Influence of Whole-Body Vibration on Dynamic Response of Lumbar Spine after Transformal Lumbar Interbody Fusion

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Introduction: Occupational whole body vibration (WBV) plays a major role in determining dynamic responses of the lumbar spine. WBV has been shown to cause low-back problems and degenerative disc diseases. Fusion surgery such as trans-formal lumbar inter-body fusion (TLIF) have been widely utilized to treat such disorders. **Materials and Methods**: In this study, finite element method (FEM) was used to investigate dynamic responses of the lumbar spine due to WBV with the frequency in the range of regular physiologic activities after TLIF. A FE model of the L1-L5 lumbar spine was modeled and cyclic loading with the frequency of 1 Hz and 5 Hz were exerted to the model. Then, the disc bulge and stress distribution on the annual ground substance and vertebral bodies were measured. **Results**: It was observed that the maximum disc bulge (MDB) and maximum von-Mises stress (MMS) occurred in proportion to the loading frequency; overall, in the 5 Hz model, MDB and MMS were detected to happen 5 times more frequently as compared to the 1 Hz model. However, the magnitude of MDB and MMS were not generally affected by the loading frequency. **Conclusions**: It can be concluded that different frequency of WBV, although in the physiologic range, can alter dynamic responses of the lumbar spine and, thus, their fatigue behavior. In the results can be of assistance to broaden the understanding regarding the dynamic responses of the lumbar spine during WBV after TLIF.

Keywords: whole-body Vibration; Dynamic Analysis; Finite Element Analysis; Lumbar Spine; Axial Cyclic Loading

Introduction

Occupational whole-body vibration (WBV) has been shown to be an important contributor of low-back problems. The cyclic loading exerted to the human vertebral body due to WBV can yield to several degenerative spinal disorders (1-4). Several surgical techniques, notably those related to the lumbar interbody fusion, have been proposed to treat such disorders (5, 6). Lumber interbody fusion can be performed through different approaches which mainly are: (i) anterior lumbar inter-body fusion (ALIF), (ii) posterior lumbar inter-body fusion (PLIF), and (iii) trans-formal lumbar inter-body fusion (TLIF) (7, 8).

Overall, these surgical techniques have been praised for their ability to effectively reduce pain and to provide desirable mechanical stability for the spinal segment (5). It has been shown that ALIF can pose some undesirable clinical outcomes in the long term. For instance, in a follow up study performed by Penta *et al.*, it has been reported that ALIF can cause adjacent segment degeneration (9). PLIF and TLIF are both posterior fusion procedures. The lesser neurological complications, reduced invasiveness and shorter operation time are the advantages of TLIF over PLIF (10).

Numerical methods such as finite element method (FEM) have been widely utilized to investigate mechanical responses of the spinal vertebrae and discs to dynamic loadings (11-14). Specifically, after fusion surgery, the FEM can be employed to predict vulnerable areas of different components of the spinal segment due to WBV. But, these are almost impossible to be evaluated using experimental approaches. Previous studies investigated the effects of dynamic loading on mechanical responses of the lumbar spine through finite element simulation. In the study performed by Goel *et al.*, it has been revealed that dynamic loading produces more damaging effect on the human lumbar spine as compared to the static loading (15). The study performed by Wei and Li-Xin indicated that the mechanical response of human lumbar spine is dependent on the frequency of dynamic loading, and as the loading frequency approaches the resonant frequency, the responses will be greater (12).

