Biomechanical Analysis of the Waist Movement of Taijiquan Based on Finite Element Method

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Abstract: *Finite element method is a calculation method that can comprehensively and objectively analyze the stress and strain of complex objects. It is mostly used in biomechanics research of human complex structure. In Taijiquan exercise, the waist drives the motion of the body, which adapts to the physical condition of human body. Hence, the waist plays an important role in Taijiquan exercise. This paper applied CT imaging method and CAD modeling to establish a finite element model of the L4-L5 segment to explore the effect of finite element method on the waist, taking two actions of standing with the waist relaxed and pushing hands as examples. It was found that when the movement of Taijiquan pushing hands deepened, the flexion of the waist increased and the muscular strength of the erector spine increased gradually. However, the muscular force of erectors under the same curvature gradually decreased with the increase of the follower force. The cancellous bone pressure was the largest in the standing state, which was about 1.9 MPa. With the increase of the curvatures, the cancellous bone showed a tendency of first decreasing and then increasing. The pressure in the lumbar disc was the lowest of all values in an upright position. With the deepening of pushing hand movements, the waist curvature becomes larger, the pressure inside the lumbar disc also became larger; in the case of the same curvature, the greater the follower forceb, the greater the pressure. Therefore, waist bending angle in Taijiquan exercise has an important impact on the spine strength and lumbar disc pressure.*

Keywords: *Taijiquan, Waist, Finite element method.*

Introduction

As China's precious national cultural heritage, Taijiquan has a good promoting effect on the nervous system, sensory system and heart of the human body. Studying the biomechanics of the body during the specific exercises has both theoretical and practical significance [14, 17]. As the waist is the key of trunk movement, studying the biomechanics of the waist is helpful for us to learn more about Taijiquan, so as to better practice it. Ibarz et al. [3] established a complete three-dimensional finite element model of the lumbar spine (vertebrae, disc, ligament) based on the finite element model and found that the application of disc degeneration (L5-S1) allowed flow in different lumbar segments. Liebschner et al. [8] established and validated a three-dimensional finite element model of thoracolumbar spine based on quantitative CT scan. Meng and Bao [10] established a complete model of the lumbar spine stage and simulated the movement of dumbbell lifting preparation to analyze the force conditions, which verified that finite element method could be applied for analyzing the biomechanics of the waist. The finite element method divides a complicated object into a finite number of units by discrete methods and assembles them into a new integral equation to solve according to the link between the units [2]. Finite element modeling mainly includes slice method and three-dimensional measurement method, which can be further divided into modeling stage, calculation stage and post-processing stage [4, 6, 13].

This study established a finite element model of the L4-L5 segments with CT image method and CAD modeling method to study the pressure on the waist based on the two basic movements of Taijiquan, i.e., standing with a relaxed waist and pushing hands. The research results showed that various degrees of pressure was produced on the erector spinae, cancellous bone, intervertebral disc and nucleus pulposus during the movement of pushing hands as the waist bending degree increased.

Materials and methods

Experimental objects

Based on the length of Taijiquan exercise and the professional degree, one subject (age 26, height 178 cm, weight 78 kg) was selected from the applicants in the Hunan Taijiquan association, with normal L4-L5 anatomical parameters and no related lumbar diseases. Before the experiment, relevant experiments were introduced to the subject and his consent was obtained. The CT image of the waist of the subject is as follows:

Fig. 1 L4-L5 bone tissues under CT scanning

Experimental equipment

The equipment is as follows: a Dutch Philips 16-row large aperture CT machine provided by the Hunan Provincial People’s Hospital; a computer provided by the Hunan Provincial People’s Hospital; Finite element analysis software ANSYS 9.0; three-dimensional finite element modeling software Mimics 12.0.

Experiment method

Image acquisition processing of the L4-L5 segments

The subject underwent CT scanning, with the scanning area on the L4-L5 segments and a scanning layer thickness of 0.6mm. The scanning image was directly input into the three-dimensional finite element modeling software MATLAB12.0. Through grey values, the tissues were separated and manual burr processing work was carried out to obtain relatively independent individuals so as to divide each part more completely. Afterwards, mesh generation was performed on each part and then the processed parts were input into the finite element analysis software ANSYS 9.0 for constraint loading in order to obtain the final finite element model.

Finite element model building process

The constructed finite model includes the cortical bone, nucleus pulposus, cancellous bone, articular cartilage, endplate and other structures. There are more than 60,000 nodes on the

L4-L5 segments and the specific cell division and material properties are shown in Table 1.

