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Biodynamics Characterization of Subject Specific Lumbar Spine under Ambient Condition Using Operational Modal Analysis

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Abstract

The determination of the dynamic behaviour of the lumbar spine is a vital step to fully comprehending the cause of back pain. This study examined the efficacy of operational modal analysis (OMA) to predict the natural frequency of the lumbar spine with random loading from exercise conditions. This study aimed to determine the subject-specific natural frequency and vibration mode of L4–L5 (one motion segment). OMA was performed on a healthy subject (H = 1.65 m, W = 58 kg) who underwent a jumping activity. Four uniaxial accelerometers were mounted on the L4–L5 segments. The accelerometer output responses were acquired and processed in OMA to obtain the dynamic characteristics of the lumbar spine. The dynamic characteristics, such as natural frequencies and mode shapes, were obtained through the peak-picking technique in the frequency domain decomposition (FDD) algorithm. The required parameters were decomposed from a singular value decomposition (SVD) plot, and the results were verified using the auto-modal assurance criterion algorithm. The natural frequencies for axial, flexion-extension and anterior-posterior modes were 1.31, 2.63 and 5.25 Hz, respectively. The results demonstrated the potential of OMA using the FDD algorithm in the measurement of the dynamic characteristics of the human lumbar spine.

Discipline: Biomechanics, Biomedical Engineering

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1 Introduction

Low back pain is commonly observed among patients subjected to long exposure to whole-body vibration (WBV) (Wahlström et al., 2018). The effects of vibration on different areas of the human spine vary. The lumbar portion is the most common spinal area, where spinal deformities, lumbago and sciatica develop (Bogadi-Sare, 1993). The anterior area of L3–L5 exhibits a small vibration amplitude, but the posterior area vibrates at a larger amplitude (Guo et al., 2005). The vibration due to human-machine interaction causes the degeneration of the spine lumbar, leading to the loss of stiffness and increased spine mobility (Jia et al., 2019;

Wahlström et al., 2018). Spine degeneration occurs regardless of the frequency and amplitude of vibration (Guo et al., 2005); however, exciting the lumbar at or close to its natural frequency causes considerably higher stresses and serious spine injury due to resonance (Guo & Teo, 2005; Jia et al., 2019; Wang et al., 2010). The duration of vibration exposure must be reduced, and the vibration source should be optimised to reduce the risk of failure (Ruoxun et al., 2019). Therefore, the specific biodynamic characteristics of the human spine must be determined to optimise the source of vibration, which leads to the avoidance of resonance.

Resonance causes a high amplitude of vibration, which increases the stress condition in the affected area. This condition is undesirable because the dynamic effect will generally shorten the life of the lumbar spine. Thus, this study was carried out to obtain the essential natural frequencies for normal lumbar spine cases, namely, axial, flexion-extension (F-E) and anterior-posterior (A-P) modes. These critical modes must be properly understood because of their contribution to the high-stress occurrence in the lumbar spine.

2 Literature Review

In a previous study, the dynamics of the human spine were characterised to determine the modal parameters (free vibration) and observe its biodynamic response to various sources of vibration (forced vibration). Several finite element (FE) studies were conducted to predict the natural frequency of the human spine. The natural frequency in the vertical direction was inversely proportional to the number of motion segments (Schmidt et al., 2013). The fundamental resonance frequency between 23.5 and 26.7 Hz was extracted from one motion-segment FE model with a carrying mass of 40 kg (Guo et al., 2009; Kasra et al., 1992). Ruoxun et al. considered one motion segment; however, they reported that resonance occurred at 3.5 Hz when the excitation frequency was varied between 2 and 5 Hz with 720–880 N sinusoidal loads without carrying any mass (Ruoxun et al., 2019). Meanwhile, a fundamental axial frequency of about 17 Hz was reported for two motion-segment FE models (Guo et al., 2009; Kong & Goel, 2003).

