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Material property sensitivity analysis on resonant frequency characteristics of the human spine

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Abstract

The aim of this study is to investigate the effect of material property changes in the spinal components on the resonant frequency characteristics of the human spine. Several investigations have reported the material property sensitivity of human spine under static loading conditions, but less report was given to the material property sensitivity of spinal biomechanical characteristics under vibration environment. A detailed three-dimensional finite element model of the human spine T12-Pelvis was built and used to predict the influence of material property variation on the resonant frequencies of the human spine. The simulation results reveal that material properties of spinal components have obvious influences on the dynamic characteristics of the human spine. The annulus ground substance is the dominate component affecting the vertical resonant frequencies of the human spine. The percentage change of the resonant frequency relative to the basic condition was more than 20% if the Young's modulus of disc annulus is less than 1.5 MPa. The vertical resonant frequency may also decrease if Possion's ratio of nucleus pulposus of intervertebral disc decreases.

Key words: Lumbar spine; Dynamic analysis; Finite element method, Biomechanics, Frequency.

Introduction

According to the surveys conducted on truck drivers and other drivers, chronic occupational whole body vibration (WBV) exposure might accelerate lumbar spine degeneration and structural changes (**Wilder *et al*., 1982**). Low back pain and degenerative diseases of the human spine were more frequently found among vehicle drivers exposed to vibration than those in representative control groups (**Frymoyer *et al*., 1983; Kumar, 2001**). Long-term WBV was also found to cause health risks for the lumbar spine, especially for the lower lumbar motion segments (**Fritz, 2000; Pankoke *et al*., 2001).** Experimental studies indicated that prolonged vibration may cause muscle fatigue (**Broman *et al*., 1991**), decrease the proteoglycan and cause degeneration of the intervertebral discs (**Yao *et al*., 2002).** There were many investigations carried out to get insights into the vibration mechanism of the human spine and the relation of vibration with the spine diseases. Besides experimental approaches and mathematical modeling analyses, many of these investigations were focused on the relationships of the low back pain, spine diseases under the static loadings using finite element (FE) methods (**Shirazi-Adl *et al*., 1984; Goel *et al*., 1995; Chen *et al*., 2001; Zander *et al*., 2002; Teo *et al*., 2004**), as well as the relationships of the low back pain and WBV (**Goel *et al*., 1994; Matsumoto & Griffin, 2002**). Recently, a few investigations have been focused on the application of FE models to predict the dynamic characteristics of the human body (**Kong & Goel, 2003; Guo & Teo, 2005, Guo *et al*., 2008**).

From mechanics, it is known that structural system frequencies are directly related to the geometrical configuration, mass distribution and material property. For human spine, the shapes of articulating bony vertebrae, associate tissues and mass distribution of all the spinal components are relatively constant. However, due to aging or disease, the material characteristics of spinal components might change (**Diamant *et al.*, 2005**). Thus it is believed the material property of spinal component is a main factor affecting the frequency characteristics of the FE models of human spine. The material sensitivity of single intervertebral disc **(Shirazi-Adl *et al.*, 1984; Spilker *et al.*, 1986),** single motion segment **(Rao & Dumas, 1991)** and two motion segments **(Kumaresan *et al.*, 1999a; Ng *et al.*, 2004)** had been analyzed by comparing the mechanical responses of these FE models under static conditions. It is unknown how this material property sensitivity will affect the dynamic characteristics of the human spine.

Accordingly, this study will principally analyze the influence of material property sensitivity of spinal components on frequency characteristics of the human spine. The results may help us to understand the influence of the material property changes of spinal components on the resonant frequency of the FE models of the human spine.

Methods

A detailed three-dimensional FE model of the spinal motion segment T12-Pelvis (in Figure 1) was developed from the geometrical coordinates of cadaveric specimen using the flexible digitizer technique (**Teo *et al.*, 2004; Guo &**

Teo, 2005, Guo *et al.*, 2007). The T12-Pelvis model consists of vertebrae, intervertebral discs, endplates and ligaments. The vertebral body consists of cortical bone, cancellous bone and posterior bony structure. The intervertebral disc consists of disc nucleus, disc annulus and annulus fibers. The ligaments were incorporated into the FE model using two-noded tension only cable elements. The vertebrae, endplates and intervertebral discs except annulus fibers were modeled by block elements. The structure and heights of the intervertebral disc and endplates are similar to those reported in some literatures (**Shirazi-Adl *et al.*, 1984, 1986; Goel *et al.*, 1995; Gilad & Nissan, 1986**). For modeling, the procedures, methods and material properties were based on the literatures (**Shirazi-Adl *et al.*, 1986; Goel *et al.*, 1994; Sharma *et al.*, 1995).** The nucleus pulposus was created as nearly incompressible fluid and the annulus fibrosus was modeled to make up of 3 radial consecutive laminar layers of composite materials consisting of annular fibers embedded in the solid matrix elements. The annulus fibers modeled by 3D tension-only cable elements were arranged at about ±30° angles in relation to the adjacent endplates (**Goel *et al.*, 1995**). The total volume of annulus fibers was assumed as 19% of the annulus volume (**Sharma *et al.*, 1995**). The cross-section area of nucleus was assumed to be 40% of every disc area.

