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Vertical Modal Characteristics of the Human Lumbar Spine Under Compressive Follower Preload: A Finite Element Study

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Keywords： lumbar spine, modal characteristics, compressive follower preload, finite element.

ABSTRACT

The vibrational stimuli, particularly when it approximates the resonant frequency of human spine, can subject the spine to significant forces, heightening the risks of damage and potentially causing devastating consequences. Although numerous biomechanical inquiries have delved into the resonant frequency and its corresponding mode shape of the human lumbar spine, the majority overlooked the influence of physiological compressive loading stemming from muscular contractions. Consequently, this research aimed to scrutinize the modal characteristics of the entire human lumbar spine under the influence of this loading. Initially, a computed tomography-based, 3-dimensional ligamentous finite element model of the human T12–pelvis spinal segment was created and validated. Subsequently, modal analysis was conducted on this model, incorporating varying levels of compressive preload applied via a follower load method, to determine its resonant frequency and corresponding mode shape in the vertical plane. The results showed that the T12–pelvis model exhibited a vertical resonant frequency of 6.49 Hz under no preload. Furthermore, the observed vertical mode shape showcased the lumbar spine engaging in not just vertical motion, but also anterior-posterior and rotational motions. Additionally, it was found that the modal responses were preload-dependent. As the preload increased, the vertical resonant frequency increased, whereas the vertical displacement of the vertebrae decreased. The present findings have the potential to enhance our comprehension of vibrational responses in the human lumbar spine, thus offering crucial insights in reducing injuries and discomfort among individuals exposed to vibration environment.

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INTRODUCTION

It has been reported that exposure to vibration alters the biomechanical reactions of human lumbar spine, potentially contributing to the low back discomfort and the progression of degenerative spinal conditions (Bovenzi et al., 2017). Vibrational stimuli, particularly when it approximates the resonant frequency of human spine, can subject the spine to significant forces, heightening the risks of damage and even causing devastating consequences (Fan et al., 2021a; Zhang et al., 2022). Currently, although experimental measurement prevails as the primary method for elucidating the inherent link between vibration and spinal health hazards, it poses significant challenges in quantifying vibrational impact on the spine's geometric and structural alterations. Conversely, finite element method has gained momentum in investigating intricate biological systems, providing a more viable approach for this complex analysis (Moalla et al., 2023; Xu et al., 2019; Xiao et al., 2021).

Over the past two decades, there has been a growing inclination toward utilizing the finite element approach to quantify the influence of vibration on dynamic mechanical responses of human spine. The spine modal characteristics have been investigated using finite element model. For example, Kong and Goel (2003) proposed a head–sacrum model of upper body to extract the resonant frequency and transmissibility under vertical vibration. Fan et al. (2021b) analyzed the effects of anterior-posterior shifting of upper body mass on the modal characteristics of human lumbar spine. Despite the ubiquity of current finite element models utilized for the modal analyses, they often overlook the significant impact of the physiological compressive loading on the lumbar spine, which stems primarily from the muscular system and inherently occurs during routine daily activities (Foresto et al., 2018; Patwardhan et al., 2001). Therefore, this study initially presented development and validation of a finite element model of the human T12–pelvis spine segments under physiological compressive preload. Subsequently, vertical modal responses in terms of resonant frequency and mode shape for the whole lumbar spine were predicted using the T12–pelvis model under different levels of the preload.

MATERIALS AND METHODS

Development of the finite element model

A 3-dimensional finite element model was reconstructed based on a set of computed tomography data of the human T12–pelvis spinal segment deriving from a 48-year-old female (162 cm and 58 kg) with no known spinal and pelvic diseases, as illustrated in Figure 1a. The modeling of each vertebra took into account the distinction between cancellous bone and cortical shell (inclusive of inferior and superior endplates) (Figure 1b), where the cancellous bone was represented by 4-node tetrahedral elements, and the cortical shell, including its endplates, was represented by 3-node triangular elements. The shell elements maintained a uniform thickness of 0.7 mm (El-Rich et al., 2009). Each intervertebral disc, positioned between adjacent vertebral endplates, comprised a central nucleus pulposus encircled by an annulus fibrosus (Figure 1c). The annulus was modeled utilizing 8-node hexahedral elements to form a consistent base, while six fiber layers reinforced it radially, employing 2-node tension-only truss elements oriented at an angle of ±30° relative to the horizontal axis. The pelvis consisted of sacrum and two innominate bones, interconnected through pubic symphysis and two sacroiliac joints (Figure 1d). The pelvic was modeled utilizing 4-node tetrahedral elements. The spinal and pelvic ligaments were modeled utilizing 2-node tension-only truss elements. Materials properties obtained from the literature for the developed finite element model are listed in Table 1.