In a detailed FE model that considered the stiffness of the spine from the head to the sacrum, the resonance frequency in the axial mode decreased further to 8.32 Hz. With the inclusion of muscles, the resonance frequency increased slightly to 8.91 Hz (Kong & Goel, 2003). The correlation between a number of motion segments and the first resonance frequency of the spine in the F-E mode was comparable to that of the axial mode. The fundamental frequency was around 4 Hz for one motion segment, and it decreased to 0.782 Hz for the T12-S1 spine FE model (Goel et al., 1994; Guo et al., 2009). The effect of spine injuries, including denucleation and removal of capsular ligaments, further reduced the resonance frequency to 0.733 Hz (Guo et al., 2009).

Although FE models can be used to predict the dynamic behaviour of the spine, explain the effect of mass, preload, and ligament stiffness; quantify strain and stress in spinal components, their evident limitation is the model's accuracy in yielding the actual natural frequency and the corresponding vibration mode. Previous experimental studies have reported that the fundamental frequency of axial mode lies between 4 to 6 Hz based on different subjects (Panjabi et al., 1986; Pope et al., 1987; Sandover, 1988). However, these in vivo studies applied measured sinusoidal input and impact on the subject, and the response of the spinal column was acquired.

The operational modal analysis (OMA) or as often called, ambient analysis) provides a much-needed tool for determining the dynamic characteristics of any system, mainly when input forces cannot be directly controlled or measured. This technique is based on the strict measurement of a system's output signals, which are directly or randomly excited by operating forces in an actual condition (Brincker et al., 2000; 2003). As a result, the dynamic characteristics of the human spine can be obtained using the OMA method because the modal decomposition is performed directly on the measured response without the input force information.

In this study, OMA was implemented to extract the modal parameters of the lumbar spine of a healthy subject without measuring the excitation applied to the patient. Data acquisition was performed on a healthy subject (H = 1.65 m, W = 58 kg) where uniaxial accelerometers were mounted on L4–L5 segments. The dynamic characteristics of the lumbar spine were obtained using the frequency domain decomposition (FDD) algorithm.

3 Method

This study performed OMA on a healthy subject (H = 1.65 m, W = 58 kg) undergoing jumping activity. The dynamic properties of the L4–L5 lumbar spine were obtained through measurements and post-data processing. The data acquisition was carried out using Bruel & Kjaer PULSE™ Multi-Analyzer System and the Modal Test Consultant™ (MTC) (Figure 1). The geometry of the lumbar spine structure was constructed to allocate the measurement points and capture the required modal data. The accelerometer Type 4508 with variable sensitivities ranging from 0.9994 mV/ms^{-2} to 1.025 mV/ms^{-2} was used. It can measure frequencies ranging from 0.1 Hz to 8000 Hz, and its resonance frequency is 25 kHz. The mass of the accelerometer was estimated to be 1/10 of the mass of the structure tested. The additional mass will add unwanted weight, leading to the deviation of the modal parameters of the test structure.

A. Bruel & Kjaer (B&K) Type 3560-D (Multichannel Portable Data Acquisition Unit)
B. Accelerometer Type 4508-B
C. Mounting Clip Type UA-1407
D. Laptop
E. LAN cable
F. Accelerometer Cables
G. Power Box Connector

Figure 1: Bruel & Kjaer PULSE™ Multi-Analyzer System connect to a computer with MTC™ and OMA Pro™ software.

Four (4) accelerometers, that is, 4 DOFs, were used in this study, where two accelerometers were mounted on each lumbar. Only one measurement was performed. Thus, only one data set was generated. Therefore, no reference accelerometer was needed. The spine was randomly excited for 112 s by the jumping activity of the subject. Fast Fourier transform (FFT) analysis was set up based on the needed frequency range of the spine (3–5 Hz), as reported in previous studies (Panjabi et al., 1986; Pope et al., 1987; Ruoxun et al., 2019; Sandover, 1988). The acceleration data consisting of geometrical values and measurement responses were then exported to the OMA Pro™ software for post-processing. In data post-processing, the FDD technique was applied. In this technique, the vibration modes can be determined from the computed spectral densities, and the modal parameters are obtained directly from the calculations in signal processing. The singular value decomposition (SVD) of each power spectral density matrix was used to construct the vibration mode for each resonance frequency. Figure 2 shows the flowchart of OMA in this study.