To mimic the upper body mass, a preload point mass of 40kg was added on the top of T12-pelvis model. The lumped mass point was directed vertical down passing through a point with 1.0 cm anterior to the L3-L4 vertebral centroid, as suggested in other references (**Pearsall *et al.*, 1996**). The facet articulating surface areas were developed and conformed to their respective actual geometrical curvature.

Surface-to-surface contact element type was applied to mimic the conditions of facet articulations. For modeling simplification, only the contact areas of ilia were created and the areas were fixed during modal analyses. All the modeling and simulations were completed using the commercial FE analysis software ANSYS 10.0.

Validation of resonant frequencies for the model by different motion segments had been conducted elsewhere **(Guo & Teo, 2005)** with the experimental results and FE analysis results from the available literatures **(Goel *et al*., 1994; Kong & Goel, 2003; Kasra *et al*., 1992)**. The frequencies of L1-L5 and L1-S1 of this study are 11.5Hz and 9.12Hz, which are near the results of **Kong & Goel (Kong & Goel, 2003)**. The inclusion of thoracic spine and cervical spine on the T12-Pelvis may decrease the resonant frequency of T12-Pelvis by as much as 20% **(Kong & Goel, 2003)**, which might make the first-order vertical resonant frequency of the T12-Pelvis model approach to the experimental measurement results of 4-6Hz **(Panjabi *et al*., 1986; Pope *et al*., 1987; Sandover, 1988)**.

The material property changes of spinal components due to age, gender, component degeneration may occur concurrently **(Diamant *et al*., 2005)**, which might influence the dynamic characteristics of human spine. Therefore, sensitivity analysis was carried out to determine influence of the material parameters (Young’s modulus of vertebral body, endplate, ligament and intervertebral disc) on the predicted frequency characteristics of the spine.

Table 1 shows the material property (for the basic model parameters) of the T12-Pelvis FE model and the varying ranges of Young's Modulus of the spinal components reported **(Goel *et al*., 1995; Shirazi-Adl *et al*., 1986; Sharma *et al*., 1995; Lavaste *et al*., 1992; Goel *et al*., 1993; Kumaresan *et al*., 1999a, 1999b; Lee *et al*., 2000; Kim, 2001)**. For examples, the Young's modulus of nucleus pulpous varies from 0.13 to 4.0 MPa (Table 1). The Young's modulus of annulus ground substance varies from 0.8MPa to 4.2MPa which is more than 400%. The analyzed spinal components include cortical shell, cancellous bone, bony posterior element, nucleus pulposus, annulus ground substance, annulus fiber and ligaments. The ligaments were partitioned into two groups as shown in Table 2. The ligament group 1 consists of anterior longitudinal ligaments and posterior longitudinal ligaments, and the ligament group 2 consists of other ligaments except those in the ligament group 1. Several spinal component groups are also assigned, e.g. vertebra group includes cortical bone, cancellous bone and bony posterior element; ligament group includes all ligaments; and intervertebral disc group includes nucleus pulposus, annulus ground substance and annulus fiber. For the comparison convenience, the elastic modulus of each spinal component is assumed to vary by +/-30% against the basic model in this study. In addition, +/-80% variations are assigned to Young's modulus of disc annulus based on the parameter of the basic model and this makes Young's modulus of disc annulus vary from 0.84MPa to 7.56MPa. This study might let us further understand the biomechanical characteristics of disc annulus.

In this study, 29 runs of FE modal analyses were conducted to extract the resonant frequencies of the T12-Pelvis model under the high and low values of material property against the basic model. Besides these, 17 runs were specially performed to analyze the influence of Young's modulus variation of disc annulus on the resonant frequency of the T12-Pelvis model. Additional 2 runs were also conducted to the material property of Possion's ratio of nucleus pulposus of intervertebral disc.

Results

Fig. 2 shows the first-order vertical resonant frequencies of the T12-Pelvis models obtained by +/-30% variations of Young's moduli of the component groups of vertebral body VT1 to VT5 (Table 2). It shows bony posterior elements (VT3 in Fig. 2) have a more obvious influence on the resonant frequencies than cortical bones, cancellous bones and endplates. The reason is that the lumbar spine exist a small-range flexion-extension movement despite of the human upper body conducting a vertical vibration. Fig. 3 exhibits the effect of the variations of the elastic modulus of the component groups of intervertebral disc on the resonant frequencies of the model. The results (Fig. 3) indicate that the elastic modulus variation of disc annulus has greater influence than other disc components. Fig. 4 exhibits the effect of elastic modulus variations of ligaments on the resonant frequencies of the model. The results (Fig. 4) show that the influence of elastic modulus variations in LT2 is slightly greater than that in LT1. Fig. 5 and Fig. 6 show the resonant frequencies and their relative percentage changes (against the basic model) for the spinal component units: endplate, vertebra, intervertebral disc, ligament and all spinal components due to +/-30% variations of the material properties of the T12-Pelvis FE model, respectively. The results (Fig. 5 and Fig. 6) indicate that the intervertebral disc has a greater role on the resonant frequency of the spine. It can be found that the first-order vertical resonant frequency of the model decreases by 19.2% if Young's moduli of all spinal components decrease by 30%, based on the material properties of the basic model.