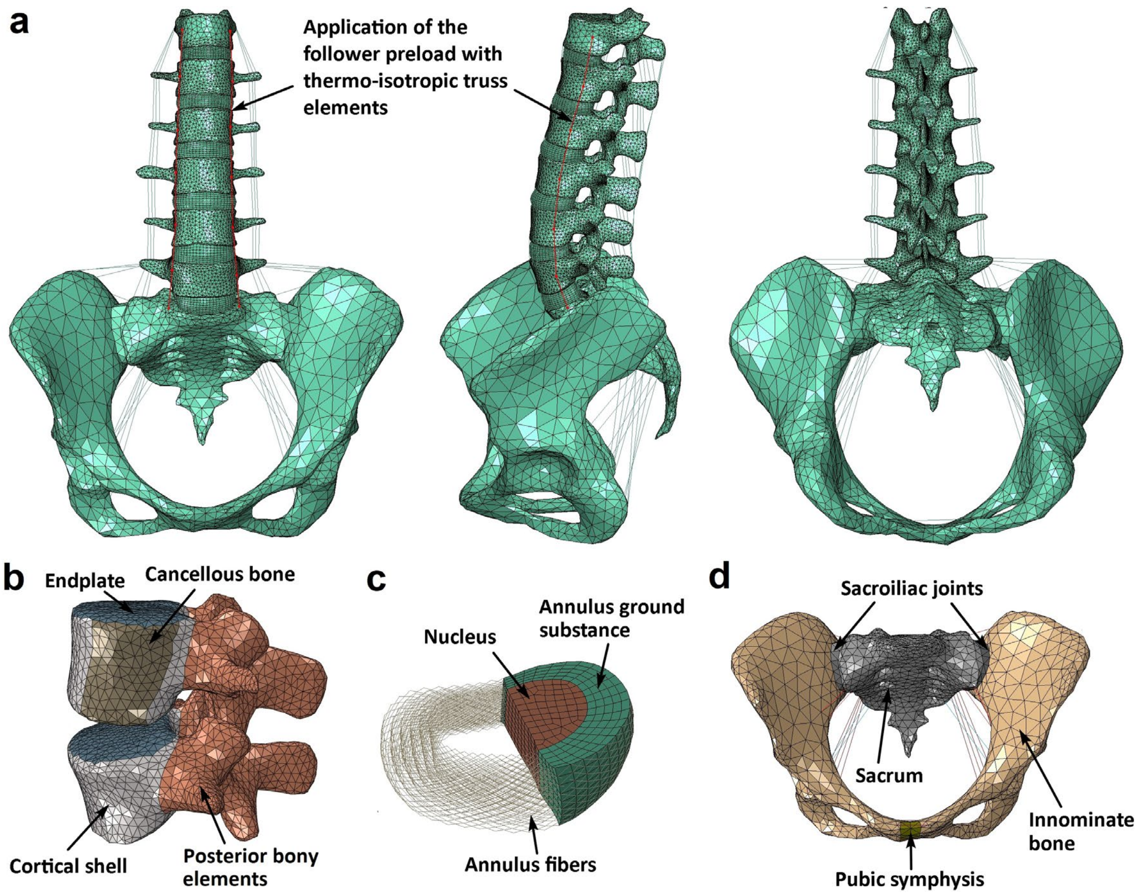

Fig. 1. Finite element modeling description for the T12–pelvis motion segment. (a) The whole model; (b) Modeling of the vertebra; (c) Modeling of the intervertebral disc; (b) Modeling of the pelvis.

Table 1. Material properties for each component in the finite element model.