The quality of data obtained was considered in this experimental approach, and measures have been taken, particularly on the time required for data recording based on the minimum natural frequency value, the number of sensors, and other technical aspects, as suggested in a previous study (Anuar et al., 2018).

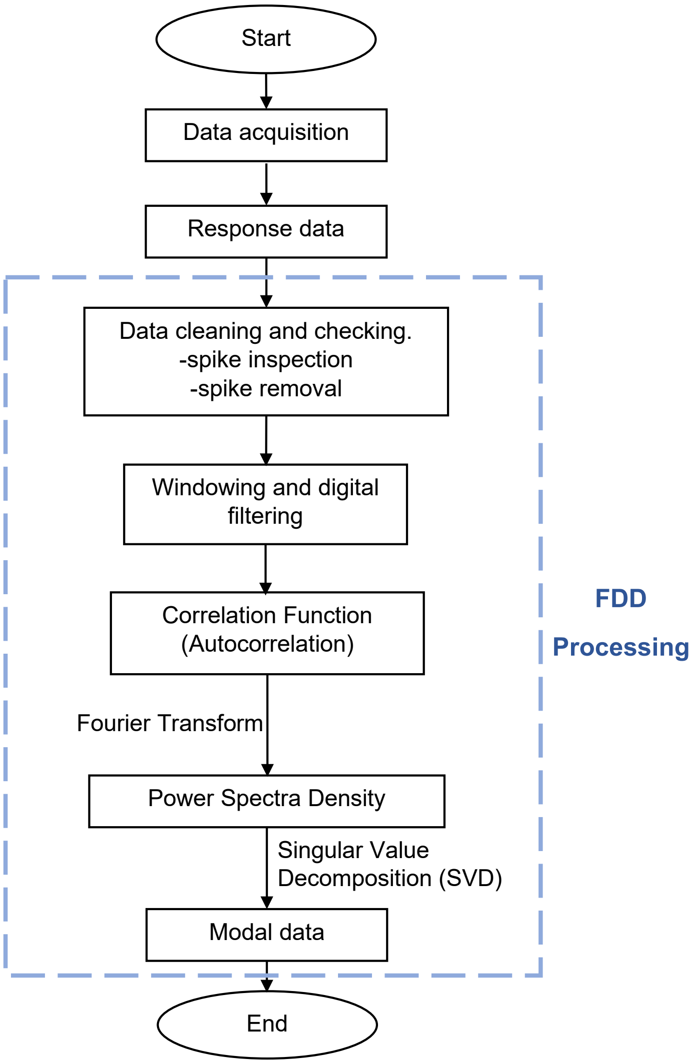


Figure 2: Flowchart of OMA.

4 Result and Discussion

Figure 3 shows the singular value of spectral density matrices, where the processed data from each structure condition are represented. Figure 4 illustrates the FDD peak-picking SVD plot for the spine structure. The principle of the FDD technique is the approximate decomposition of the system response into a set of independent single-degree-of-freedom systems, that is, one for each mode. The needed singular values and vectors were decomposed from each of the estimated spectral density matrices to identify the natural frequencies and mode shapes.

Initially, from the OMA Pro software, peak picking in the frequency domain was conducted automatically through the FDD technique. However, after the analysis of the results of the natural frequencies obtained by the automatic peak-picking technique, the values were determined to be not that relevant compared with the auto modal assurance criterion (AutoMAC). The dominant peaks were indicated and selected in the FDD peak-picking SVD plot, where several peaks were identified, providing approximately close modes. Therefore, for this case study, manual peak picking was preferred over automatic peak picking.