Of all the spinal components, the disc annulus took the most prominent contribution on the resonant frequency of the human spine (Fig. 5 and Fig. 6). Therefore, additional analyses were carried out to understand the influence of Young's modulus variation of disc annulus on the resonant frequency of the human spine. Fig. 7 illustrates the resonant frequency and relative frequency percentage change of the model due to the variations (against the basic model) of Young's modulus of disc annulus. It can be found that the relative percentage changes of the resonant frequencies of the model varied from -29.0% to 15.5% while the Young's modulus of disc annulus varied from 0.84MPa to 7.56MPa. The figure (Fig. 7) also shows that the resonant frequency of the human spine model will decrease remarkably when the Young's modulus of disc annulus is less than 2.0.

In addition, the variation effect of Possion's ratio of nucleus pulpous on the resonant frequency of the human spine was also analyzed. The results show that the resonant frequency of the human spine might decrease by 18% and 16% if Possion's ratio of nucleus pulposus decreased by 30% and 20% against the material property of the basic model, respectively.

Discussion

The variation in the material properties of multiple spinal components due to age, gender and component degeneration may occur concurrently *in vivo* and these variations on the biomechanical behaviors of the human spine are unknown. In this study, a detailed three-dimensional FE model (Fig. 1) of the whole lumbar spine segment T12-Pelvis was developed including T12-L1 segment, L5-S1 segment and sacroiliac joints. The experimental studies demonstrated that the nucleus pulposus of intervertebral discs has a solid-like behavior under dynamic loading and with degeneration and aging **(Iatridis *et al.*, 1997)**. In addition, although the viscoelastic / poroelastic nature of the disc exists in the spine under time-durative compressive loading, a FE modal analysis needs not include the time parameter. Therefore, the solid-like property of nucleus pulposus is used in this study. To understand correctly the findings of this study, it should be noted that the T12-Pelvis FE model did not include the muscle components, cervical spine, thoracic spine and rib cage of human upper body. An addition of the cervical spine and thoracic spine may decrease the resonant frequency of the T12-Pelvis FE model and the addition of muscles and a rib cage may increase the resonant frequency of the T12-Pelvis FE model.

The bony posterior elements might suffer more influence from a vibration environment due to bony posterior elements having greater influence on the vertical vibration than cortical bone, cancellous bone and endplates. Under long-time compressive repeating loading, the trabecular bone might cause a physiological change. Keller *et al*. **(Keller *et al.*, 1989)** had reported that the compressive strength and stiffness of trabecular bone of spine bony posterior elements increased with increasing bone density. The investigations **(Keller *et al.*, 1990; Polikeit *et al.*, 2004)** indicated that material property variation in vertebral body might result in spine diseases. From simulation results of different material parameters defined for vertebra, intervertebral disc and ligament, as shown in Fig. 2, Fig. 3 and Fig. 4, they show the intervertebral disc is a main component influencing the resonant frequency of the human spine (Fig. 3, Fig. 5 and Fig. 6). In addition, in other material property sensitivity studies **(Kumaresan *et al.*, 1999a; Ng *et al.*, 2004)** under static compression loading, the similar findings were also achieved**.** Kumaresan *et al.* **(Kumaresan *et al.*, 1999a)** had reported that the material property variations in intervertebral discs result in significant changes in the angular rotation and disc stress. Of all the components in the intervertebral disc, the annulus ground substance has a significant influence on the vertical resonant frequencies of the spine by comparing with nucleus pulposus and annulus fibers (Fig. 3 and Fig. 5). The annulus ground substance also had a significant role on the static biomechanical behaviors of the spine as reported in the study (**Ng *et al.*, 2004**). Rao & Dumas **(Rao & Dumas, 1991)** and Kumaresan *et al.* **(Kumaresan *et al.*, 1999a)** also underscored the importance of the material property of soft tissue structures in the FE studies of the human spine.

As shown in Fig 3, the nucleus pulposus (DT1) is less sensitive than annulus (DT2) though it has lower elastic modulus than annulus ground substance in this study. The reason is that the nucleus pulposus is enclosed within the annulus and two vertebrae. Generally, the Young's modulus of nucleus pulposus will increase with aging and degeneration of the spine (**Keller *et al.*, 1990**). However, while the elastic modulus of nucleus increases its Possion's ratio decreases **(Goel et al., 1995; Kumaresan *et al.*, 1999a)**. The simulation results in this study show the vertical resonant frequency will decrease if Possion's ratio of nucleus pulposus decreases. For the serious degeneration with cave emergence, this phenomenon will reduce the vertical resonant frequency of the spine. However, for the serious degeneration of the spine, the loss of disc height (**Kumaresan *et al.*, 1999a**) may also increase the resonant frequency.

