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Finite element method-based study for effect of adult degenerative scoliosis on the spinal vibration characteristics

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ABSTRACT

Finite element analysis was used to investigate the responses of five healthy subjects and five adult degenerative scoliosis (ADS) subjects to cyclic vibration. The dynamic responses of the healthy and scoliotic spines to the sinusoidal cyclic vibrations have been investigated in previous studies by simulation or experimental approaches. However, no simulation or experimental results were available for the ADS subjects. The effect of the ADS on the vibrational characteristics of spines remained unknown. The objective of this study was to compare differences of the dynamic responses to the cyclic vibration input between the healthy subjects and subjects with ADS. Based on the simulations results in this study, the scoliotic spines are more sensitive to the cyclic vibrations than the healthy spines. More resonant frequencies were predicted in the scoliotic spines than the healthy spines. The scoliotic deformity in the spine was to make the vibrational response of the spine significantly more complex at the apical scoliotic region. This study suggested that ADS could severely increase spinal response to the cyclic vibrations, which could potentially lead to further scoliotic deformity in the spine.

1. Introduction

Adult degenerative scoliosis (ADS) is a disorder that results in 3-dimentional abnormal spinal deformity in the adult spines, which is commonly correlated with degenerative intervertebral discs. Since the loads on the scoliotic spines are asymmetric, scoliosis subjects are subjected to higher risk of lower back pain (LBP) than the healthy population [15,26]. Chronic exposure to whole-body vibration (WBV) on the spine has been identified as one important inducer of LBP [4,16]. With long-term occupational exposure to WBV, truck drivers and helicopter pilots suffer from spinal degenerative diseases and LBP more commonly than normal populations as results from the degenerative and anatomic changes in the spine especially in the lumbar spine region [14,18,27]. Cyclic vibration on the spine could catalyze the spinal tissue fatigue, intervertebral disc degeneration, and eventually the abnormal spinal deformity [25].

To understand the vibration-induced spinal pain and injury mechanism, in the literature, both computational method [2] and experimental approach [12,13] have been conducted to investigate the spinal vibration characterizations. Compared with experimental studies, computational studies have the advantage of lower cost and higher efficiency. The computational studies of the vibration harmfulness on the spine mainly contained two methods: multi-body dynamic simulations [2,26] and finite element (FE) analysis [9,10,11,14,15]. Although with good calculation efficiency, two-dimensional (2-D) and three-dimensional (3-D) multi-body dynamic spine models can't fully represent the realistic geometries of the vertebrae and other spinal soft tissues [14], which might affect the predicting capability of the biomechanical properties of the models. FE method has been widely utilized to study the spinal biomechanics for the past four decays [22], which is able to accurately represent the complex spinal geometry ([26]; Dreischarf et al [6]). FE analysis can also capture the internal mechanical parameters such as stress and strain, which is difficult to measure in the experimental tests ([6,22]; Ayturk et al [1]; [26]). It has been shown that dynamic cyclic loads could cause higher responses in stress, intradiscal pressure, disc bulge, and facet joint force compared to the static loads [8]. Li et al. [15] proved that scoliotic spines are more sensitive to the dynamic cyclic load which is used to simulate the WBV environment. There is increasing clinical interest in studying the effect of scoliosis on the vibration characterizations of the human spine [14,15]. Although FE studies have been employed by researchers to study the vibration-induced responses of healthy subjects [8,9,10,14] and adolescent idiopathic scoliosis subjects [15], no study has been reported to study the vibration characteristics of ADS to the best of our

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knowledge. Furthermore, all of those previous studies only utilized one deterministic FE spine model [8,9,10,11,14,15]. However, great inter-subject variations exist among spines including the spinal geometries and material properties, which raised concerns about the reliability and comparability of the prediction results reported by single deterministic FE spine model [6]. To address this issue, one possible solution is to build a fully probabilistic model (Little and Adam [17]), which has been proved to be difficult and time-consuming [6]. Instead, Dreischarf et al. [6] reported that the combined simulation results obtained from several distinct deterministic FE models could act as one improved and feasible option to overcome the limitation of single deterministic FE model. By investigating multiple healthy and scoliosis subjects, one is able to obtain some insights of vibration characteristics in healthy and scoliotic spines.

The objectives of this study are: (1) to investigate the vibration characterizations of five healthy and five scoliotic spines using FE method; and (2) to reveal the effect of ADS on the spinal vibrational characteristics by comparing the healthy subjects and scoliotic subjects. After the comparison of vibrational characteristics in healthy and scoliotic spines, we should have better understanding of the influence of scoliosis on the spinal response to the WBV and how such influence will affect the spinal health or trigger LBP.

2. Method

Ten 3-D FE spine models were developed to represent five healthy and five pre- surgical scoliotic spines (Fig. 1) based on in vivo computed tomography (CT) scans with a gap of 0.5 mm ([19,28] submitted). The modeling methods employed to develop these FE spine models were extensively validated in our previous study [28] and have been employed to study the biomechanics of scoliotic spines under static loading conditions ([19] submitted). The FE spine models utilized in this study were described in details in our previous study ([19,28] submitted), which were briefly reviewed in this study.