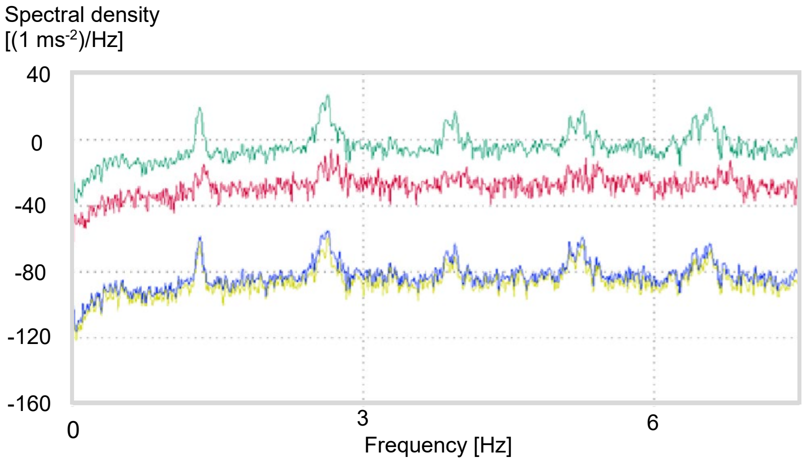


Figure 3: SVD of L4–L5 lumbar spine.

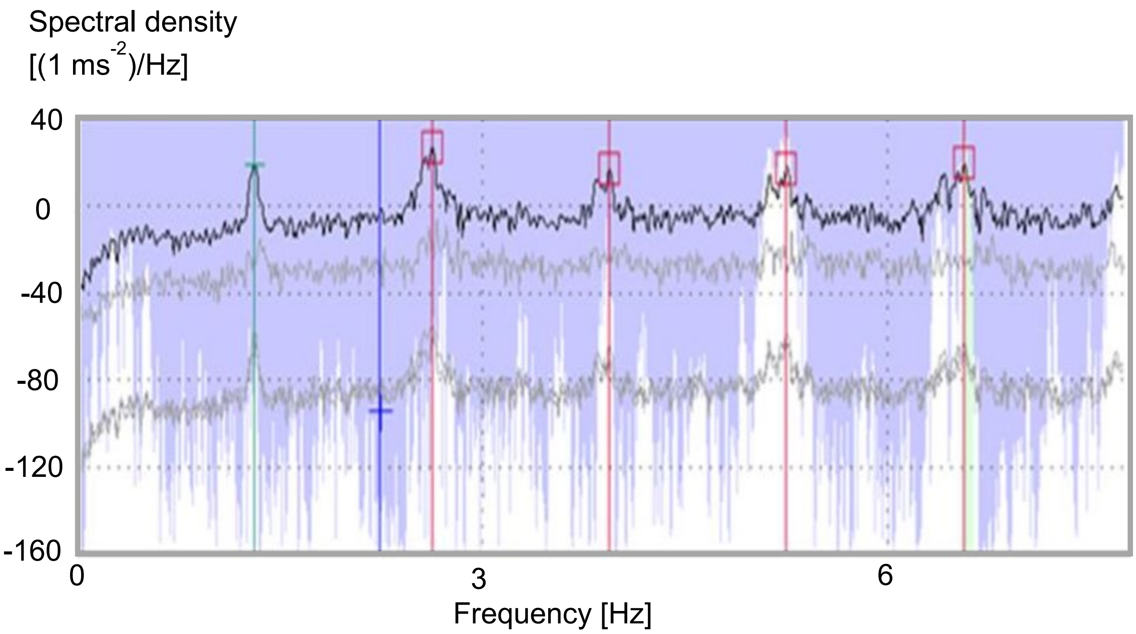


Figure 4: Peak-picking SVD plot of L4–L5 lumbar spine.

