Effect of Cage Insertion Orientation on Stress Profiles and Subsidence Phenomenon in Posterior Lumbar Interbody Fusion

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***Abstract*—Posterior lumbar interbody fusion has been widely accepted as one of the surgical procedure to treat clinical problems. However, vertebral endplate subsidence failure has been detected as one of its major problems that might increase the potential of pain and mechanical instability. Therefore, posterior instrumentation (PI) has been introduced alongside with double fusion cages implant to limit segmental movement and to facilitate fusion. Nevertheless, the use of two interbody fusion cages will be likely to incur higher cost and more risky. Hence, single oblique cage insertion surgical procedure has been reported as one of the reliable solution. In the present study, an image-based finite element analysis was used to evaluate a subsidence phenomenon based on the fracture risks evaluation and the stress profiles at cage-endplate interface in two different cage insertion orientations namely as double cages and single oblique cage. Apparently, the single oblique inserted cage with PI has significantly produced lower stress than the double inserted cages at the cage-endplate interfaces. At higher impact loading (2000N), the total number of compressive deformations of the double cages outnumbered the single oblique cage at the cage-endplate interface junctions and the deformations were more uniformly distributed. Obviously, there was a trade-off between the stress generation, the implant stability and the risk of vertebral bone failures. The single oblique cage insertion method could be considered as one of the best alternative for the posterior lumbar interbody fusion surgical procedure due its structural symmetry that could provide similar stability as two cages did.**

***Index Terms*—interbody fusion, cage insertion, posterior instrumentation, cage-endplate**

I. Introduction

Posterior lumbar interbody fusion (PLIF) is a surgical technique that involves removing a disc and fusing vertebrae together in the lower back (lumbar region). It has become a widely accepted surgical procedure in the field of spinal surgery to stabilize unstable segment due to disc degenerations or could be used as a postoperative assistive devices [1]. It was reported that 80,000 lumbar interbody fusion were implanted worldwide from 1995 to 1999 [2]. Currently, numerous cage designs have been commercialized by taking into account its primary function as a load-bearing structures that is capable to withstand post-operative spine motions, to avoid bone graft collapse and subsequently to promote biological formation of a full thickness of bone bridges. However, its unavoidable clinical implications such as cage subsidence, cage migration and cage failures were still occurred, which forcing the used of posterior instrumentation (PI) to mitigate the impacts.

The use of two cages combined with PI seems to be an ideal solution to limit segmental movement and to facilitate fusion. However, it will be likely to incur higher cost and more risky [3]. In addition, inserting bilateral PLIF cages required a wider laminectomy and facetectomy. Moreover, the risk of neurologic injury as well as risk of dural tear is increased due to bilateral nerve root manipulation. Based on these considerations, there is a strong argument on the effectiveness of using two cages for a successful PLIF. For that reason, single oblique cage insertion surgical procedure has been introduced as one of the viable solution that has the same potential as two cages did [4]-[6].

In the present study, finite element analysis was used to evaluate a subsidence phenomenon based on the fracture risks evaluation and cage-endplate interface stress distributions in two different cage insertion orientations namely as double cages and single oblique

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cage. Five spine motions were considered namely as compression, flexion, extension, axial rotation and lateral bending movements [7].

II. Materials and Methods

A. FE Modelling

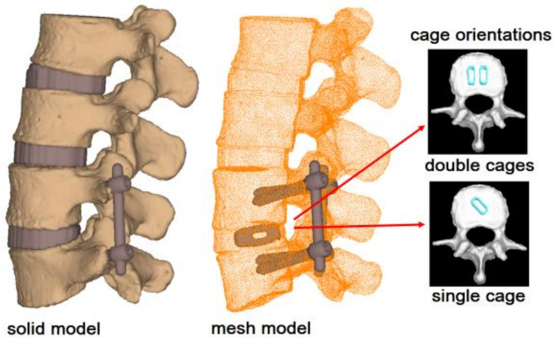
The FE models were constructed in MECHANICAL FINDERTM software (Research Center of Computational Mechanics Co. Ltd. Japan). Written informed consent, permission and cooperation of 29-year-old Japanese male healthy subject (78kg weight and 176cm height) was obtained. To create the FE models, CT scan images of the healthy subject (Juntendo University) was taken and transferred to FE software. From the obtained CT scan images, the FE model was then constructed based on the extracted bone edges of the region of interests (ROI) around the outer region of the cortical bone to obtain the anatomical structure of the spinal bone. The FE model was then modelled with 1mm linear tetrahedral and triangular elements (thickness of 0.4mm) to represent the inner portion of the cortical and the cancellous bone, and the outer cortex, respectively.

