

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

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## **Abstract**

### **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 N·m, 4 N·m, 5 N·m and 6 N·m, 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.

**Keywords:** lumbar vertebrae; Pedicle screw; Range of motion; Mechanical loading

## 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, pseudarthrosis 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.

## Materials and methods

### 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  $-40\text{ }^{\circ}\text{C}$  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).

### Experimental Setup

The spinal specimens fixed with pedicle screws were placed in the Instron Universal testing machine using UH-ProTest 2000 software (Figure 1) [20]. Prior to the data collection procedure for each testing, an 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  $5\text{ N}\cdot\text{m}$  was initially applied to reduce the influence of the viscoelasticity of the intervertebral disk and stabilize the samples. For mechanical testing, all samples were subjected to flexion, posterior extension, left-side bend and right-side bend under couple

moments of 3 N·m, 4 N·m, 5 N·m and 6 N·m, 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 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 into UH-ProTest 2000 before pre-conditioning force was applied and changes to specimen geometry were then automatically accounted for within the UH-ProTest 2000 software. Between each test, the samples were sprayed with Ringer's solution to keep hydrated and reduce the tissue degeneration.

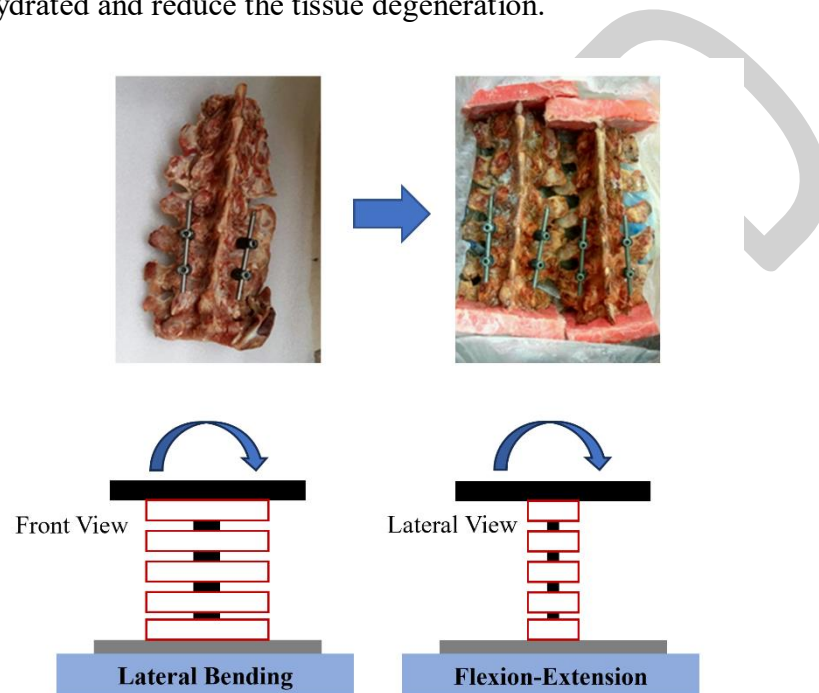


Figure 1: Experimental setup for the compressive mechanical testing of porcine lumbar multi-segmental vertebral specimens.

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 ( $\theta$ ) 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 overall range of motion is equal to the sum of the range of motion of each segment (Figure 2). The lumbar 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.