Of all the components in the intervertebral disc, the disc annulus takes a quite prominent contribution on the resonant frequency of the human spine (Fig. 5 and Fig. 6). Therefore, it is necessary to further understand how the Young's modulus of the annulus ground substance affects the resonant frequency of the FE model of human spine. From Fig. 7, it can be found that the percentage change of the resonant frequency relative to the basic condition is more than 20% if the Young's modulus of disc annulus is less than 1.5 MPa, and the relative percentage changes of the resonant frequencies of the model is nonlinear and likes a part of conjugate hyperbolas. The degressive rate of the relative percentage change is faster due to the decrease of elastic modulus of the disc annulus than the ascensive rate due to the increase of elastic modulus of the disc annulus (Fig. 7). This implies that young individuals might have low resonant frequency on the condition that the person was with same weight of trunk mass. Going with increase of age, the rigidity or elastic modulus of annulus fibrous will increase **(Keller *et al.*, 1989)**, even severe degeneration for elders, those might increase the resonant frequency of the spine.

Although there were many early investigations about material property sensitivity of the human spine, there was no investigation of material property sensitivity on the spinal dynamic characteristics. This study, in a certain aspect, may provide insights into the material property sensitivity, as results of ageing and spine degeneration, of the spine components on the dynamic characteristics of the human spine. In the same time, by understanding to the material property sensitivity of the spine, it may be helpful to adopt correct material property parameters in FE modeling of the human spine.

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Dear Sir

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Best regards

Yours sincerely,

Li-Xin Guo, PhD

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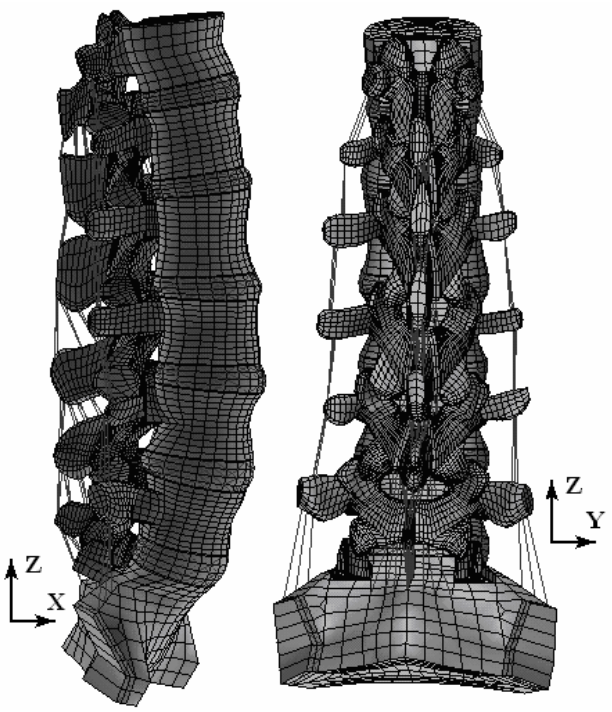


Figure 1 The three-dimensional finite element model of the spine T12-Pelvis segment

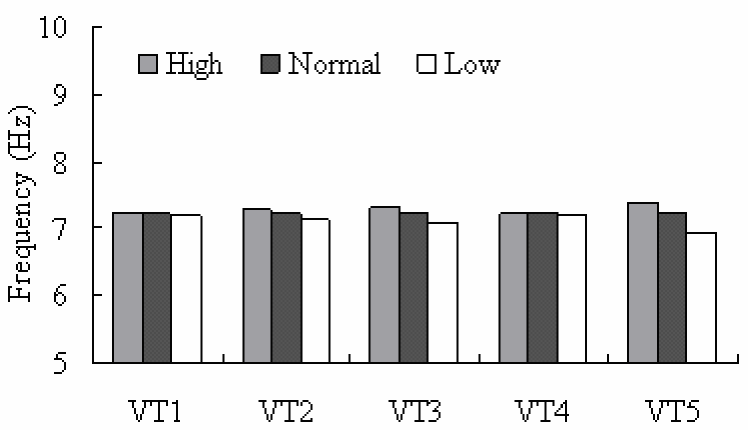


Fig 2 The resonant frequencies of the finite element models due to variations of the material property for the component groups VT1, VT2, VT3, VT4 and VT5. The parameter abbreviations in the figure from VT1 to VT5 are defined in Table 2. The normal value means that no change is given to the material property parameters of the spinal components and the normal values are shown in Table 1. The high value and low value in the figure, as well as the following relevant figures, mean that the material property parameters are increased or decreased by 30%, respectively.

