Optimization of nucleus pulposus removal rate in the intervertebral disc during artificial nucleus replacement using lumbar finite element model simulation

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Abstract

A herniated intervertebral disc (HIVD) is a disease caused by the prolapse of the nucleus pulposus of the intervertebral disc due to aging and repeated damage. To treat this, artificial nucleus replacement (ANR) is used to restore the height and flexibility of the reduced intervertebral disc by replacing a portion of the aged nucleus pulposus with an artificial one. However, few studies provide quantitative criteria for partial nucleus pulposus removal. Therefore, through finite element model (FEM) simulation of the lumbar spine (L4-L5), we obtained the optimal location and rate of nucleus pulposus removal and analyzed the movement of the model after ANR in this study. We modeled the FEM in which 60%, 80%, 87%, and 93% of the total nucleus pulposus were replaced by the artificial nucleus pulposus in each of the four directions (left, right, anterior, posterior). Then, a z-axis load of 400N was applied to the model to obtain an axial compression displacement, and a y-axis moment of -6 Nm~+6 Nm was applied to the model to analyze a flexion-extension range of motion (ROM). As a result, regardless of the location of the remaining nucleus pulposus, the compression displacement of the 80% and 87% nucleus pulposus removed model was restored to about 98% of that of the intact model. In addition, the ROM of the 87% nucleus pulposus removed model was restored in 96% of that of the intact model. It is expected that the data obtained through this study can be utilized in digital twin research to predict the prognosis of ANR and to improve surgical techniques.

Keywords: Finite element model simulation, Artificial nucleus replacement, Herniated intervertebral disc

Introduction

A herniated intervertebral disc (HIVD), in which the nucleus pulposus of the intervertebral disc prolapses, causes back pain, and radiating pain. To treat HIVD, total discectomy surgery is generally used. However, after the surgery, excessive movement of the adjacent segment decreases the normal range of motion (ROM), resulting recurrence of the disease.[1-3] To compensate for this shortcoming, artificial nucleus replacement (ANR) has been proposed, in which a part of the nucleus pulposus is removed and then an artificial nucleus pulposus is inserted. Clinical studies of ANR are still lacking, and there are few studies on intervertebral finite element analysis on spine movement after surgery.[4] The purpose of this study is to investigate the optimal location and rate of nucleus pulposus removal through FEM simulation and to analyze the axial compression displacement and flexion-extension ROM of the lumbar spine after ANR.

Methods

The intact FEM of the fourth and fifth lumbar spine consists of the cortical bone, annulus fibrous, endplate, and nucleus pulposus. The ANR FEMs are designed in the form of removing 60%, 80%, 87%, and 93% of the total nucleus pulposus in the left, right, anterior, and posterior directions. The removed part was filled with a fluid cavity with a density of 1000 kg/m^3. To obtain the axial compression displacement, we applied a z-axis load of 400 N to the center of the model which is perpendicular to the transverse plane.[5,6] And, to analyze the flexion-extension ROM, we applied a moment of -6 Nm ~ +6 Nm along the y-axis to the model.

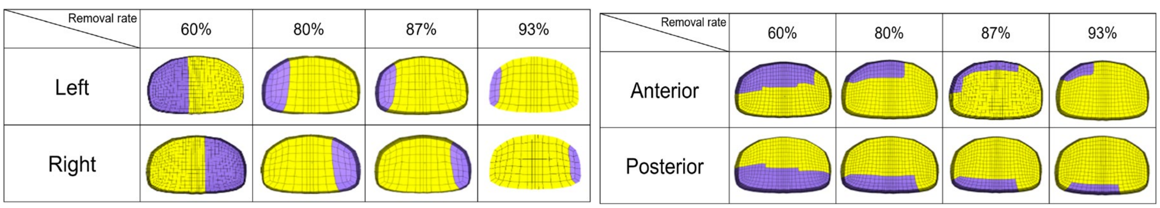
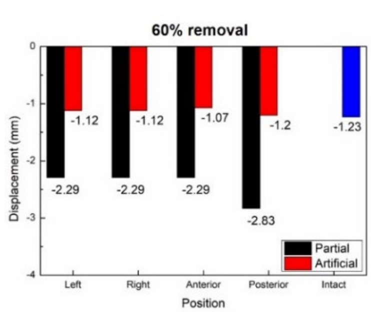
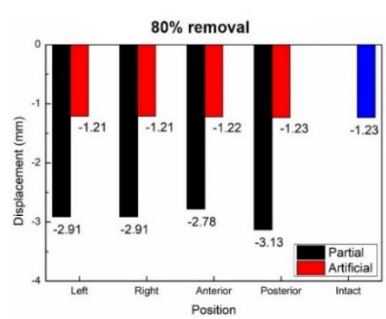


Figure 1. ANR FEMs with 60%, 80%, 87% and 93% nucleus removal. (Purple: original, Yellow: removed)

Results

The graphs below are the axial compression displacement graphs of the model when a 400 N load was applied. To verify that ANR is better than just removing the nucleus (partial discectomy), we compared all ANR data with partial discectomy data. Regardless of the location of the remaining nucleus pulposus, the displacement of the 80% and 87% nucleus pulposus removed model was restored to about 98% of that of the intact model. In addition, when the -6 Nm ~ +6 Nm moment was applied, the flexion-extension ROM of the 87% nucleus removed model in the posterior direction was restored in 96% of that of the intact model while that of partial discectomy was restored in 93% in the same conditions.





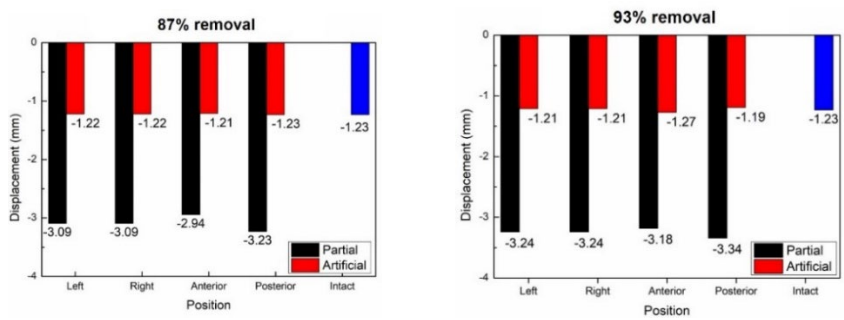


Figure 2. Axial compression displacement when applied 400 N to the model.

Discussion and Conclusions

Overall, ANR is more useful because the compression displacement and flexion-extension ROM of ANR are smaller than partial discectomy data. Moreover, compared to partial discectomy, ANR showed 5% more enhancement in flexion ROM and 2% in extension ROM. Combining the above results, the optimal ANR method is to replace 87% of the nucleus pulposus while remaining the original nucleus pulposus in the posterior direction. These results can be used in digital twin research to improve ANR surgical techniques.

Acknowledgments

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