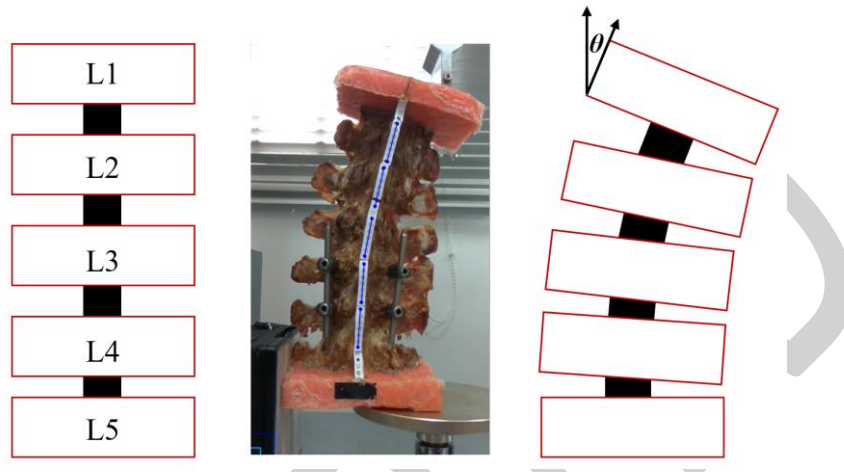


Figure 2: Measurement of the range of motion for each segmental vertebral specimen.

### 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  $p < 0.05$ .

### Results

Figure 3(a) and Figure 3(b) displayed the relationship between pedicle screw internal fixation combination group and loading condition and the range of motion, respectively, at all four couple moments of investigated. 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.

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  $3 \text{ N} \cdot \text{m}$  while there was no significant difference between group A and group B. For other tested moments of  $4 \text{ N} \cdot \text{m}$ ,  $5 \text{ N} \cdot \text{m}$  and  $6 \text{ N} \cdot \text{m}$ , a similar trend of ROM was found with no significant difference ( $p > 0.05$ ) between pedicle screw internal fixation groups. Group A showed a lowest mean value of  $14.3^\circ$  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  $17.1^\circ$  in ROM, followed by the specimens from the group B with  $16.1^\circ$ .

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 ( $p > 0.05$ ) with  $17.2^\circ$  and  $17.6^\circ$  over tested moments, respectively. There was also no significant difference between specimens tested under flexion and posterior extension, with  $12.1^\circ$  and  $10.7^\circ$ , respectively. For specimens tested at moment of  $4 \text{ N} \cdot \text{m}$  and  $5 \text{ N} \cdot \text{m}$ , 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 left and right side bend has a greater impact on the flexibility of joint activities.

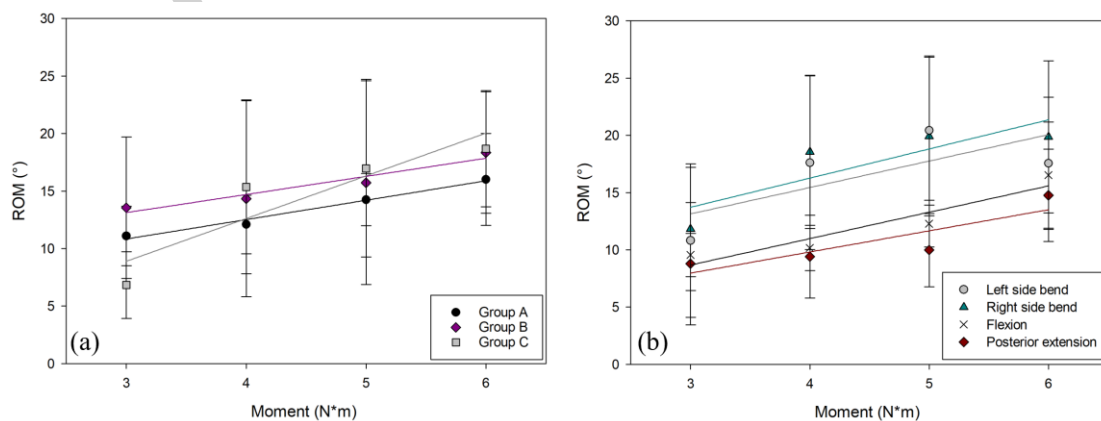




Figure 3: Variation of ROM with the bending moment of lumbar multi-segmental vertebra for (a) three pedicle screw internal fixation combinations (Group A: universal screws on both sides, Group B: universal screws on the left and one-way dynamic screws on the right and Group C: one-way dynamic screws 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.