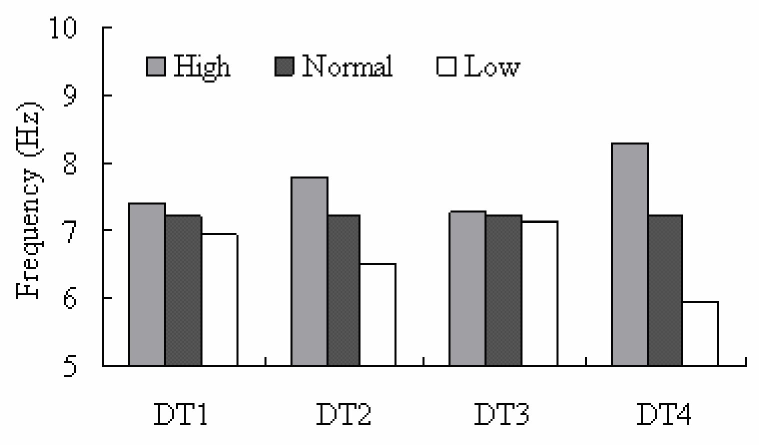


Fig 3 The resonant frequencies of the finite element models due to variations of the material property for the component groups DT1, DT2, DT3 and VT4. The abbreviations in the figure are defined in Table 2.

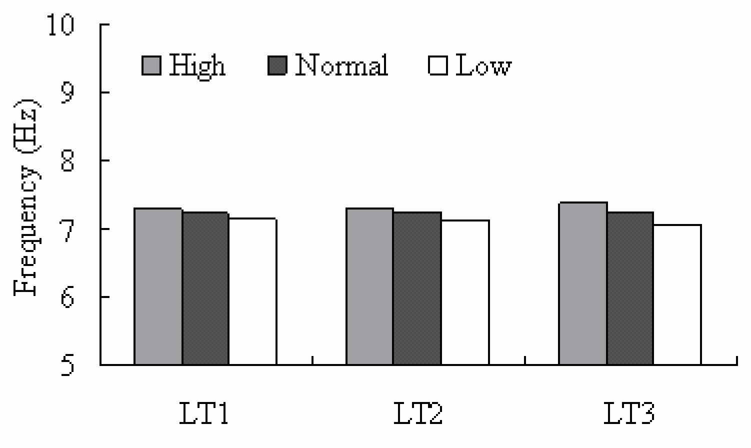


Fig 4 The resonant frequencies of the finite element models due to variations of the material property for the component groups LT1, LT2 and LT3. The abbreviations in the figure are defined in Table 2.

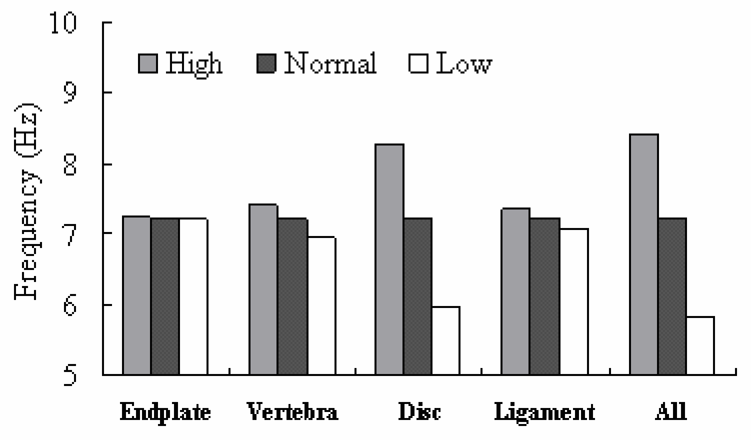


Fig 5 Comparing the effects of variations of the material properties of the main spinal component groups on the resonant frequencies of the spine. The abbreviations in the figure are defined in Table 2.

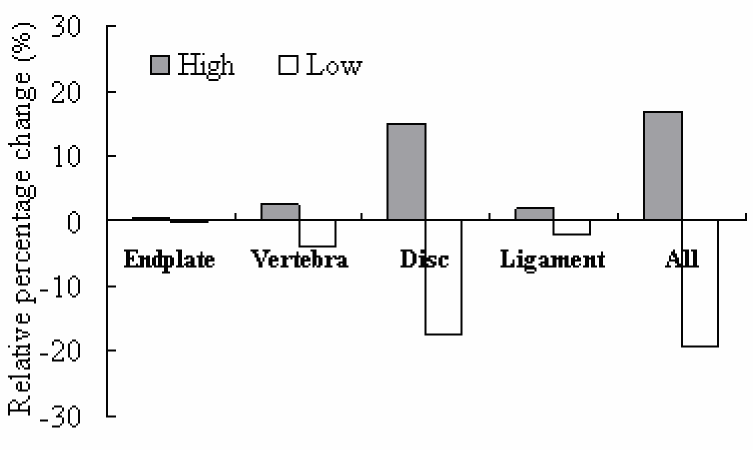


Fig 6 The relative percentage changes of resonant frequencies of the T12-Pelvis finite element model for different spinal component groups due to the variation of material property against the basic model.