Component	Young's modulus (MPa)	Poisson's ratio	Density (kg/mm^3)	References
Spinal segment				
Cortical bone	12000	0.3	1.7e-6	Xu et al., 2017
Cancellous bone	100	0.2	1.1e-6	Xu et al., 2017
Posterior bony elements	3500	0.25	1.4e-6	Xu et al., 2017
Endplate	23.8	0.4	1.2e-6	Xu et al., 2017
Annulus ground substance	4.2	0.45	1.05e-6	Kong and Goel, 2003
Nucleus pulpous	1.326	0.4999	1.02e-6	Kong and Goel, 2003
Annulus fibers	360-500	0.3	1.0e-6	Polikeit et al., 2003
Spinal ligaments	Hypoelastic, Nonlinear stress–strain curves	0.3	1.0e-6	Kim et al., 2015
Pelvis				
Sacrum cortical bone	12000	0.3	1.7e-6	Xu et al., 2017
Sacrum cancellous bone	100	0.2	1.1e-6	Xu et al., 2017
Innominate bones	5000	0.2	1.83e-6	Du et al., 2014
Sacroiliac cartilages	0.75	0.4	1.4e-6	Lee et al., 2017
Pubic symphsis	5	0.45	1.4e-6	Dub´e-Cyr et al., 2021
Pelvic ligaments	Hypoelastic, Nonlinear stress–strain curves	0.3	1.0e-6	Yao et al., 2023

Boundary and loading conditions

The T12–pelvis model was fixed at the two acetabulum surfaces (Dube-Cyr et al., 2021; Yao et al., 2023). Before performing modal analysis, the follower load technique (Fan and Guo, 2017; Patwardhan et al., 2001) was employed to simulate the physiological compressive preload stemming from muscular contractions on the lumbar spine. Different levels of the preload (0, 400, 600 and 800 N) were considered in this study. After the model stabilized from the preload, the state was propagated and used as an initial condition for the modal analysis. Within the framework of modal analysis, the mass of the upper body was considered by imposing a mass point of 40 kg on the top vertebra of the model (Fan et al., 2021b; Schmidt et al., 2013). All the finite element analyses were performed using the ABAQUS software (Dassault Systèmes, Simulia Inc., Providence, RI, USA).

Model validation

Due to the scarcity of studies focusing on the whole T12–pelvis model, a dissection approach was implemented to segregate it into three distinct segmental models: T12–L1, L1–S1 and S1–pelvis, which underwent individual validation processes through comparisons with both experimental and numerical results from literature. The loading and boundary conditions during these validation tests were precisely replicated in accordance with the protocols in these published studies (Table 2). It was observed from Figure 2 that there was a reasonable agreement between the present predictions and the published data, and most of our results fell within one standard deviation of the experimental results.

Table 2. Summary of the simulations for validation tests.

Segmental models	Load case	Load values	References
T12–L1	Flexion	M=7.5 Nm	Oxland et al., 1992; Qiu, 2005
	Extension	M=7.5 Nm	Oxland et al., 1992; Qiu, 2005
	Lateral bending	M=7.5 Nm	Oxland et al., 1992; Qiu, 2005
L1–S1	Follower load	F=1200 N	Renner et al., 2007; Du et al., 2016
	Follower load + Flexion	F=100 N, M=10 Nm	Panjabi et al., 1994; Moramarco et al., 2010
	Follower load + Extension	F=100 N, M=10 Nm	Panjabi et al., 1994; Moramarco et al., 2010
	Follower load + Lateral bending	F=100 N, M=10 Nm	Panjabi et al., 1994; Moramarco et al., 2010
S1–pelvis	Flexion	M=42 Nm	Miller et al., 1987; Mao et al., 2014
	Extension	M=42 Nm	Miller et al., 1987; Mao et al., 2014
	Lateral bending	M=42 Nm	Miller et al., 1987; Mao et al., 2014

M and F represent the bending moment and compressive preload, respectively.