Table 1. Finite model parameters of the L4-L5 centrums of the subject

Structure position	Element type	Elasticity modulus	Poisson's ratio	Area
cortical bone	6-node hex	12000	0.3	-
cancellous bone	10-node hex	100	0.2	-
nucleus pulposus	10-node hex	1	0.5	-
cartilago articularis	10-node hex	10000	0.3	-
posterior structure	10-node hex	35000	0.25	-
fibre ring	10-node hex	4.2	0.45	-
collagenous fiber	2-node hex	nolinear	nolinear	-
anterior longitudinal ligament	2-node link	7.8 (< 0.12)	20 (> 0.12)	73.9
posterior longitudinal ligament	2-node link	10 (< 0.11)	20 (> 0.11)	52.2
ligamentum flavum	2-node link	15 (< 0.062)	19.5 (> 0.062)	75.7
supraspinous ligament	2-node link	8 (< 0.12)	15 (> 0.12)	74.5
interspinous ligaments	2-node link	10 (< 0.14)	11.6 (> 0.14)	35.6
intertransverse ligament	2-node link	10 (< 0.18)	58.7 (> 0.18)	31
capsular ligament	2-node link	7.5 (< 0.25)	32.9 (> 0.25)	1.8

Because the thickness of the human lumbar spine differs from person to person, in this experiment, the angle between the two surfaces of the lumbar disc was set to be 5°. The cartilage endplates of the upper and lower surfaces were discretized by an eight-node hexahedral element with a thickness of 1 mm. The cortical bone in the vertebral body is approximately 1.3 mm thick and is also a hexahedral element. The unit is shaped like a square and has a length of about 2 mm. There is a convex forward bending in the lumbar vertebrae of the human body, in this experiment there exists a 9° angle value between the lower end of the L5 and the horizontal plane. The rear structure is a tetrahedron unit, connected by means of node coupling, with a gap of 0.5 mm and a friction coefficient of 0, which only transfers the opposite pressure. The total number of units in the model is as presented in Table 2.

Boundary conditions

The experimental model is based on the physical unit. To control the scale of analysis, only half of the total number of units in this structural site is selected. Based on symmetry, the symmetric part of the model is allowed to move up and down, forward and backward while forbidden to move left and right. The waist carried the gravity of the upper body, i.e. 390 N. Under the upright standing position, the center of gravity was in the rotating central part of the lumbar vertebra, 28 mm away from the ventral side and 300 mm away from the top of the L4. When the subject was to push hands, the center of gravity would move forward, and the force condition of lumbar muscles was more complex. In this study, we adopted a simplified load mode, which simplified the erector spinae to concentrated force, located at 38 mm behind the vertebral rotation center along the vertebral tangent direction. Following load refers to the pressure which acts on the center of gravity of the centrum and directs at a nearby center of rotation, in the direction of the tangent line. While doing the pushing hands movement, the bending degree of the waist was 0°, 15°, 30°, respectively, and the corresponding gravity and following load was 390 N, 0 N; 390 N, 200 N; 390 N and 400 N, respectively. The stress on the erector spine and the L4-L5 segments were studied on this basis. The Taijiquan pushing hands action is shown in Fig. 2.

Table 2. Total number of units of different structural parts

Structural part	Total number of units
cortical bone	495
cancellous bone	3965
nucleus pulposus	190
cartilago articularis	215
posterior element	25050
fibre ring	2600
collagenous fiber	250
anterior longitudinal ligament	5
posterior longitudinal ligament	3
ligamentum flavum	3
supraspinous ligament	1
interspinous ligament	3
intertransverse ligament	1
capsular ligament	3

Fig. 2 Continuous action chart of pushing hands

The Taijiquan station type body standing method is different from ordinary standing, as shown in Fig. 3. The general standing waist physical bending was significantly greater than the Taijiquan stand-type method of standing and Taijiquan stand-type method of standing had a better mitigation effect on the lumbar spine.