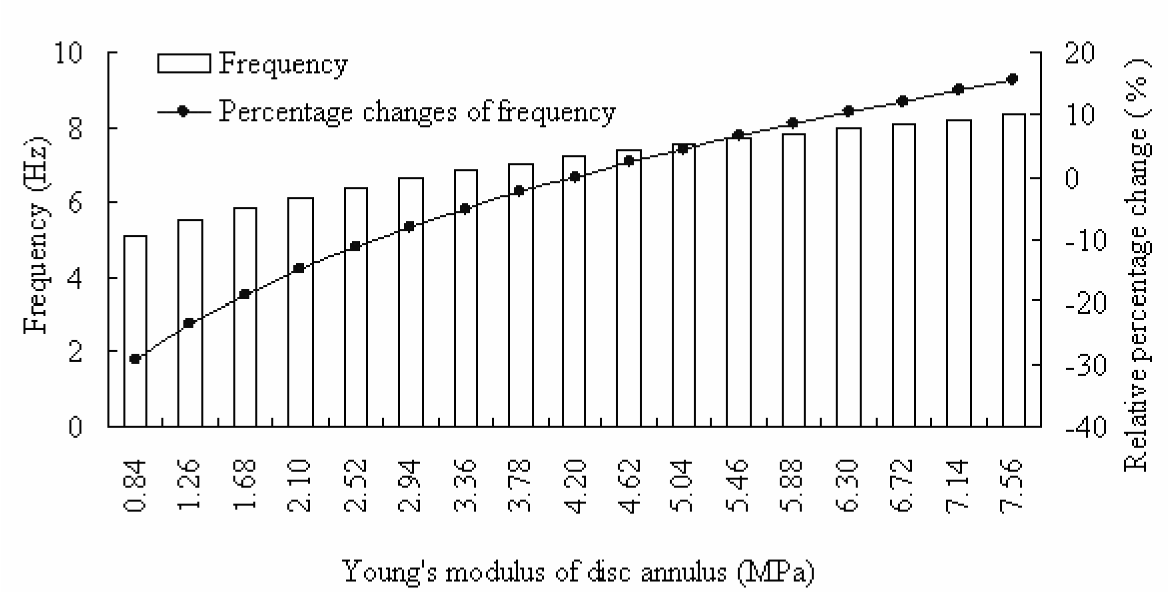


Fig 7 The resonant frequencies and relative frequency percentage changes of the T12-Pelvis finite element model due to the variations of Young's modulus of disc annulus from 0.84MPa to 7.56MPa.

Tables

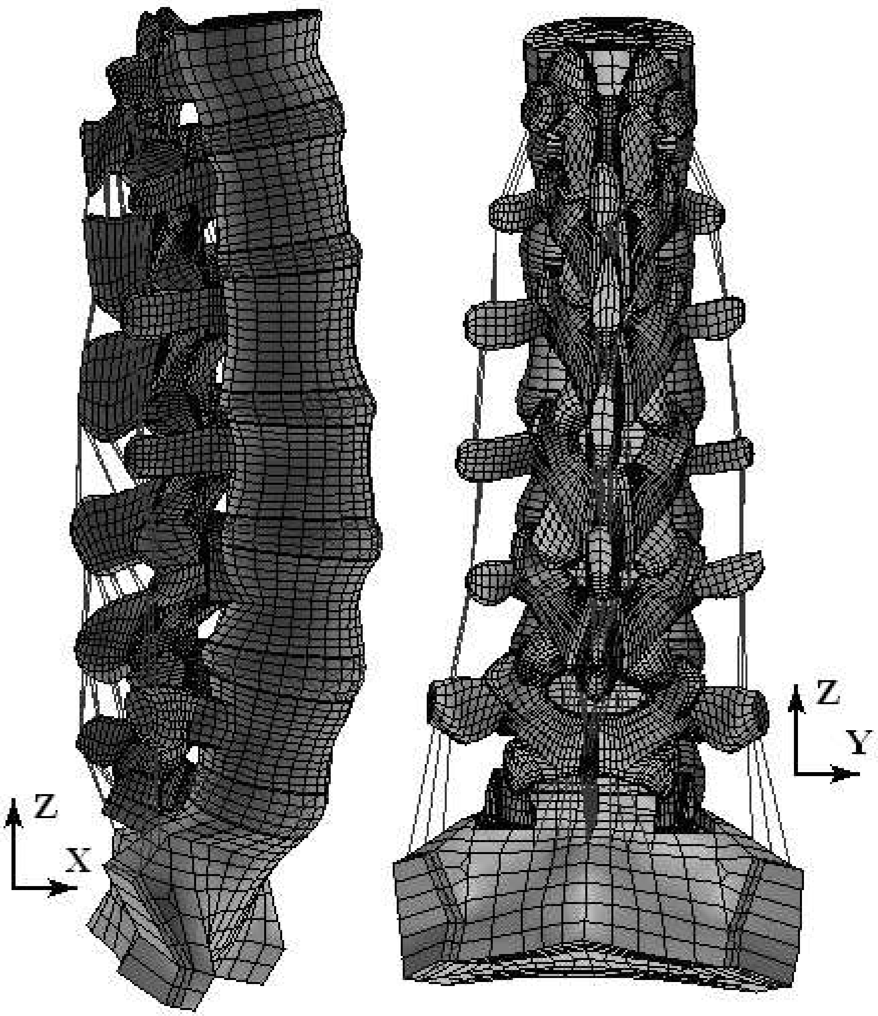
Table 1 The material property of the T12-Pelvis finite element model (Basic model) and the varying ranges of Young's Modulus of the spinal components.

