Study on the effects of the psoas major muscle and facet joint orientation on the intradiscal stress of the lumbar spine

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Abstract:

Background: The psoas major muscle plays an important role in sharing the external loads applied on the lumbar spine, and the facet joint orientation is considered as a congenital anatomical factor of lumbar degeneration. However, since the effects of the two factors on the stress distribution of the lumbar spine have rarely been studied, the influences of the psoas major muscle and fact joint orientation on the intradiscal stress are here investigated.

Method: To consider the influence of the psoas major muscle, a lumbar spine of a health volunteer was first scanned, and the obtained CT images were used to establish the finite element (FE) lumbar model A by the software Simpleware. Then, based on the model A, a model B with the muscle was developed, and further the model B was employed to construct three facet joint orientations (F45, F50, F55) of the L3-L4 lumbar segment. All the FE model were import into the FE software ABAQUS to perform simulations of six motions including flexion, extension, left and right lateral bending, left and right rotation.

Result: Under flexion, the intradiscal stress of the model B was 18.99% lower than the model A, and 23.42% lower in extension. In the left and right lateral bending, the stress was reduced by 36.63% and 27.20%, respectively. But in the left and right rotation, the changes of intradiscal stress were only 1.49% and 2.97%. In the lumbar flexion and extension, the orientation F55 showed the maximum intradiscal stress, and the orientationF45 showed the maximum intradiscal stress in the rotation, but all the orientations (F45, F50 and F55)share the similar intradiscal stress in lateral bending.

Conclusion: The psoas major muscle alleviates the intradiscal stress, and different facet joint orientations dominate the stress in different motions. This work could be useful for the researchers and clinicians to evaluate the stress distribution of the lumbar spine.

Keywords: Lumbar spine, Psoas major muscle, Facet joint orientation, Intradiscal stress, Finite element analysis.

1. Introduction

Degenerative lumbar scoliosis (DLS) often develops in the L4-L5 lumbar spine, and its occurrence is increasing with age. To prevent the lumbar degeneration, it is necessary to identify the factors that promote the degeneration.

Facet joint is formed by the superior facet and inferior facet, and it is regarded as a congenital anatomical factor in lumbar degeneration, and as one of the primary structures of the spine, it prevents excessive translation and rotation, and thus stabilizes the spinal motion. The facet joint orientation is defined as the direction of the joint surface and the coronal plane, and it influences intervertebral joint translation and rotational displacement, in other words, with different facet joint angles, the displacement of the intervertebral joint can be very different. SamartzisD et al. [1] reported that the sagittal facet angle was associated with L4-L5 degeneration in lumbar spine through the study of 349 patients, and the critical value of the facet joint angle was about 32 degrees. Therefore, the facet joint orientation is a potential anatomical predisposing factor of the lumbar degeneration that may lead to early degeneration of the intervertebral disc or degenerative spondylolisthesis [2]. Moreover, literature reported that experiments revealed the stabilizing effect of the psoas major muscle on the lumbar spine under the static state, and driving effect of the muscle on the dynamic extension of spine [3], but the biomechanical effects have not yet been validated.

Finite element method is often used to simulate the complex spinal system and using this method, Kim et al. [2] showed that a facet tropism structure could make the L3-L4 segment more vulnerable to external loads, and Christophy et al. [4] modelled the psoas major muscle in a finite element lumbar spine as springs which connected the L1-L4 vertebral body and the small rotor of femur. Hence, the finite element method is expected to be an effective tool to quantify the biomechanical effect of facet joint orientation and psoas major muscle.

In this study, the biomechanical effect of the psoas major muscle and the facet joint orientation on the intradiscal stress under six specific motions (i.e., flexion, extension, left and right lateral bending, left and right torsion) are studied.

2. Finite Element Method

To investigate the effects of the psoas major muscle and the facet joint orientation on the intradiscal stress, a normal lumbar model A without the muscle and model B with the muscle were established, and based on the model B, three facet joint orientations were considered, thus there are four cases in total. For the four cases, six motions (i.e., flexion, extension, left and right lateral bending, left and right torsion) were considered.

Geometrical models

Model A without the psoas major muscle: L1-L5 CT images of the lumbar spine from a healthy adult male (37-years-old, 75 kg, 178 cm)were used to establish a normal finite

element lumbar model A by the ScanIP module of the commercial software Simpleware (*Synopsys Inc*, UK), and the model mesh was generated by its mesh module (Figure 1B).