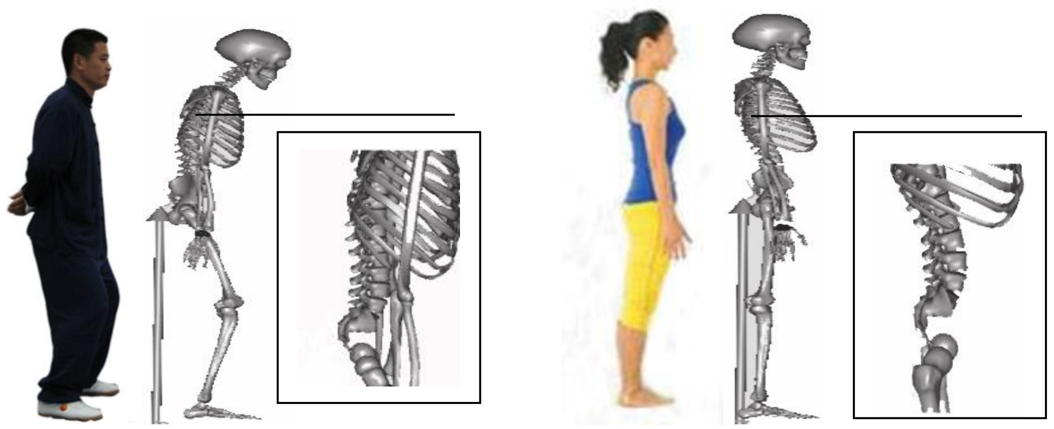

Fig. 3 Taijiquan standing with a relaxed waist (left) and ordinary standing (right)

The establishment of the finite element model

In this model, the sagittal angle is 30° and the load is 400 N. The cortical bone, cancellous bone and nucleus pulposus are the key structures in this model. Based on the principle of the three-column mechanics of the spine [1], the upper and lower structures of the intervertebral discs and the connections as well as the joints contacting parts were designed as close as possible to reality. As shown in Fig. 4, the nucleus pulposus was inserted into the mid-posterior position of the annulus fibrosus, which was bilaterally symmetrical. The red and blue highlighted part was like a lantern, suggesting that the pulposus was embedded in the fiber annulus in a lantern shape. It can also be found that this model was more regular in appearance, with smooth transition between organizations and reasonable and orderly unit division, suggesting that there was a good simulation results.

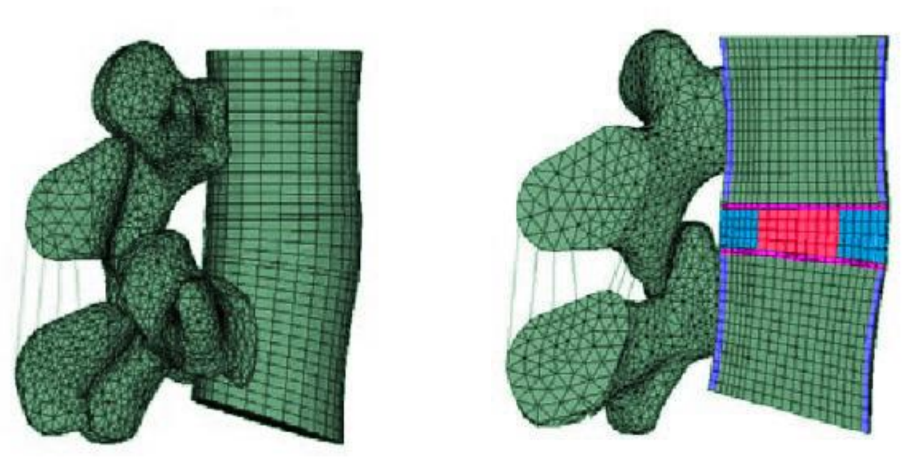

Fig. 4 The finite element model of the L4-L5 segments (left) and the actual image data (right)

Results

Waist erector spinal muscle strength

Erector spinae (vertical ridge muscle) is the long muscle at the back of the spine, filled in the groove between the spinous process and the rib angle. From the standing position to the movement of pushing hands, the waist bending degree increased gradually. Accordingly, the vertical ridge strength also increased gradually (Fig. 5). However, with the continuous increase of the follower force, the vertical ridge muscle strength under the same bending degree gradually decreased. When there was no following load, the erector's force was about 520 N, and when the following load increased to 200 N and 400 N, the erector's force was only about 450 N and 400 N. If the role of following load is ignored, then 50% of the upper body weight will bend the lower lumbar forward by about 50°. Therefore, the following load must be taken into account to avoid influence on the experimental results.

Cancellous bone

As shown in Fig. 6, the stress was the largest in the standing state, about 1.9 MPa, when there was only 390 N gravity. With the increase of the bending degree, the cancellous bone showed a tendency to decrease first and then rise. There was also a significant effect of the vertical ridge strength on the stress of the cancellous bone. When the bending degree was 15°, the stress on the cancellous bone increased from 0.5 MPa to 2.8 MPa with the effect of the erector spine.