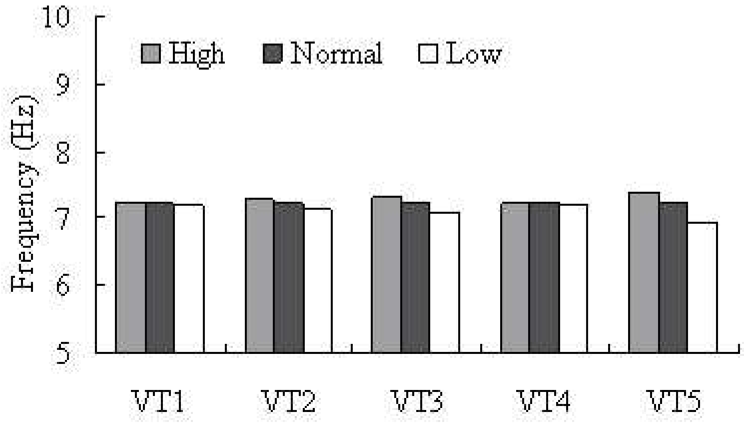
Spinal components	Young's Modulus (MPa)/ Poisson's ratio of the basic model	The varying ranges of Young's Modulus(MPa) from the references*
Cortical bone	10000 /0.3	6000-12000
Cancellous bone	100 /0.2	100-1000
Bony posterior element	3500 /0.25	1000-3500
Endplate	500 /0.25	24-10000
Nucleus pulposus	1 /0.49	0.13-4
Annulus ground substance	4.2/0.45	2-6
Annulus fiber	500	59-500
Capsular ligaments	7.5	7.5-32.9
Intertransverse ligaments	10	10-58.7
Supraspinous ligaments	8	8-15
Interspinous ligaments	10	2.4-11.6
Ligamentum flavum	15	2.4-19.5
Anterior longitudinal ligaments	7.8	7.8-20
Posterior longitudinal ligaments	10	10-20
Iliolumbar ligaments	10	10-58.7
Anterior sacroiliac ligaments	20	
Posterior sacroiliac ligaments	20	
Interosseous sacroiliac ligament	500	

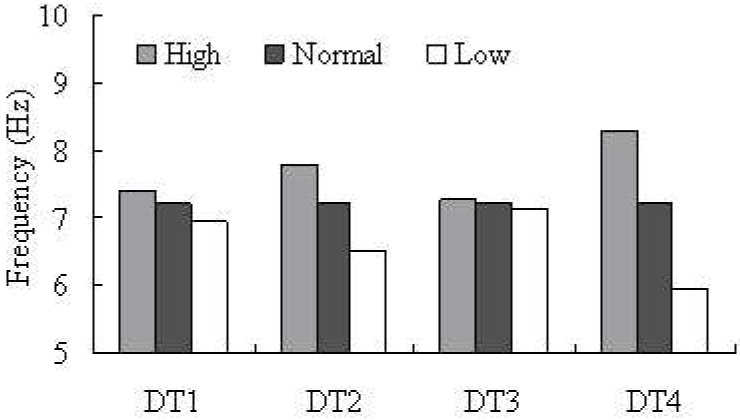
*The varying ranges of Young's Modulus were determined from the available references **[Shirazi-Adl et al. 1986, Lavaste et al. 1992, Goel et al. 1993, 1995, Sharma et al. 1995, Kumaresan et al. 1999, Lee et al. 2000, Kim, 2001]**.

Table 2 The analyzed component groups of the human spine in this study

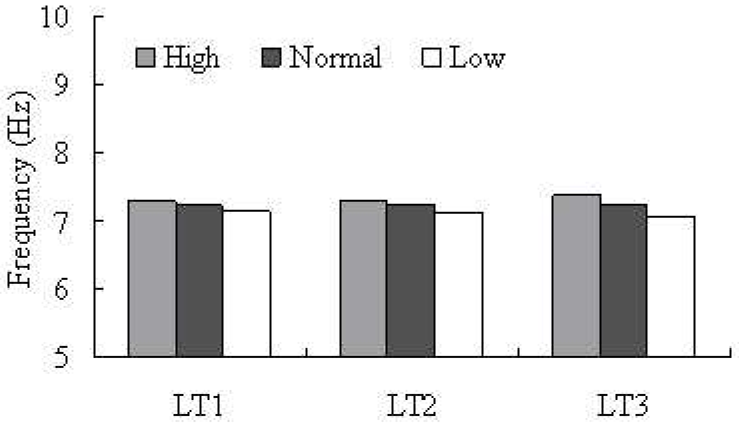
Component Groups		Description
Vertebra tissue	VT1	Cortical bone
	VT2	Cancellous bone
	VT3	Bony posterior element
	VT4	Endplate
	VT5	Vertebra (including Endplate, Cortical bone, Cancellous bone, Posterior element and endplate)
Disc tissue	DT1	Nucleus pulposus
	DT2	Annulus ground substance
	DT3	Annulus fiber
	DT4	Intervertebral disc (including Nucleus pulposus and disc annulus and annulus fiber)
Ligament tissue	LT1	Anterior Longitudinal Ligaments and Posterior Longitudinal Ligaments
	LT2	All ligaments except of LT1
	LT3	All ligaments
All spinal components	All	Including all spinal components