To reflect the heterogeneity of the FE models, the mechanical properties for each element was calculated from the Hounsfield Unit (HU) values. Young's modulus was obtained using the relationship as reported by Keyak et al. [8]. Poisson's ratio was set to a constant value of 0.4 [8]-[10]. Facet joints and intervertebral discs were created based on the approximation and visualization of their actual structure and position, which were verified by orthopaedic surgeons. Poisson's ratio for the intervertebral disc and the facet joint were set at 0.45 and 0.2, correspondingly [7]. Meanwhile, Young's modulus were set at 8.4MPa and 11MPa for the intervertebral disc and the facet joint, respectively [7].

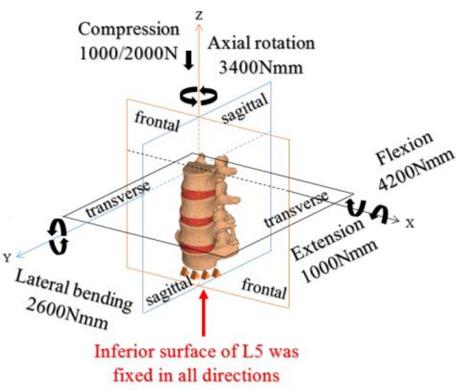
A 23mm long ogival interbody PLIF cage (OIC) made of titanium alloy (Ti-6Al-4V) was simulated. In this study, we simulated decompression surgery by deleting some annulus fibrosus as well as nucleus pulposus, which were necessary to insert bilateral cages and adding posterior pedicle screws-rods system with the diameters being 6.2mm (rods and screws) and the screw length being 51.8mm. Thus, a complete model of post-PLIF was built (Fig. 1a). Two types of cage insertions surgical procedures were simulated namely as: (a) traditional bilateral cages; (b) unilateral oblique cage (Fig. 1a).

B. Analysis

The FE models were loaded with compressive and four rotational loads (flexion, extension, lateral bending and axial rotation) to stimulate the physiological motions of the spine. The loads were applied on superior surface of L2. The inferior surface of L5 was fixed in all directions (Fig. 1b). Maximal Drucker-Prager stress from different cage orientations and loading activities were compared to evaluate the subsidence phenomenon. The prediction of bone fracture sites for each of the model was also evaluated based on the Newton-Raphson nonlinear fracture analysis method [11].



a.



b.

Figure 1. (a) Simulated PLIF model with PI; (b) Loads and boundary condition.

III. Results and Discussions

The Drucker-Prager stress distributions of the different cage orientations under the different loading conditions were shown in Fig. 2. In most of the cases, the maximal Drucker-Prager stresses were detected and concentrated on the interface between the cage and the endplate of the fourth and fifth lumbar vertebrae. Based on these stress distributions the maximal Drucker-Prager stresses were plotted as depicted in Fig. 3. The maximal Drucker-Prager stress was used as a criterion of failed construct when maximal distortion energy theory was applied. For the double cages orientation, the maximal Drucker-Prager stresses were 11.6MPa with compression of 1000N, 26.3MPa with compression of 2000N, 0.7MPa with flexion, 2.3MPa with extension, 3.0MPa with lateral bending and 2.0 with axial rotation. For the single oblique cage orientation, the maximal Drucker Prager stresses were 7.2MPa, 12.7MPa, 0.6MPa, 2.7MPa, 1.9MPa and 1.9MPa for compression of 1000N, compression of 2000N, flexion, extension, lateral bending and axial rotation, respectively.