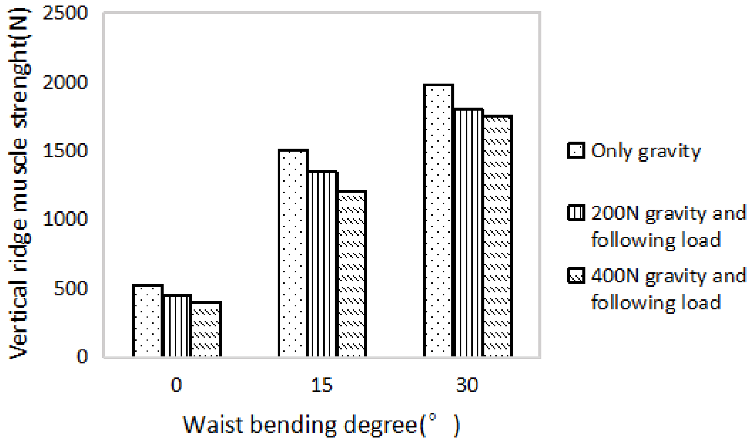

Fig. 5 The values of the vertical ridge muscle strength
(the gravity here refers to the gravity of the upper body, i.e. 390 N)

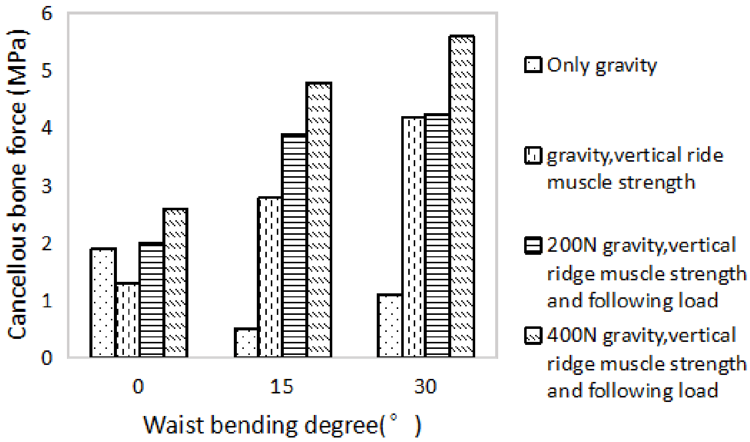

Fig. 6 Stress on the cancellous bone

Intervertebral disc internal stress

When the waist was upright, the pressure in the lumbar disc was the smallest. With the ongoing of the movement of pushing hands, the lumbar disc internal pressure increased with the increase of the waist bending degree. Under the same bending degree, the greater the following load, the greater the pressure. As shown in Fig. 7, when the degree of bending was zero and there was no following load, the internal pressure was about 0.9 MPa; when the following load was 400 N, the disc pressure was about 1.5 MPa. Also, we can see the influence of the erector spinae in the figure, i.e., under the influence of the vertical ridge muscle strength, the growing rate of the lumbar disc pressure reduced. When the bending degree was 30°, the pressure was in a balanced distribution.

Waist nucleus pulposus internal pressure

As shown in Fig. 8, the stress of the nucleus pulposus in the presence of gravity only decreased with the increase of the bending degree. When the bending degree was 15° and 30°, the stress of the nucleus pulposus increased with the influence of following load. While when the bending degree was 0° in the standing state, the stress of the nucleus pulposus decreased before increased. When the bending degree was 30° and the following load was 400 N, the stress of the nucleus pulposus increased to the maximum value.

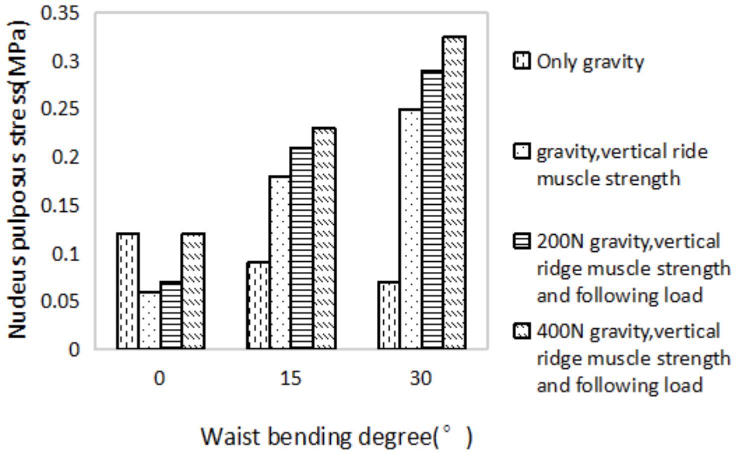

Fig. 7 The values of disc pressure (the gravity here refers to the gravity of the upper body, i.e. 390 N, and the gravity plus erector spinae strength was 910 N)