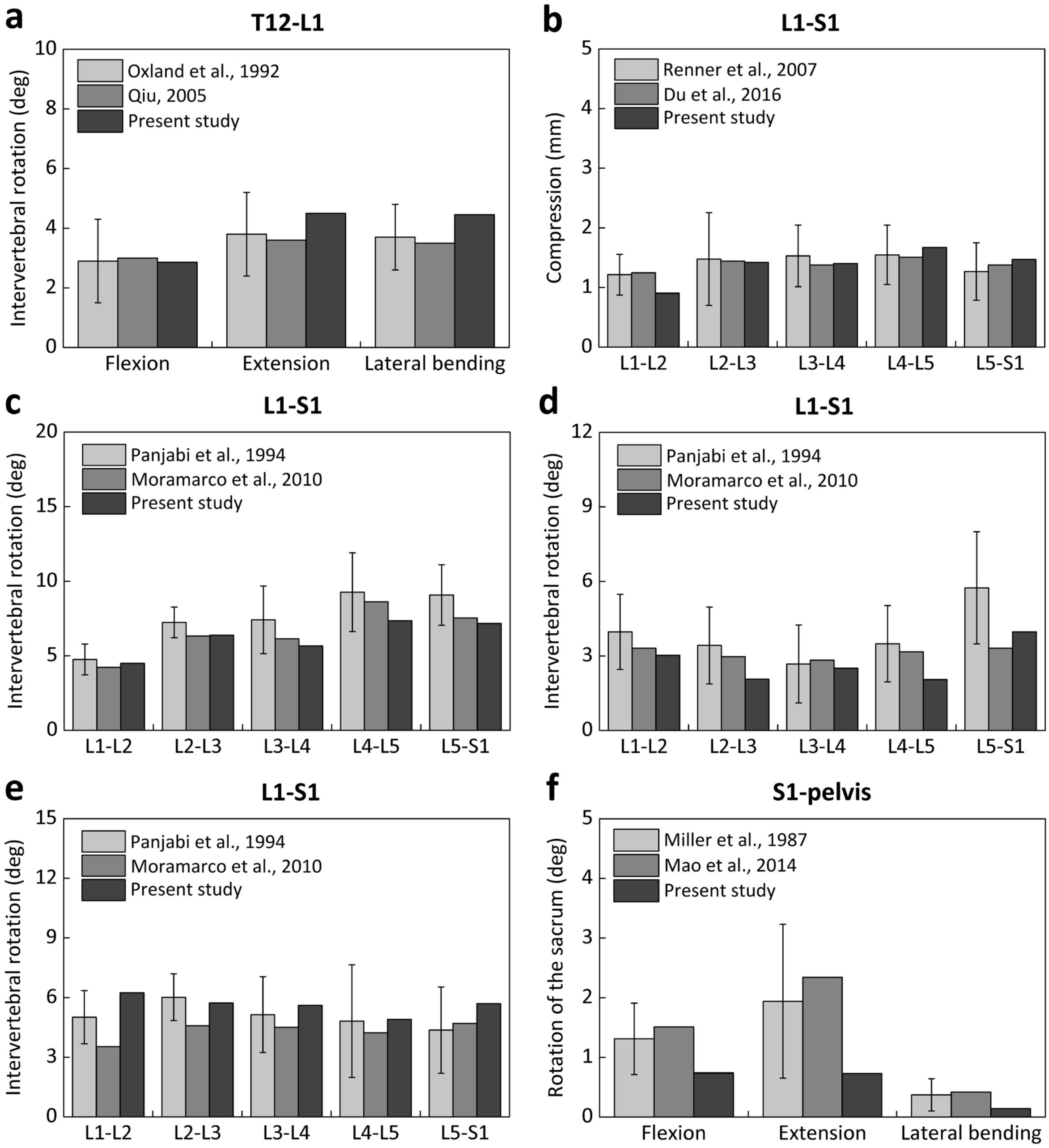

Fig. 2. Predicted results of the present study versus the published experimental and numerical data for: (a) the T12–L1 segment under pure moments; (b) the L1–S1 segment under follower load; (c–e) the L1–S1 segment under follower load combined with flexion, extension and lateral bending moments, respectively; (f) the S1–pelvis segment under pure moments.

RESULTS

Figure 3 illustrates the first three modal responses of the model. It was found that the first-, second- and third-order modal responses (Modes 1, 2 and 3) were in the flexion-extension, lateral bending and vertical directions, respectively. Due to the fact that vertical vibration has a major effect on the lumbar spine (Jia et al., 2023; Schmidt et al., 2013; Xu et al., 2019), the vertical modal responses (Mode 3) were specially described in this study. Vertical resonant frequencies of the T12–pelvis model was 6.49, 7.27, 7.55 and 7.76 Hz, respectively, under 0, 400, 600 and 800 N compressive follower preloads (Table 3).

It was observed from vertical mode shape that the lumbar spine performed vertical motion with anterior-posterior and rotational motions (Figures 4 and 5). Figure 4 shows that the vertebrae had different vertical displacements, and the largest one occurred at vertebra T12. Moreover, increasing the preload decreased vertical displacements of all the