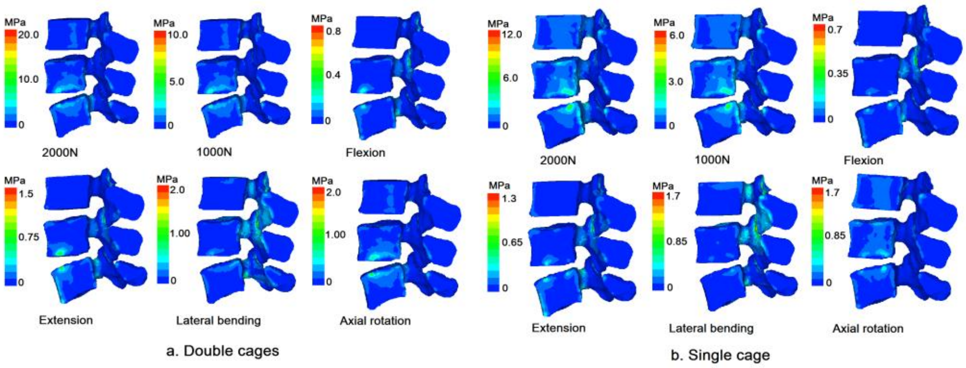


Figure 2. Drucker-prager stress distributions for (a) double and (b) single cage(s).

The relative maximal Drucker-Prager stresses difference of the different implant modalities were also calculated and plotted in Fig. 4. In most of the spine activities, the double cages group has significantly produced higher stress than the single oblique cage group in compression of 1000N (38.3%), compression of 2000N (51.6%), flexion (14.9%), lateral bending (35.6%) and axial rotation (4.4%) activities. However, in extension activity the single oblique cage group outnumbered the double cages group by 16.7%. The possible explanation for this condition was due to better structural symmetry exhibited by the single oblique cage position has effectively diminished the stress concentration within the structure and therefore, it must be given the highest priority and consideration in surgery [1]. Theoretically, placing the cage sagittally in the midline could provide the best symmetry, but it requires excessive retractions on the nerve roots and might results in nerve root damage, especially at higher lumbar levels. A big portion of loads of the single oblique cage was believed had been transferred through the stiff structure of the PI as indicated by the higher number of tensile failure elements around the attachment point between the pedicle screws and the vertebrae as depicted in Fig. 5. The used of the PI itself could reduce the stress of the cage-endplate interface by 50-60% compared to non-instrumented cage [1]. Moreover, the risks of the cage migration and the cage failures were assume reduced.

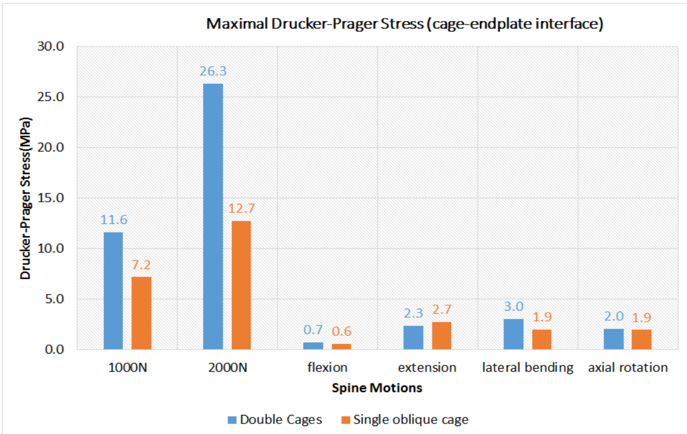


Figure 3. Maximal Drucker-Prager stress distributions at cage-endplate interface.