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

The ROM of the adjacent-segment intervertebral discs between L1 and L5 was analysed (Figure 4). In general, L2-L3 showed the smallest value of  $3.1^\circ$  in ROM, followed by the L3-L4 with  $4.5^\circ$  while L1-L2 and L4-L5 had the greater range of motion with  $5.8^\circ$  and  $6.2^\circ$ , respectively. From the specimens tested from various pedicle screw internal fixation groups shown in Figure 4(a), specimens with universal screws on both sides showed significantly lower ( $p < 0.05$ ) ROM compared with 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 Figure 4(b), 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 the impact of different pedicle screw internal fixation combinations on them were similar.

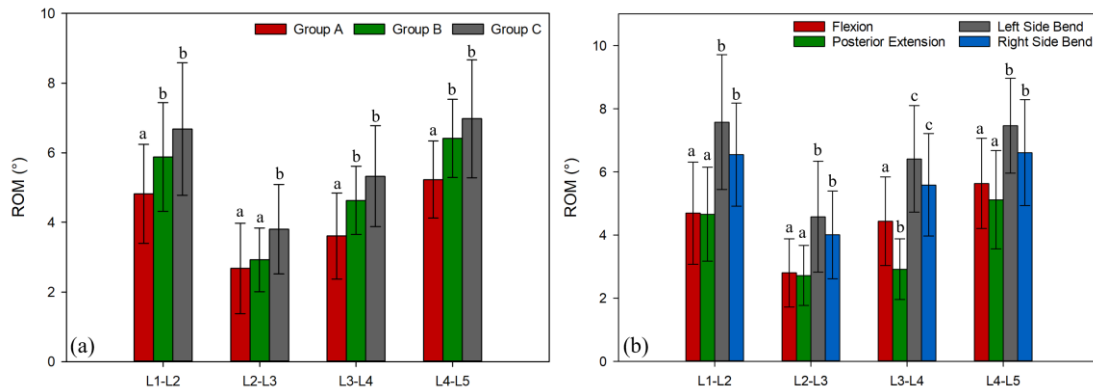


Figure 4: Grouped vertical bars of ROM (mean  $\pm$  95% confidence intervals) for L1-L5 lumbar multi-segmental vertebra tested from (a) three pedicle screw internal fixation combinations (Group A: universal screws on both sides, Group B: universal screws on the left and one-way dynamic screws on the 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).

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 (Figure 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, respectively. No significant differences were found between three combination fixations in flexion and posterior extension.

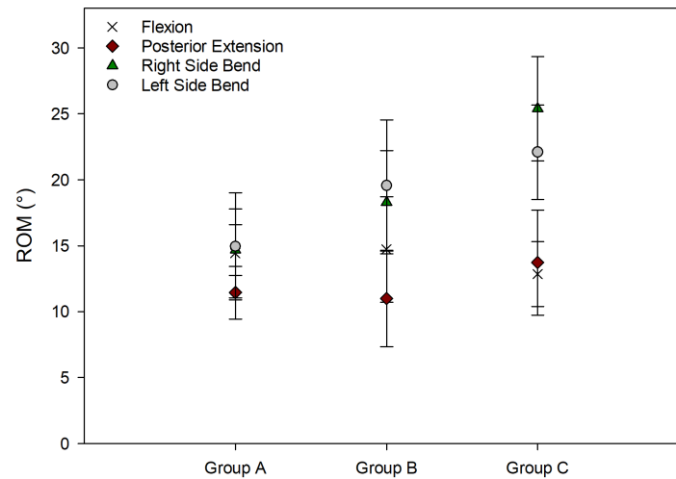


Figure 5: Mean range of motion (ROM) of three pedicle screw internal fixation combinations (Group A: universal screws on both sides, Group B: universal screws on the left and one-way dynamic screws on the right and Group C: one-way dynamic screws on both sides) at four loading conditions. Error bars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

## 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 N·m and 4 N·m 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 to a study where the whole porcine was tested at bending moments of 1-7.5 N·m [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 to 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 with 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, follower loads caused changes in the range of motion under various postures [4]. The effect of follower 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 the fixation systems were more stable in flexion and extension which is consistent to the results in this 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.

## **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.**

## **Declarations**

## **Acknowledgements**

Not Applicable

## **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).

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## **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.

## **Consent for publication**

Not applicable.

## **Competing interests**

The authors declare that there is no conflict of interest.

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