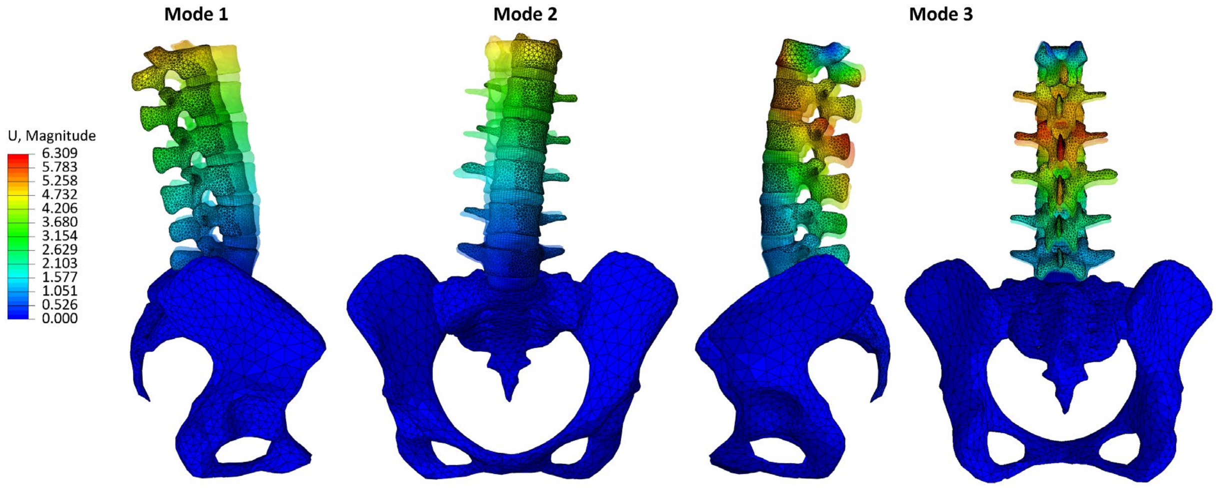

Fig. 3. The first three modal responses of the T12–pelvis finite element model. Mode 1, Mode 2 and Mode 3 represent the first-, second- and third-order modal responses, respectively.

Table 3. Vertical resonant frequencies of the T12–pelvis model under different compressive follower preloads.

	Compressive follower preload (N)			
	0	400	600	800
Resonant frequency (Hz)	6.49	7.27	7.55	7.76

vertebrae. Figure 5 shows that the anterior-posterior displacements and rotational angles of different vertebrae in the sagittal plane were also different. Specifically, vertebrae T12 to L4 moved anteriorly, while vertebrae L5 moved posteriorly (Figure 5a). Vertebrae T12 and L1 performed rotation in extension, while vertebrae L2 to L5 performed rotation in flexion (Figure 5b). Moreover, increasing the preload increased anterior-posterior displacements and rotational angles of all the vertebrae.

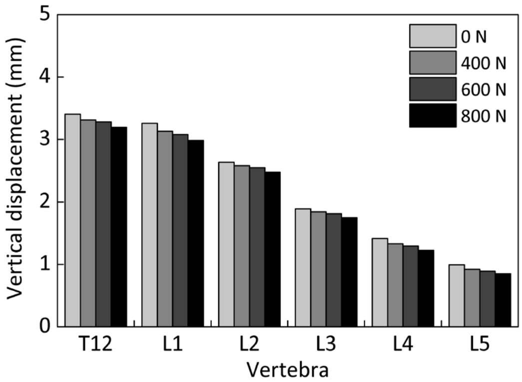

Fig. 4. Vertical displacement at different vertebral centers for the vertical mode shape under the different compressive follower preloads.

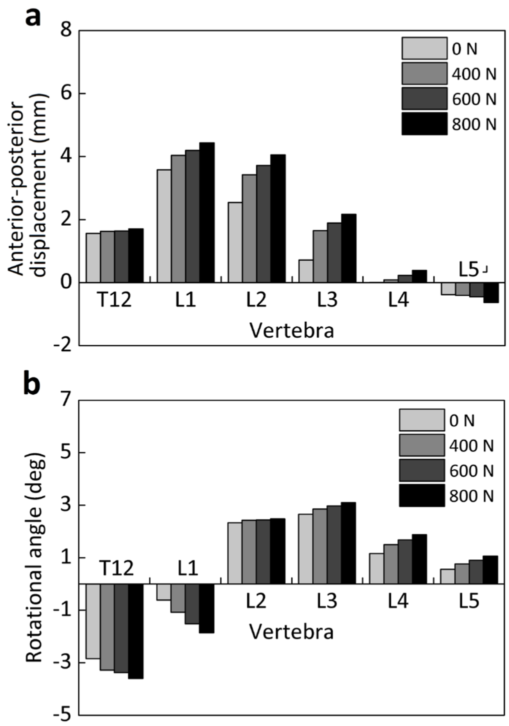

Fig. 5. (a) Anterior-posterior displacements and (b) rotational angles of the vertebrae in the sagittal plane for the vertical mode shape under the different compressive follower preloads