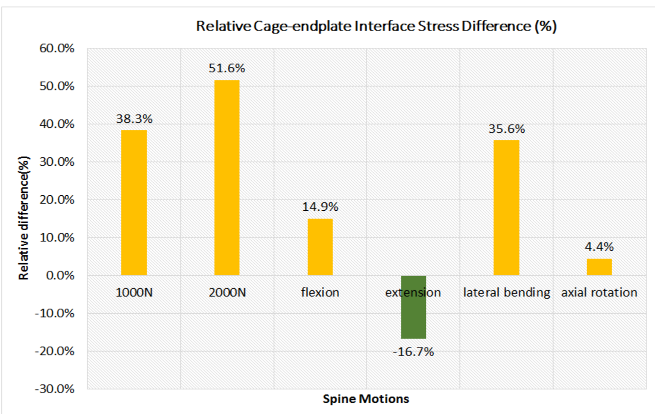
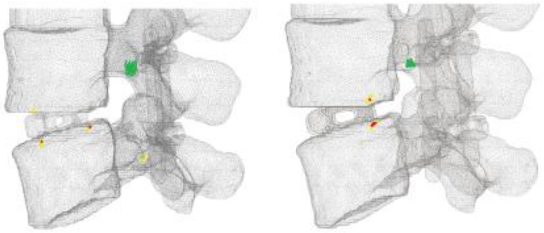


Figure 4. Relative maximal Drucker-Prager stress difference between two cage orientations.

Fig. 5 shows the distributions of failure and yielding elements in the cancellous bone and the inner portion of the cortical bone in the Newton-Raphson loop under the application of the compressive load of 2000N to simulate the worst loading condition. In general, for the both cage orientations almost all of the failure and the yielding elements could be detected at the cage-endplate interface and around the posterior-lateral region of 4th and 5th lumbar vertebrae. The posterior-lateral region was the area in which pedicle screws were inserted, and the region is important in terms of supporting and transferring loads between the vertebra and the screw [11]. The tensile failure elements were densely distributed widely along the axis of the inserted screw, while few and no compressive yielding and failure elements were found, respectively. The compressive yielding and failure elements only could be found at the cage-endplate interface, which was highly related to subsidence phenomenon that was prevalently happened in interbody fusion surgery method. Even though the models did not reach a state of whole fractures, the existence of the failure and the yielding elements on that areas indicating that these regions still faces higher risks of fracture.

In Table I, the total number of the failure and the yielding elements were comparably higher for the single oblique cage (107 elements) than the double cages (84 elements). In addition, the failure and the yielding elements for the single oblique cage were distributed more uniformly than the double cages group. However, the total numbers of compressive deformations were slightly surpassed the double cages group by 12 elements and these conditions were highly correlated with the existence of the subsidence phenomenon (cage subsidence) created at the cage-endplate interface junctions. Less compressive deformation and lower distortion stress generation was a signed of higher structural stability offered by the single oblique cage than the double cages PLIF. Lower distortion stress generation of the single oblique cage (12.7MPa) was accompanied with higher number of tensile failure elements (59 elements), while higher distortion stress generation of the double cages (26.7MPa) was accompanied with lower number of tensile failure elements (27 elements). These compensatory mechanisms were inevitable and ultimatum in considering the best combination of the implant modalities. The occurrence of the tensile failures suggested that the stress concentration might cause the screw to slip and loosen and this problem is believed could be overcome by increasing the rod sizes or used flexible fixation for load dispersions and to provide an appropriate load path in the vertebrae and screws.



(a) (b)

Figure 5. Distribution of failure and yielding elements: (a) Single oblique cage and (b) Double cages

TABLE I. NUMBER OF FAILURE AND YIELDING ELEMENTS

Failure type	Number of element	
	Double Cages	Single oblique cage
Compressive failure	31	9
Compressive yielding	26	39
Tensile failure	27	59

IV. CONCLUSION

These results suggested that the used of unilateral oblique PLIF cage could be considered as one of the optional alternative to replace the bilateral PLIF cages by thorough consideration of its stress distortion, structural stability and subsidence effect. Obviously, single oblique cage would produce lower maximal Drucker-Prager stresses at cage-endplate junction, more stable and could potentially reduce the subsidence (compressive deformation) effect on that areas. However, its inevitable effect of higher tensile deformation seems unavoidable. Hence, single oblique cage PLIF has the same potential as double cages did and last but not least, it may also reduce medical cost and surgical risk without compromising its structural stability.

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