Model B with the psoas major muscle: According to Christophy et al [4], we first determined the connecting position of the psoas major muscle, namely, one end of the muscle is located at the rear side of the low edges of L1-L4 vertebrae, and the other is at the end of the small rotor of femur(Figure 1C). Here, under the six motions, the pelvis was considered to be motionless, and this was reasonable when the motions occur from up-right standing state. Therefore, two fixed reference points replaced the two connecting positions at the small rotor of the femur, and the coordinates of the reference points were determined by measuring the distance between the small rotor and the lumbar spine on the CT images of the volunteer. After determining the connection of the muscle, it was incorporated into the meshed model A in the commercial finite element software Abaqus (*SimuliaInc*, USA), see Figure 1D.



Figure 1.Three-dimensional finite element model of a lumbar spine of the volunteer. (A) A CT image with L1-L5 lumbar segments on the saggital plane; (B) The normal finite element lumbar model; (C) The CT image with L4/L5 lumbar segment and pelvis; (D) L4/L5 lumbar segment with the psoas major muscle. (E) The whole model with psoas major muscle.

Facet joint orientations of L3-L4 lumbar segment: Here, on the basis of clinical experience, different facet joint orientations were only considered to occur at the L3-L4 lumbar segment of the model B, which have a facet joint angle of 50° (marked by F50). To construct the other two lumbar models with L3-L4 facet joint orientations of 45° and 55° (marked by F45 and F55, respectively), the CT images of L3-L4 lumbar segment were modified in the Simplware by the fusion and segmentation operations.



Figure 2.Facet joint orientations with different facet joints angles. (A) F45; (B)F50; (C)F55.

Material properties of components and boundary conditions

The lumbar model was divided into two parts, the vertebral body (L1-L5) and the intervertebral disc (D1-D4).For the vertebral body, it was constituted by four components, i.e., articular cartilage, cortical bone, cancellous bone, posterior structure where the facet joint belongs, andthe contact between the four components were all coupled. The thickness of the articular cartilage was defined as 0.5 mm, and that of the cortical bone as 3 mm, and they were assigned by shell element; and the cancellous bone and posterior structure were assigned by the C3D4solidelement.Moreover, the surface-to-surface contact was used between the superior and inferior articular process. For the intervertebral disc, it consisted of fibrous ring and nucleus pulposus, and the contact between vertebral body and fibrous ring was tied, plus the ligament and muscle were tied to the vertebral body, and they were assigned with the spring element [5].

All the materials in the models were simplified to be isotropic and linear elastic, and nucleus pulposus was approximately modelled as an incompressible material. Their Young's modulus and Poisson's ratios were listed in Table 1.

For all the motions, a 400N concentration force was applied on the reference point located at the centre of the top surface of the first lumbar segment (L1) to simulate the body weight above the L1, and the loading direction is along the z axis. Plus, due to bending moment induced by the six motions, a 10N m moment was also applied on the reference point [9]. Then, all the caseswere simulated by the software Abaqus (*SimuliaInc*, USA) to study the intradiscal stress undersix motions.

Components	Young's modulus(MPa)	Poisson's ratio
Cortical bone	12000	0.3 ^[6]
Cancellous bone	100	$0.2^{[6]}$
Posterior element	3500	0.25 ^[6]
Articular cartilage	24	0.4 ^[7]
Fibrous ring	4.2	0.45 ^[6]
nucleus pulposus	1.0	0.4999 ^[8]
Anterior longitudinal ligament	20	0.3 ^[9]
Posterior longitudinal ligament	70	
Ligamentum flavum	50	
Interspinous ligament	28	
Supraspinous ligament	28	
Intertransverse ligament	28	
Capsular ligament	20	
Psoas major	45 ^[4]	