DISCUSSION

A 3-dimensional, finite element model of the T12–pelvis segment was created and validated in this study. The model was used to predict vertical modal responses of the lumbar spine under physiological compressive preload. Although several finite element models have been developed to investigate modal responses of the whole lumbar spine, the existing models mainly focused on predicting the passive responses alone without consideration of the muscle contraction, especially in the deep spinal muscle, that was naturally present and could generate a compressive load on the lumbar spine. In this research, a novel approach was adopted to incorporate the physiological compressive loading during modal analysis. Specifically, the follower load methodology, which has proven effective in numerous in vitro experiments and numerical simulations for replicating in vivo muscle contractions, was employed to impose a compressive preload onto the T12–pelvis model.

The predicted vertical resonant frequency for the T12–pelvis model with a 40 kg upper body mass was 6.49 Hz under no preload, and inclusion of the compressive follower preloads of 400, 600 and 800 N increased it to 7.27, 7.55 and 7.76 Hz, respectively (Table 3). This could be due to the stiffening effect caused by the preload increase, which led to an augmentation in the axial stiffness of the spine, thereby altering the responses. The resonant frequencies exhibited by the current model fell outside the typical range of 4–6 Hz that has been measured in the human spines, as reported in the in vivo study of Panjabi et al. (1986). This notable discrepancy could potentially be attributed to the exclusion of head-to-thorax segments in the model. Kong and Goel (2003) have suggested that the inclusion of these segments could result in a decrease in the resonant frequency by up to 20%. Therefore, incorporating these missing segments into the current model is expected to bring the predicted frequency closer to the experimentally measured values in the human spines.

It was observed from the vertical mode shape that not only did the lumbar spine undergo vertical motion, but it also exhibited anterior-posterior motion (Figures 4 and 5a). This finding was consistent with the in vivo results that the spine exhibited displacements perpendicular to the vibration direction (Baig et al., 2014). Rotation was also observed at different vertebrae (Figure 5b). It implies that intervertebral discs will suffer from increasing tensile or compressive stresses in their anterior or posterior regions during vibration and lead to the acceleration of lumbar degradation. Additionally, several studies have demonstrated that the compressive follower preload could affect the spine biomechanics such as intradiscal pressure and facet joint forces under static loading (Du et al., 2016). The present study found that the preload also played an imported role in vertical modal shape. Increasing the preload led to a decrease in vertical displacements of all the vertebrae but an increase in their anterior-posterior displacements and rotational angles.

The clinical implications of the research findings offer meaningful insights that may contribute to the advancements in therapeutic interventions, designs of spinal implants, and creations of rehabilitation devices. By understanding how preload and vibration affect the lumbar spine biomechanics, surgeons and engineers could develop more effective treatments and devices that address these dynamic factors. For instance, the knowledge gained from this study may help guide the formulation of vibration therapy protocols that minimize detrimental stresses on intervertebral discs while promoting beneficial effects on spinal health. In the context of engineering design, the results suggest that the future spinal implants and orthoses should incorporate mechanisms to adapt to the preload variations and mitigate the adverse effects of vibration on spine motion. This could facilitate the development of more biocompatible and effective devices that enhance patient outcomes.

There were also a few limitations encountered in this study. Firstly, the present in vitro model excludes muscles as a component. Although the follower load technique partially compensated for this limitation, it may not fully replicate the intricate contributions of muscles. Secondly, the model does not account for the mass distribution of the human upper body. However, since the focus of this study was primarily on analyzing the vertical modal characteristics of the lumbar spine, the impact of mass distribution was minimized. Thirdly, the model does not incorporate the material anisotropic properties (typically exhibited by ligaments and soft tissues) due to the lack of available material parameters. In addition, the model is a specimen-specific one, implying that the results obtained may not be directly extrapolated to the entire population. However, it is believed that the present study still contributes to understand lumbar spine mechanics by demonstrating trends and patterns potentially observable in a broader context. To enhance applicability and generalizability of the model, future research endeavors will include exploring individual differences and conducting further validation studies with a larger, more diverse sample.

CONCLUSION

The present study developed and validated a T12–pelvis finite element model to scrutinize the vertical modal characteristics of the human lumbar spine under the influence of physiological compressive loading (applied via follower load technique) generated by muscle contractions. The vertical mode shape showcased the lumbar spine engaging in not just vertical motion, but also anterior-posterior and rotational motions. Additionally, it was found that the modal responses were preload-dependent. As the preload increased, the vertical resonant frequency increased, whereas the vertebral vertical displacement decreased. These findings have potential applications in both clinical practice and engineering design, aiding in the development of more effective protective measures and engineering solutions by enhancing understanding of the lumbar spine's biomechanical response to vibration and preload.