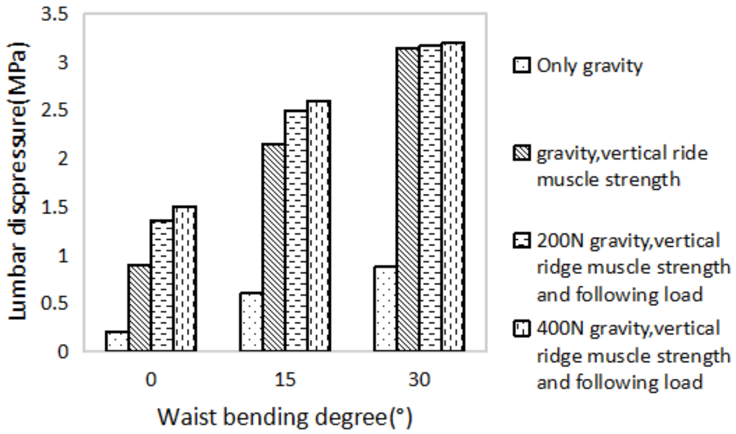

Fig. 8 Pressure on the nucleus pulposus of the L4-L5 segments (the gravity here refers to the gravity of the upper body, i.e. 390 N, and the gravity plus erector spinae strength was 910 N)

Discussion and conclusion

In this experiment, we studied the pressure on the lumbar spine, the cancellous bone, the intervertebral disc, and the nucleus pulposus in the movement of pushing hands in Taijiquan exercise. Erector spinae is the long muscle behind the spine and the contraction of it can make the spine stretch backwards. Meanwhile, it is also an important part to maintain the upright posture [7]. The scaffold structure of the cancellous bone helps to maintain the bone morphology, and resist the internal and external pressure, and it is also the main component of most of the axial bones [9]. The intervertebral disc is composed of the nucleus pulposus and annulus fibrosus and the nucleus pulposus is an elastic colloid [11]. With the increase of age, the nucleus pulposus loses water and the collagen is replaced by the fibrocartilage, which can easily cause disc herniation [16]. Therefore, the above indicators can well reflect the pressure on the waist.

The erector spinae, cancellous bone, intervertebral disc and nucleus pulposus of the elderly will gradually degenerate with the increase of age, so it is necessary for the elderly to be more cautious when doing the Taijiquan exercise. The experiment found that, in the standing state, the erector spinae and the following load were added, thus the stress of nucleus pulposus showed a rising trend after decrease, which was caused by the pressure on the nucleus pulposus since the center of rotation was moved to the front of the vertebral body at the bending moment of the waist. Simplified load mode was used. Following load was simplified to pressure acting on the center of gravity of vertebral body. It passed the center of rotation and pointed out the center of rotation of the adjacent segments. The direction of following load was consistent with the tangential direction of the segment direction.

Tang et al. [12] established lumbar intervertebral bone graft models at different intervertebral heights and studied the changes of the pressure on the nucleus pulposus and annulus fibrosus. To study the relationship between lumbar intervertebral and lumbar muscles, Kim et al. [5] established the lumbar degeneration model by combining the T12-L1 motion segment with the corresponding muscle on the basis of the previous model and the results showed that lumbar disc degeneration significantly increased the activity of superficial muscle while reduced the activity of deep muscle. In this study, a finite element model was established based on CT image method and CAD modeling, with advantages of simplicity and reliability. The experiment found that the erector spinae, cancellous bone, intervertebral disc stress and nucleus pulposus pressure would increase with the increase of the amplitude of Taijiquan. When the load was 400N, the disc pressure was the closest to the normal range, which was different from the results found by Wilke et al. [15] that 200N was closest to the physiological range.

However, the experiment was carried only on the L4-L5 segments, thus further studies are needed in the future on other segments to fully explore the pressure on the waist during Taijiquan exercise.

During the movement of pushing hands in Taijiquan exercise, much pressure can be caused on the erector spinae, cancellous bone, intervertebral disc and nucleus pulposus of the waist of the exerciser. Therefore, the elderly, who are the primary Taijiquan exercisers, need to be more cautious practising this movement and avoid large amplitude of movement since their waist tolerance capacity is not in as good condition as the young's.

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