Table 1.Material properties employed in the FE models

3. Model Validation

The rotational displacement of each intervertebral disc with respect to its bottom surface or the rotational stiffness defined as the moment to the rotational displacement, were calculated in flexion and extension states to validate the model. For the rotational stiffness, a concentrate force of 400N and a moment of 5 N m were applied to the model A to compare the present result with Kim et al. [10], see Figure 3A. It shows a weak difference of the results by Kim et al., and this study presents similar stiffness of D1 and D2 as the literature, but D3 and D4 showed a large discrepancy between the present study and literature. Moreover, to further validate the model, a concentrate force of 150N and a moment of 10 N m were applied to the model A to compare with the results of the rotational displacement by Yamamoto et al.[12] and Shirazi-Adl et al.[13]. Similarly as the comparison of the rotational stiffness, the results of D1 and D2 are comparable, and D3 and D4 are apparently different, in particular, the rotation angle of D4 was almost zero, see Figure 3B,C. This is because the model in the literature contains the sacrum and an extra disc between the L5 and the sacrum, whose bottom was fixed, and the model is more flexible, thus the stiffness is less than the present work, but the rotational displacement is greater than the present study, which does not have the sacrum and fixed at the bottom of the L5.



Figure 3.Validation of the original model. (A) Stiffness comparison with Kim et al.[10]; (B/C) Rotation angle comparison with Qin, Yamamoto and Shirazi-Adl et al. under flexion/extension.

4. Results

Effect of the psoas major muscle

Figure 4 shows the effect of the psoas major muscle on the greatest intradiscal stress of all discs for all the motions. Generally, the stress of the model A without the muscle is greater than that of the model B, and the maximum stress is on the D1. Moreover, the stress is in the order of D1 > D2 > D3 > D4 except in the extension, and under the extension, the variation of stress on last D2-D4 discs was opposite to the others. In detail, without the muscle, the stress of the model A increased by 18.99% under the flexion; under extension, the increment is 23.42%; the stress increase was 36.63% for left bending and 27.20% for right bending, respectively; but the stress increase was only 1.49% (left rotation) and 2.97% (right rotation). This indicates that the psoas major muscle bears a part of the load induced by the motions.



Figure 4.The intradiscal stress of the models A and B under six motions

Effect of facet joint orientation

Figure 6 shows the effect of three facet joint orientations on the greatest intradiscal stress of all discs of the model B for all the motions. Generally, they eakly differ, and the greater stress and stress discrepancy between the three orientations is at the upper disc, i.e., D1, and there is not common variation. In detail, as mentioned in Section 2, only the facet joint orientation of the L3-L4 was changed. In this regard, under the flexion and extension, the orientation produce a common influence on the D3, i.e., F45<F50<F55; under the left and right bending, the influence on the D3 are very weak, especially for the right bending; for the left and right rotation, the common order isF50<F55<F45 for the stress on the D3. This means that people with larger facet joint angle would more easily get injured for the flexion and extension, and people with less facet joint angle get injured for the rotation.



Figure 5.Intradiscalstress of D1-D4intervertebral discs in the three orientations (F45, F50 and F55). (A) Flexion (B) Extension (C) Left bending (D) Right bending (E) Left rotation (F) Right rotation.

5. Discussions and Conclusions

Since the psoas major muscle and facet joint orientation play an important role maintaining the stability of lumbar spine, this study aims to use finite element method to study their effects on the intradiscal stress in several motions.

Firstly, the model validation by comparing the present result with the literature, to some extent, they are in an agreement, and the difference mainly caused by the different geometrical models, but it still illustrate the availability of the present model.

For the effect of the muscle, it proved that the inclusion of the muscle in the model indeed shared the load of the body weight and applied moment, and reduces the stress magnitude of the intradiscal stress. This also illustrates that the finite element models in literature without the muscle over-estimated the stress distribution. As for the facet joint orientation, compared to other literature, our study provides an effective method to construct the model with different orientations, and a comprehensive research on the biomechanical mechanism of the facet joint orientation in occurrence and development of degenerative lumbar scoliosis based on the intradiscal stress. It is worth mentioning that only the facet joint orientation D3 is considered. Plus, the greatest intradiscal stress always locates at the fibrous ring, which may indicate the position of back pain or other clinical symptoms.

In summary, we have studied the effects of the psoas major muscle and facet joint orientation on the intradiscal stress of the lumbar spine. The maximum intradiscal stress always located at the first disc D1, and the psoas major muscle indeed reduces the stress of the intradiscal stress and improves the prediction. Different facet joint orientation induces maximum intradiscal stress under different motions. The present study could be helpful to the researchers or clinician to treat relevant lumbar diseases.

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