., HARTMANN S., LENER S., RIETZLER A., SABRINA N., THOMÉ C., *Minimally invasive spine surgery in lumbar spondylodiscitis: a retrospective single-center analysis of 67 cases*, European Spine Journal, 2017, 26, 3141–3146.

[37] WANG H., PENG J., ZENG Q., ZHONG Y., XIAO C., YE Y., HUANG W., LIU W., LUO J., *Dynesys system vs posterior decompression and fusion for the treatment of lumbar degenerative diseases*, Medicine, 2020, 99.

[38] WILKE H.-J., GEPPERT J., KIENLE A., *Biomechanical in vitro evaluation of the complete porcine spine in comparison with data of the human spine*, Eur. Spine J., 2011, 20, 1859–1868, DOI: 10.1007/s00586-011-1822-6.

[39] WILLETT K., HEARN T., CUNCINS A., *Biomechanical testing of a new design for Schanz pedicle screws*, Journal of Orthopaedic Trauma, 1993, 7, 375–380.

[40] YAMAN O., DEMIR T., ARSLAN A.K., IYIDIKER M.A., TOLUNAY T., CAMUSCU N., ULUTAS M., *The comparison of pullout strengths of various pedicle screw designs on synthetic foams and ovine vertebrae*, Turkish Neurosurgery, 2015, 25.

[41] YILDIRIM O.S., AKSAKAL B., HANYALOGLU S.C., ERDOGAN F., OKUR A., *Hydroxyapatite dip coated and uncoated titanium poly-axial pedicle screws: an in vivo bovine model*, Spine, 2006, 31, E215–E220.

[42] ZOU X., LI H., TENG X., XUE Q., EGUND N., LIND M., BÜNGER C., *Pedicle screw fixation enhances anterior lumbar interbody fusion with porous tantalum cages: an experimental study in pigs*, Spine, 2005, 30, E392–E399.