Each vertebra has a cancellous core surrounded by a cortical shell layer with thickness from 0.5 to 1 mm [29]. Cartilaginous endplates at the ends of each vertebra were modeled with a thickness of 0.8 mm [1]. The facet cartilage joints of the vertebra were modeled as a soft frictionless contact with an initial gap of 0.5 mm [29]. There are seven major ligaments: anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), flaval ligament (FL), facet capsular ligament (CL), intertransverse ligament (ITL), interspinous ligament (ISL), and suspraspinous ligament (SSL). These ligaments were meshed with 4-node shell elements [3] and the ligaments were described with nonlinear stress-strain curves [7]. A compressive follower load with optimized path through the vertebrae was used to represent local muscle forces in the lumber spine [5]. The intervertebral disc models were adopted from Schmidt et al. [23]. The nonlinear mechanical behavior of the fibers was modeled as a stress-strain curve [24]. The orientations of the collagen fibers were defined with a 30- or 150-degree angle from the horizontal surface defined by the bottoms of intervertebral discs [20]. In the post-surgical scoliosis FE models, the linear stress-strain material properties of titanium were applied to the pedicle screws and rods. The material properties of the spinal tissues assigned to the FE models in this study were adopted from Xu et al. [28].

For each FE model, the body mass above the simulated spinal segments was assigned as lumped mass on top of the superior endplate of the upmost-superior vertebra [9,10,11]. The damping ratio in the dynamic FE analyses in this study was set as 0.08 [15]. The sacrum of each subject was fixed in all degrees of freedom. The excitation was applied on the superior endplate of the upmost vertebra as sinusoidal force with magnitude of 40 N in the axial direction [8,9,11,14,15]. The frequency range of the excitation was 1–25 Hz. The resonant responses of the apical vertebrae and upmost-superior vertebra in the pre-surgical models and the adjacent and fused segments in the post-surgical models were recorded in the three translational directions (Fig. 2). The FE simulations in this study were performed in LS-DYNA ® (Livermore Software Technology Corporation, Livermore, CA, USA).

3. Results

The vibration-induced resonant translations of different vertebrae of the five healthy and five scoliosis subjects tested in this study were summarized in Fig. 3, where the resonant amplitudes of vertebra L_3 in three translational directions (vertical, lateral, and anteroposterior) for healthy and scoliotic subjects were compared with those in the scoliotic subject reported by Li et al. [15]. To illustrate the difference in the resonant amplitudes among different vertebrae, the vibration-induced translations at vertebra L_3, L_4, and L_5 obtained from healthy and scoliotic subjects were summarized and compared with those reported by Li et al. [15]. In Fig. 5, the numbers of resonant frequencies were also compared with those reported by Li et al. [15]. In addition, the predicted first resonant frequencies of subjects in this study were compared with those in the literature [9,10,11,14,15] in Fig. 6.

As shown in Fig. 3, the maximum resonant amplitudes predicted in the healthy subjects were significantly smaller than those obtained from the scoliosis subjects in all three translational directions (P-value=0.005782). The mean values of resonant amplitudes in the healthy subjects were 73.44%, 84.26%, and 73.54% smaller than those in the scoliotic subjects in vertical, lateral, and anteroposterior directions respectively. This suggested that the scoliotic spine is more sensitive to the vibration than the healthy spine especially at the apical segment, which was consistent with the conclusion summarized by Li et al. [15]. Theoretically, the resonant amplitude in vertical direction should be larger than those in lateral and anteroposterior directions since the excitations were applied in the vertical direction. In the healthy subjects, the vertical resonant translations predicted were significantly larger than those of the lateral and anteroposterior directions. However, in the scoliotic subjects in this study, the vertical resonant translation was not significantly larger than those in the lateral directions. Different from the healthy spines, the scoliotic spines had abnormally larger resonant response in the lateral direction. The resonant amplitudes of vertebra L_3 predicted by Li et al. [15] were within one standard deviation range of the mean value of those predicted in this study in all the three translational directions. Thus, the resonant amplitudes predicted in this study in the scoliotic subjects were considered reasonable.

As shown Fig. 4, from the most superior vertebra (L_3) to the most inferior vertebra (L_5) along the spinal axis, the translational resonant amplitude decreased in both the healthy and scoliotic subjects in this study, which was consistent with the observation obtained in one scoliotic spine by Li et al. [15]. In the healthy subjects, L_3, L_4, and L_5 had resonant amplitudes with mean values of 1.62×10^{-3} mm, 0.82×10^{-3} mm, and 0.55×10^{-3} mm respectively. In the scoliotic subjects, L_3, L_4, and L_5 had resonant amplitudes with mean values of 4.51×10^{-3} mm, 3.42×10^{-3} mm, and 2.42×10^{-3} mm respectively.

As shown in Fig. 5, on average, number of resonant frequencies predicted in the healthy subjects (mean value =2.2, SD=0.4) was significantly (50.00%) smaller than those reported in the scoliotic subjects (mean value =4.4, SD=1.02), which had a P-value of 0.00545.

As shown in Fig. 6, the first resonant frequencies of the healthy subjects with L_1-S_1 spinal motion segments in this study were between those predicted by Kong and Goel [14] with L_1-L_5 motion segments and those predicted by Guo and Teo [9]. The first resonant frequencies of the scoliotic spines predicted in this study were higher than those predicted by Li et al [15].

4. Discussions

In this study, five healthy spines and five scoliotic spines were investigated in order to better understand vibrational characteristic