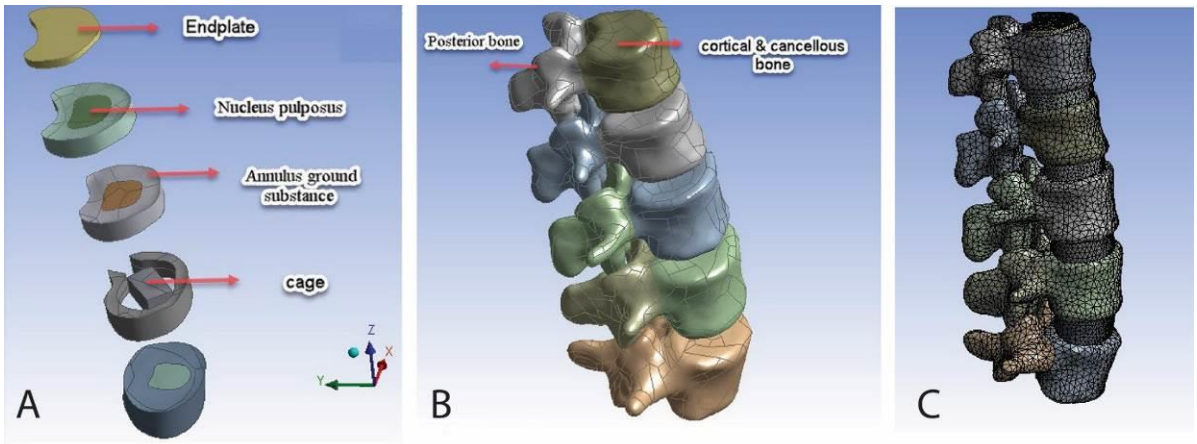

Figure 1. A) Different components of the developed finite element model including cortical & cancellous bone, posterior bony element, endplate, nucleus pulposus, annulus ground substance and cage; B) Assembling all the components together; C) Meshing the assembled model

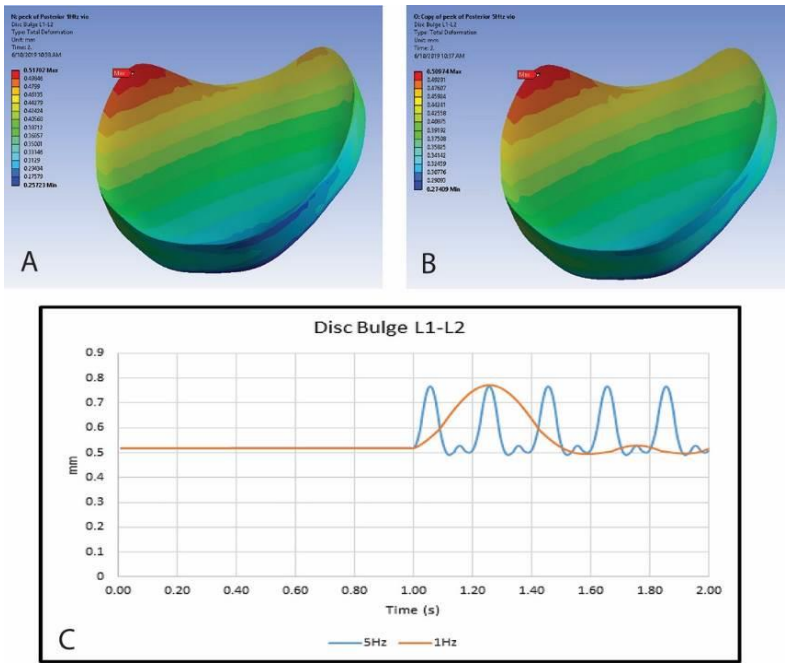

Figure 2. Disc bulge in the L1-L2 intervertebral disc at end of dynamic simulation for A) 1 Hz and; B) 5 Hz models; C) The magnitude of maximum disc bulge found in the L1-L2 intervertebral disc during dynamic simulation

Another study performed by the previous authors, investigated the role of bilateral pedicle screw fixation (BPSF) on the dynamic response of lumbar spine due to WBV. It was reported that the use of BPSF would decrease the likelihood of spinal injury caused by WBV(13). In that study, the cage in the developed model was considered to be made of polyether ether ketone (PEEK) and was assumed to behave as an isotropic elastic material. But, it has been well established that PEEK is a viscoelastic material and shows time-dependent mechanical response (16). This issue will appear to be more important when the whole structure is subjected to a dynamic loading, *i.e.* WBV.

In this study, we investigated the dynamic response of lumbar spine due to WBV after TLFS using FEM. A FE model of the L1-L5 motion segment after TLIF was developed and viscoelastic properties were assigned to the PEEK cage used in the model. This study aimed at providing more accurate dynamic responses of lumbar spine during WBV after TLIF surgery by assigning true mechanical properties of different components that are commonly used in a TLIF surgery.