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REFERENCES

Baig, H.A., Dorman, D.B., Bulka, B.A., Shivers, B.L., Chancey, V.C., and Winkelstein, B.A., "Characterization of the frequency and muscle responses of the lumbar and thoracic spines of seated volunteers during sinusoidal whole body vibration," Journal of Biomechanical Engineering, Vol. 136, No. 10, pp. 101002 (2014).

Bovenzi, M., Schust, M., and Mauro, M., "An overview of low back pain and occupational exposures to whole body vibration and mechanical shocks," Medicina Del Lavoro, Vol. 108, No. 6, pp. 419-433 (2017).

Du, C.F., Mo, Z.J., Tian, S., Wang, L.Z., Fan, J., Liu, S.Y., Fan, Y.B., "Biomechanical investigation of thoracolumbar spine in different postures during ejection using a combined finite element and multi-body approach," International Journal For Numerical Methods In Biomedical Engineering, Vol. 30, No. 11, pp. 1121-1131 (2014).

Du, C.F., Yang, N., Guo, J.C., Huang, Y.P., and Zhang, C.Q., "Biomechanical response of lumbar facet joints under follower preload: a finite element study," BMS Musculoskeletal Disorders, Vol. 17, pp. 126 (2016).

Dub´e-Cyr, R., Villemure, I., Arnoux, P.J., Rawlinson, J., and Aubin, C.E., "Instrumentation of the sacroiliac joint with cylindrical threaded implants: a detailed finite element study of patient characteristics affecting fixation performance. Journal of Orthopaedic Research, Vol. 39, No. 12, pp. 2693-2702 (2021).

El-Rich, M., Arnoux, P.J., Wagnac, E., Brunet, C., and Aubin, C.E., "Finite element investigation of the loading rate effect on the spinal load-sharing changes under impact conditions," Journal of Biomechanics, Vol. 42, No. 9, pp. 1252-1262 (2009).

Fan, R.X., Liu, J., and Liu, J., "Prediction of the natural frequencies of different degrees of degenerated human lumbar segments L2-L3 using dynamic finite element analysis," Computer Methods and Programs in Biomedicine, Vol. 209, pp. 106352 (2021a).

Fan, W., Zhao, D., and Guo, L.X., "A finite element model of the human lower thorax to pelvis spinal segment: Validation and modal analysis," Bio-Medical Materials and Engineering, Vol. 32, No. 5, pp. 267-279 (2021b).

Fan, W., and Guo, L.X., "Influence of different frequencies of axial cyclic loading on time-domain vibration response of the lumbar spine: A finite element study," Computers in Biology and Medicine, Vol. 86, pp. 75-81 (2017).

Foresto, T., Song, I., Kim, B.S., and Lim, T.H., "Stabilization of the lumbar spine by spinal muscle forces producing compressive follower loads: 3-dimensional computational study," Journal of Orthopaedic Research, Vol. 36, No. 11, pp. 3004-3012 (2018).

Jia, S.W., Lin, L.Y., Yang, H.F., Xie, J.D., Liu ZF, Zhang TY, Fan, J., and Han, L., "Biodynamic responses of adolescent idiopathic scoliosis exposed to vibration," Medical & Biological Engineering & Computing, Vol. 61, No. 1, pp. 271-284 (2023).

Kim, H.J., Kang, K.T., Son, J., Lee, C.K., Chang, B.S., and Yeom, J.S., "The influence of facet joint orientation and tropism on the stress at the adjacent segment after lumbar fusion surgery: a biomechanical analysis," Spine Journal, Vol. 15, No. 8, pp. 1841-1847 (2015).

Kong, W.Z., and Goel, V.K., "Ability of the finite element models to predict response of the human spine to sinusoidal vertical vibration," Spine, Vol. 28, No. 17, pp. 1961-1967 (2003).

Lee, C.H., Hsu, C.C., and Huang, P.Y., "Biomechanical study of different fixation techniques for the treatment of sacroiliac joint injuries using finite element analyses and biomechanical tests," Computers in Biology and Medicine, Vol. 87, pp. 250-257 (2017).

Mao, N.F., Shi, J., He, D.W., Xie, Y., Bai, Y.S., Wei, X.Z., Shi, Z.C., Li, M., "Effect of lordosis angle change after lumbar/lumbosacral fusion on sacrum angular displacement: a finite element study," European Spine Journal, Vol. 23, No. 11, pp. 2369-2374 (2014).