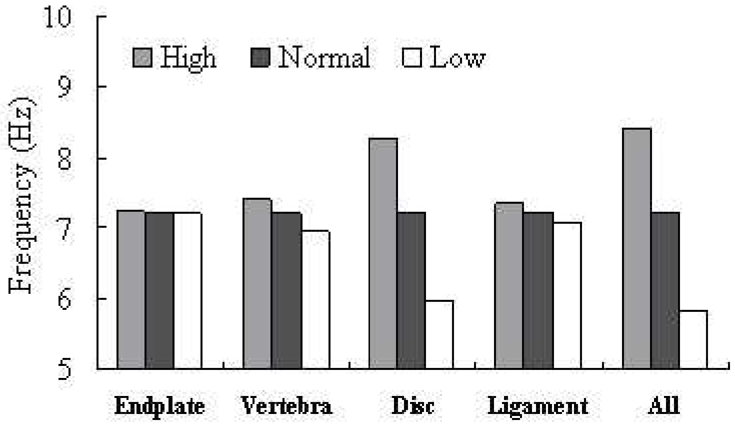

Z
X
Z
Y

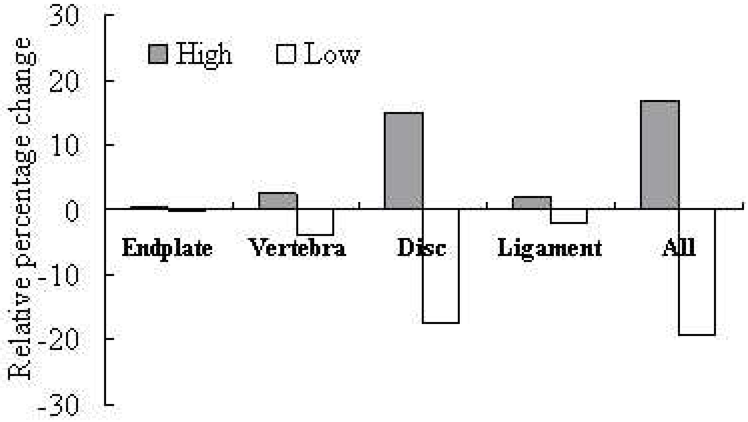

High
Normal
Low
Frequency (Hz)
10
9
8
7
6
5
VT1
VT2
VT3
VT4
VT5

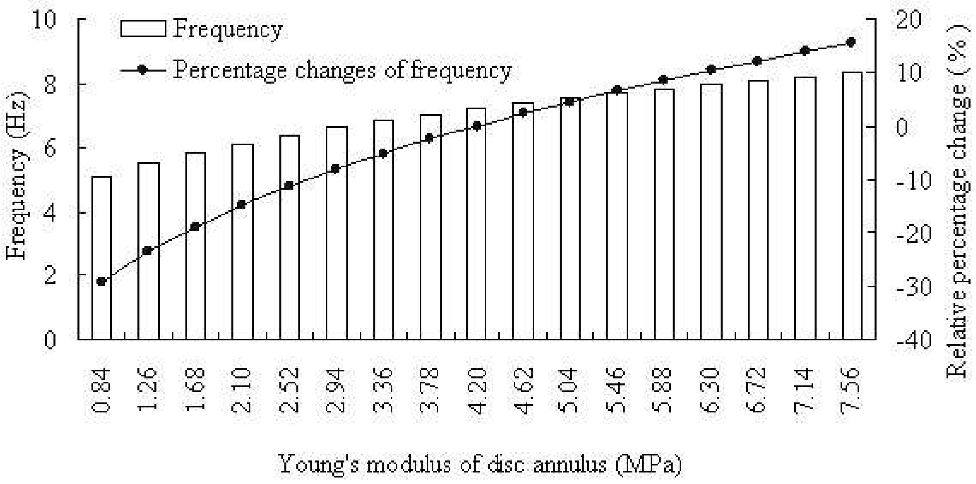


10
9
8
7
6
5
Frequency (Hz)
High
Normal
Low
DT1
DT2
DT3
DT4


10
9
8
7
6
5
Frequency (Hz)
High
Normal
Low
LT1
LT2
LT3


10
9
8
7
6
5
Frequency (Hz)
High
Normal
Low
Endplate
Vertebra
Disc
Ligament
All


30
20
10
0
-10
-20
-30
Relative percentage change
High
Low
Endplate
Vertebra
Disc
Ligament
All


Frequency
Percentage changes of frequency
Frequency (Hz)
Relative percentage change (%)
Young's modulus of disc annulus (MPa)
0
2
4
6
8
10
-40
-30
-20
-10
0
10
20
0.84
1.26
1.68
2.10
2.52
2.94
3.36
3.78
4.20
4.62
5.04
5.46
5.88
6.30
6.72
7.14
7.56