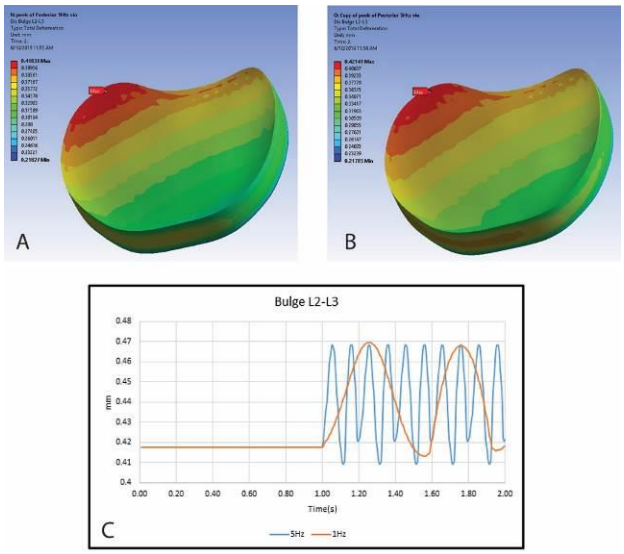

Figure 3. Disc bulge in the L2-L3 intervertebral disc at end of dynamic simulation for *A*) 1 Hz; *B*) 5 Hz models; *C*) The magnitude of maximum disc bulge found in the L2-L3 intervertebral disc during dynamic simulation

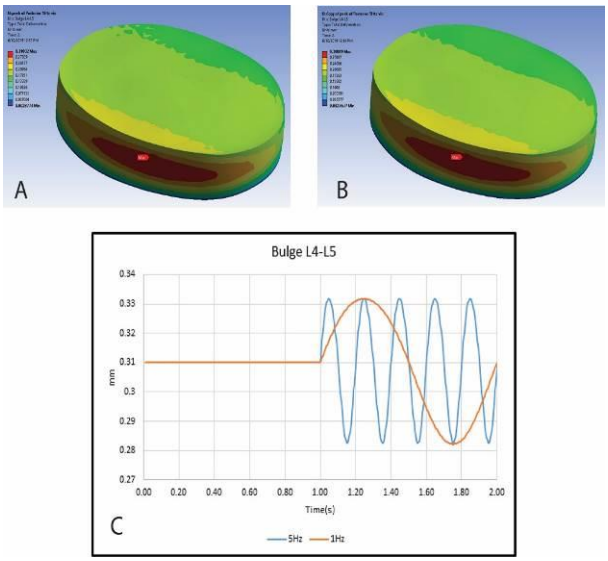

Figure 4. Disc bulge in the L4-L5 intervertebral disc at end of dynamic simulation for A) 1 Hz; B) 5 Hz models; C) The magnitude of maximum disc bulge found in the L4-L5 intervertebral disc during dynamic simulation

Materials and Methods

DICOM computer tomography images were acquired from a 20-year-old male with no signs of pathology of the vertebral column. The images were then processed via Mimics 19 software to create a model of the vertebrae and discs as shells. Next, Materialise 3-Matic software was employed to smooth rough areas on the surface of the model and to create a 3-dimensional (3-D) solid model. The anterior and posterior regions of the vertebrae were also modeled. Each vertebrate was modeled to be comprised of a cortical section, i.e. a shell with the thickness of 0.7 mm, and a cancellous section (17). The intervertebral discs were assumed to be composed of a nucleus pulposus encircled by an annulus ground substance (AGS) (18). To simulate the spinal fusion surgery, the damaged tissue of the intervertebral disc was removed and a cage was placed into the region. According the previous published study (13), the cage was modeled as a rectangular cuboid with the dimensions of 10 cm (height)*16 cm (length)*9 cm (width) using CATIA V5.21 software. In order to limit the height of the cage, its upper and lower surfaces were brought into contact with the lower surface of the L4 vertebrate and the upper surface of the L3 vertebrate respectively. The different components of the model were then assembled together. The assembled model was meshed using ANYSY Workbench18.2 software (Figure 1). A 3-D 10-node tetrahedral structural solid, with three degree of freedom at each node, was utilized to model the assembled solid structure. The developed 3-D solid model was comprised of a 259865 elements and 125634 nodes.