Miller, J.A.A., Schultz, A.B., and Andersson, G.B.J., "Load-displacement behavior of sacroiliac Joints," Journal of Orthopaedic Research, Vol. 5, No. 1, pp. 92-101 (1987).

Moalla, F., Mehrez, S., and Najar, F., "Multi-body musculoskeletal dynamic model of the human trunk based on an experimental approach," Archive of Applied Mechanics, Vol. 93, No. 3, pp. 1201-1215 (2023).

Moramarco, V., del Palomar, A.P., Pappalettere, C., Doblaré, M., "An accurate validation of a computational model of a human lumbosacral segment," Journal of Biomechanics, Vol. 43, No. 2, pp. 334-342 (2010).

Oxland, T.R., Lin, R.M., and Panjabi, M.M., "Three-dimensional mechanical properties of the thoracolumbar junction," Journal of Orthopaedic Research, Vol. 10, No. 4, pp. 573-580 (1992).

Panjabi, M.M., Andersson, G.B.J., Jorneus, L., Hult, E., and Mattson, L., "In vivo measurements of spinal column vibrations," Journal of Bone & Joint Surgery American Volume, Vol. 68, No. 5, pp. 695-702 (1986).

Panjabi, M.M., Oxland, T.R., Yamamoto, I., and Crisco, J.J., "Mechanical behavior of the human lumbar and lumbosacral spine as shown by three-dimensional load–displacement curves," Journal of Bone & Joint Surgery American Volume, Vol. 76, No. 3, pp. 413-424 (1994).

Patwardhan, A.G., Meade, K.P., and Lee, B., "A frontal plane model of the lumbar spine subjected to a follower load: Implications for the role of muscles," Journal of Biomechanical Engineering, Vol. 123, No. 3, pp. 212-217 (2001).

Polikeit, A., Ferguson, S.J., Nolte, L.P., and Orr, T.E., "Factors influencing stresses in the lumbar spine after the insertion of intervertebral cages: finite element analysis," European Spine Journal, Vol. 12, No. 4, pp. 413-420 (2003).

Qiu, T.X., "Finite element analyses of thoracolumbar junction-investigations of instantaneous axes of rotation (IARs) and burst fracture mechanism," Ph. D. Thesis, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore (2005).

Renner, S.M., Natarajan, R.N., Patwardhan, A.G., Havey, R.M., Voronov, L.I., Guo, B.Y., Andersson, G.B.J., and An, H.S., "Novel model to analyze the effect of a large compressive follower pre-load on range of motions in a lumbar spine," Journal of Biomechanics, Vol. 40, No. 6, pp. 1326-1332 (2007).

Schmidt, H., Galbusera, F., Rohlmann A., and Shirazi-Adl, A., "What have we learned from finite element model studies of lumbar intervertebral discs in the past four decades," Journal of Biomechanics, Vol. 46, No. 14, pp. 2342-2355 (2013).

Xiao, S., Qu, Z.D., Yang, J.K., Huang, J., and Chen, G., "A Study of Lumbar Disc Injury under Typical Frontal Impact Load," Journal of the Chinese Society of Mechanical Engineers, Vol. 42, No. 6, pp. 605-612 (2021).

Xu, M., Yang, J., Lieberman, I., and Haddas, R., "The effect of surgical alignment in adult scoliotic spines on axial cyclic vibration: A finite element study," Journal of Computing and Information Science in Engineering, Vol. 9, No. 2, pp. 021006 (2019).

Xu, M., Yang, J., Lieberman, I.H., and Haddas, R., "Lumbar spine finite element model for healthy subjects: development and validation," Computer Methods in Biomechanics and Biomedical Engineering, Vol. 20, No. 1, pp. 1-15 (2017).

Yao, Z.D., Li, L.X., Zhang, P., Yang, L., Bai, X.L., Peng, S.L., Lai, Y.X., "Biomechanics evaluation of sacroiliac joint pain after lumbosacral fusion: a finite element analysis," Journal of Orthopaedic Research, Vol. 41, No. 4, pp. 875-883 (2023).

Zhang, C., and Guo, L.X., "Effect of whole-body vibration at different frequencies on the lumbar spine: A finite element study based on a whole human body model," Proceedings of Institution of Mechanical Engineers Part H-Journal of Engineering in Medicine, Vol. 236, No. 12, pp. 1752-1761 (2022).