Material properties of the different components of the models were obtained from the literature (13). For the vertebrae, the posterior bony elements, cortical and cancellous bone were assumed to be isotropic elastic with the Young's modulus, Poisson's ratio, and density as reported by the previously published study (13). The AGS and nucleus pulpous were considered to be hyperplastic Mooney-Rivlin (13, 19). The PEEK cage were considered to be viscoelastic with the mechanical properties reported previously (20).

The contact surfaces of the vertebrae with the intervertebral discs as well as the cages were considered to be tie. The inferior surface of the L5 vertebrate were assigned to be stationary in all three dimensions during the simulation process. From 0 to 1 second, a linear preload with the magnitude of 0 N at 0 sec and 400 N at 1 sec was applied to the superior surface of the L1 vertebrate in the direction of Z axis. Then, a cyclic load with the magnitude of 40 N and frequency of 1 Hz (name 1 Hz model) was applied to the above-mentioned surface. In the other simulation process, a cyclic load with the same magnitude but different frequency of 5 Hz (named 5 Hz model) was exerted to the upper surface of the L1 vertebrate. Both cyclic loads were applied for 1 second. Next, the dynamic stress distribution in the cage and the dynamic response of the disc bulge were calculated after one-second application of cyclic loading.

Table 1. The maximum disc bulge for L1-L2, L2-L3 and L4-L5 intervertebral discs. All the data reported in the unit of mm

	1 Hz model	5 Hz model
L1-L2	0.52	0.51
L2-L3	0.42	0.42
L4-L5	0.31	0.31

Table 2. The maximum von-Mises stress for annulus ground substance of L1-L2, L2-L3 and L4-L5 intervertebral discs. All the data reported in the unit of MPa

	1 Hz model	5 Hz model
L1-L2	0.62	0.61
L2-L3	0.82	0.80
L4-L5	0.61	0.61

Results

Dynamic disc bulge within the intervertebral discs

Dynamic responses of the disc bulge at the adjacent levels of fused one were calculated for L1-L2, L2-L3 and L4-L5 intervertebral discs. For L1-L2 disc, the maximum disc bulge (MDB) occurred at the posterior region in both models. The corresponding maximum values were comparative (0.52 mm and 0.51 mm for 1 Hz and 5 Hz models respectively) (Table 1). The value of MDB throughout the simulation process, specifically during the cyclic loading, was also measured. It was observed that, for 1 Hz model, the value of MDB peaked only once at 1.27 sec (0.78 mm), and then decreased to 0.5 mm for the rest of the simulation process (Figure 2). For the 5 Hz model, the MDB faced the same maximum and minimum values as those of the 1 Hz model, but the corresponding maximum value was found to occur periodically for 5 times during the dynamic simulation (Figure. 2).

For L2-L3 intervertebral disc, the same trend as that of the L1-L2 disc was observed. The location of MDB was the same as that of L1-L2 disc. At time 2 sec, the maximum values of disc bulge were detected to be 0.42 MPa for both models (Figure 3 and Table 1). Investigating dynamic response of the 1 Hz model showed that the value of MDB peaked at two time points, i.e. 1.23 sec and 1.78 sec, with the same magnitude of 0.47 mm. On the other hand, dynamic analysis of the 5 Hz model revealed that the maximum value of MDB occurred 10 times with the same magnitude as that of the 1 Hz model (Figure 3).

For L4-L5 disc, the locations of MDB of at 2 sec were detected to be at superior region of the disc for both 1 Hz and 5 Hz models. The corresponding value of MDB were the same (0.31 MPa for both models) (Figure 4 and Table 1). During the dynamic simulation of 1 Hz model, the value of MDB took on a maximum and minimum once at 1.26 sec (0.33 m) and 1.77 sec (0.28) respectively. Dynamic analysis of the 5 Hz model also indicated that the maximum and minimum values of MDB were the same as those of the 1 Hz model. But, these maximum and minimum values occurred more frequently (5 times for each) during the 1-second dynamic analysis (Figure 4).

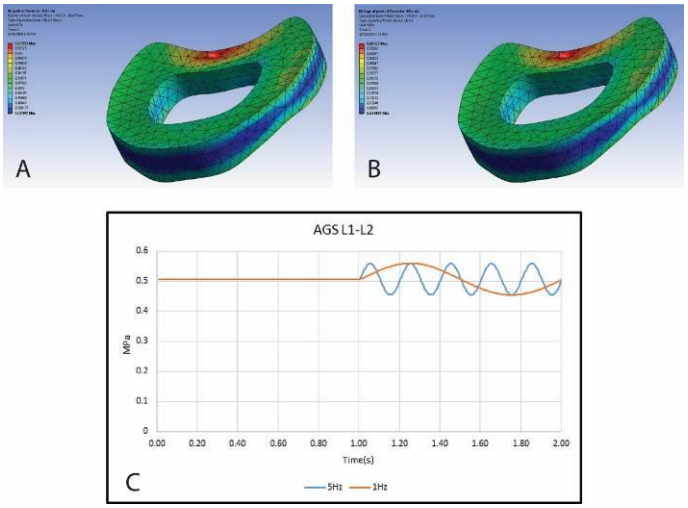

Figure 5. Von-Mises stress distribution in the annulus ground substance (AGS) of the L1-L2 disc at end of dynamic simulation for A) 1 Hz; B) 5 Hz models; C) The magnitude of maximum von-Mises stress found in the AGS of L1-L2 intervertebral disc during dynamic simulation

Dynamic stress distribution within the AGS

At 2 sec, for L1-L2 disc, the maximum Von-Mises stress (MMS) occurred at the posterior region of the AGS as indicated by Figure 5. This locations and values of the MMS were comparative for the two models (0.61 MPa and 0.61 MPa for 1 Hz and 5 Hz models respectively) (Table 2). The maximum value of the MMS within AGS was investigated during the dynamic simulation. For the 1 Hz model, it was observed that MMS took on a maximum (0.57 MPa) and minimum (0.46 MPa) once during the dynamic simulation. For the 5 Hz model, the corresponding maximum and minimum of value of the MMS were the same as those of the 1 Hz model. But, these maximum and minimum occurred repeatedly for 5 times (Figure 5).

For AGS of the L2-L3 disc, the same trend as that of the L1-L2 disc was followed, except that the value of MMS was greater for that of the L2-L3 disc (Figure 6).

For AGS of the L4-L5 disc, the MMS at the end of the dynamic simulation was found be at the posterior region of the disc for both models. The corresponding values of MMS were the same for both (0.61 MPa) (Figure 7 and Table 2). During dynamic simulation

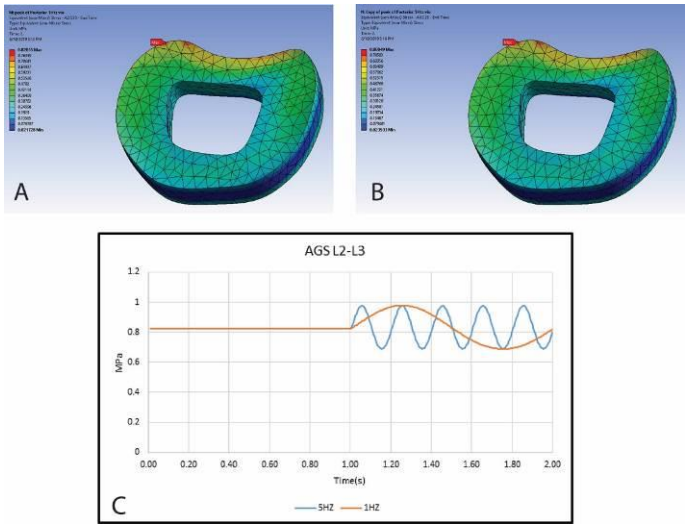

Figure 6. Von-Mises stress distribution in the annulus ground substance (AGS) of the L2-L3 disc at end of dynamic simulation for A) 1 Hz; B) 5 Hz models; C) The magnitude of maximum von-Mises stress found in the AGS of L2-L3 intervertebral disc during dynamic simulation

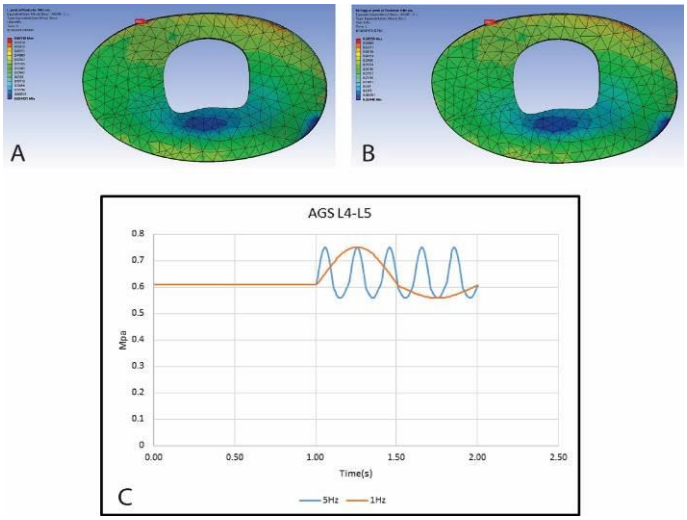

Figure 7. Von-Mises stress distribution in the annulus ground substance (AGS) of the L4-L5 disc at end of dynamic simulation for *A*) 1 Hz; *B*) 5 Hz models; *C*) The magnitude of maximum von-Mises stress found in the AGS of L4-L5 intervertebral disc during dynamic simulation

with the frequency of 1 Hz, the maximum value of MMS met its maximum (0.75 MPa) and minimum (0.57 MPa) values only once. But, dynamic simulation with the frequency of 5 Hz, caused the maximum and minimum values of MMS to happen more frequently, i.e. five times for each. However, the corresponding maximum and minimum values were the same (Figure 7).

Dynamic stress distribution within the vertebral bodies

At second 2, the MMS at the superior surface of the L4 vertebrate was found to be at the inferior region of the vertebrate for both models. The corresponding values of MMS were 0.22 MPa and 0.50 MPa for 1 Hz and 5 Hz models respectively (Figure 8). During one-second dynamic simulation, the value of MMS met drastic changes for the 5 Hz model as compared to that of the 1 Hz model. The maximum and minimum values of MMS happen more frequently in the 5 Hz model in comparison to the 1 Hz model. For the 5 Hz model, the corresponding maximum value of MMS was about 5 times greater than that of the 1 Hz model (Figure 8).

At the inferior surface of the L3 vertebrate, the abovementioned trend was followed, except that the MMS at second 2 was detected to occur at the middle region of the L3 vertebral body for the 5 Hz model (Figure 9).

Discussion

In this study, the effects of WBV on the dynamic responses of human lumbar spine after TLIF surgery were investigated in-silico. A model of L1-L5 spinal segment including vertebrae, intervertebral discs and the PEEK cage was developed and subjected to 1 Hz and 5 Hz cyclic loadings to simulate regular daily physiological activities. In particular, the PEEK cage was considered to behave as a viscoelastic material showing time-dependent mechanical response. The dynamic nature of WBV emphasizes the importance of assigning true mechanical properties to PEEK, i.e. viscoelastic characteristics; compared to the elastic materials, viscoelastic materials will show mechanical responses highly dependent of loading frequency.

Looking at the disc bulge and von-Mises stress within AGS and vertebral bodies, it is observed that the MDB and MMS would happen in proportion to the loading frequency; when the dynamic loading with 5 Hz frequency is applied, the MDB and MMS are detected to happen 5 times more frequently as compared to when the 1 Hz loading frequency is exerted. By considering the fact that increase in the stress and strain can speed up lumbar spine degeneration, it can be suggested that 5 Hz loading frequency may have more intense effects on the fatigue failure of lumbar spine and initiating of low-back disorders. It is also found that loading frequency can affect the location of MMS. For 1 Hz loading frequency, the MMS is found to occur at the central region of the L3 vertebrate, whereas when the loading frequency increases to 5 Hz, the MMS is detected to occur at the inferior region of the L3 vertebrate (Figures 8, 9). This implies that loading frequency can also alter the vulnerable areas of a vertebral body, and thus result in different mechanical failures.

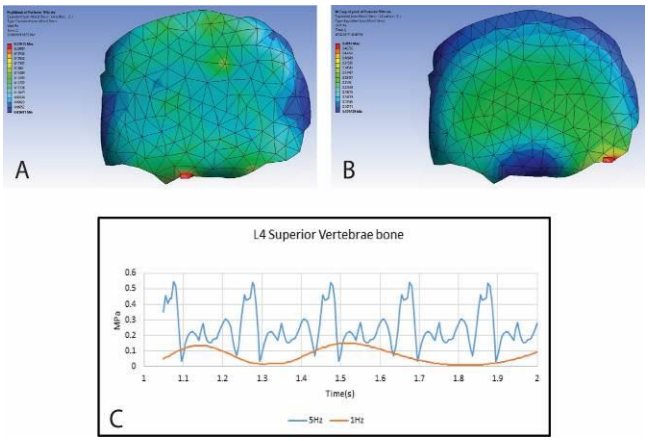

Figure 8. Von-Mises stress distribution in the superior surface of the L4 vertebrate for *A*) 1 Hz; *B*) 5 Hz models; *C*) The magnitude of maximum von-Mises stress found in the superior surface of the L4 vertebrate during dynamic simulation

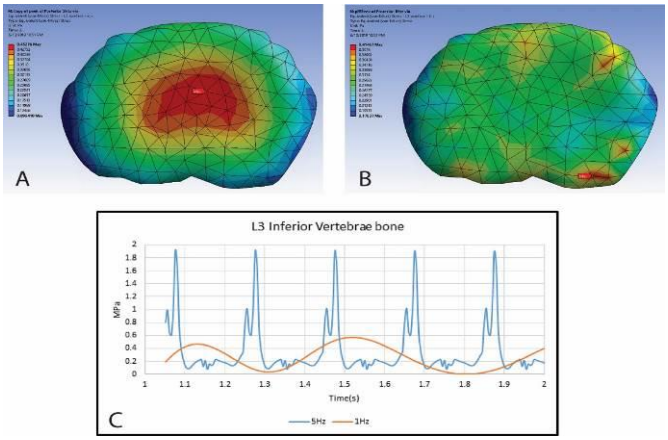

Figure 9. Von-Mises stress distribution in the inferior surface of the L3 vertebrate for A) 1 Hz; B) 5 Hz models; C) The magnitude of maximum von-Mises stress found in the inferior surface of the L3 vertebrate during dynamic simulation

The results of disc bulge indicate that L1-L2 and L2-L3 intervertebral disks show rather similar behaviors which considerably vary from L4-L5 intervertebral disk; although the magnitude of MDB is not markedly different in the abovementioned intervertebral discs, its location varies noticeably especially when L1-L2 and L2-L3 intervertebral disks are compared to the L4-L5 intervertebral disk (Figures 2-4). This implies that vulnerable areas of L4-L5 intervertebral disc are different from those of L1-L2 and L2-L3 intervertebral discs, and that they can experience different mechanical failures associated with the level of deformation or strain.

As of any simulation study, there are several limitations on this study. Here, only a portion of lumbar spine was modeled and the lumbar spinal ligaments and muscles were not modeled. However, exertion of a preload can compensate for not modeling the lumbar spinal muscles. Moreover, the connection between all components was considered to be tie and the dynamic response of lumbar spine was investigated only for two seconds. Further studies in order to investigate long-term responses of the lumbar spine due to dynamic loading and elucidate the time-varying changes of disc responses during long-term WBV are recommended.

WBV has been reported that to be a contributing factor for possible low-back disorders and intervertebral disc degeneration, possibly when the loading frequency is close to the axial resonant frequency (7.7 Hz) (12). By contrast, it is also reported that some vibrational loadings, possibly those that are far away from resonant frequency of the lumbar spine, can also relieve low-back pain (21-23). Herein, the effect of dynamic loading frequency associated with the regular daily activities, *i.e.* 1-5 Hz, was assessed on the response of lumbar spine. It can be suggested that the WBV applied to a person due to performing regular daily activities may reduce the duration of rehabilitation process from spine diseases.

Conclusions

In this study, FEM was employed to investigate the effects of loading frequency on the dynamic responses of human lumbar spine during regular daily physiologic WBV. It was found that as the loading frequency increased, the MDB and MMS happened more frequently, although without considerable changes in their magnitude. It can be concluded that dynamic loadings, with different frequencies in the range of daily physiologic activities, can yield into different time-varying dynamic responses of lumbar spine and thus cause different mechanical failures. The results can be of assistance when the consequences of fusion surgery during WBV is the focus of concern.

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Conflict of Interest: 'None declared'.

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