The AutoMAC is a value that validates the similarity of the mode shapes when comparing different modes. The AutoMAC value compares the vector for each coordinate of the mode shapes obtained. Table 1(a) shows the AutoMAC values of L4–L5 lumbar-spine vibration modes, where the degree of consistency between different modes shapes was compared. The AutoMAC values from manual peak picking produced a better result than the AutoMAC values from automatic peak picking. Table 1(b) shows the results of automatic peak picking with AutoMAC value comparison between modes. Several modes were repeated modes, as indicated by the red colour of the AutoMAC values. The AutoMAC value for the first vibration mode was close to 1 compared with the third and fifth vibration modes. However, compared with other vibration modes, the AutoMAC values for the second and fourth modes were significantly lower than 1. Thus, in this case, the modes were considered similar when the AutoMAC value was greater than 0.9 and presented as a single mode (Table 1(a)). Table 2 depicts the vibration modes of the L4–L5 lumbar spine and the corresponding natural frequencies concluded from the obtained AutoMAC values. The fundamental natural resonance frequency in the F-E mode was 1.31 Hz. In comparison, the fundamental natural frequencies for axial and A-P modes were 2.63 and 5.25 Hz, respectively.

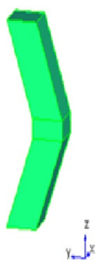
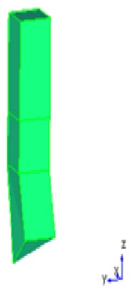
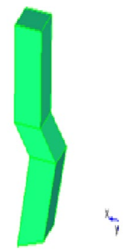
Table 1(a): AutoMAC values of different vibration modes of L4–L5 lumbar spine using manual peak picking.

	AutoMAC values		
Frequency	1.31 Hz	2.63 Hz	5.25 Hz
1.31 Hz	1	0.001358	0.035
2.63 Hz	0.001358	1	0.7058
5.25 Hz	0.035	0.7058	1

Table 1(b): AutoMAC values of different vibration modes of L4–L5 lumbar spine using automatically peak-picking.

Modal Assurance Criterion (MAC) values					
	1.31 Hz	2.63 Hz	3.94 Hz	5.25 Hz	6.57 Hz
1.31 Hz	1	0.001358	0.9304	0.035	0.977
2.63 Hz	0.001358	1	0.04993	0.7058	0.004752
3.94 Hz	0.9304	0.04993	1	0.007713	0.9239
5.25 Hz	0.035	0.7058	0.007713	1	0.01945
6.57 Hz	0.977	0.004752	0.9239	0.01945	1

Table 2: Vibration modes of L4–L5 lumbar spine and the corresponding resonant frequency.

	F-E	Axial	A-P
Vibration mode			
Frequency (Hz)	1.31	2.63	5.25

Long exposure to WBV causes a risk of injury to the lumbar spine (Guo & Teo, 2005). Previous statistical data have revealed that the risk of hospitalisation due to herniated lumbar disc increases for workers exposed to WBV (Wahlström et al., 2018). The frequency of excitation close to the resonant frequencies of the human body induced by operating transportation or machine may increase the effect on the lumbar spine vibration. An experimental study reported that the WBV at 5 Hz while seated increased creep and can cause the loss of height compared with sitting at a static position (Magnusson et al., 1992). Therefore, investigations that determine the specific dynamic characteristics of the lumbar spine are essential to gain insights into the correlation between vibration and spinal injuries.

Several studies have been conducted to obtain the resonant frequency of the spine at a particular vibration mode experimentally and via numerical modelling. Numerous FE models were developed to simulate the vibration mode of a single motion segment, multiple motion segments and the entire spine. The resonant frequency in axial mode was between 8 and 27 Hz depending on the number of motion segments, model complexity (ligament and muscle modelling), preload and carrying inertia (Schmidt et al., 2013). The FE models also demonstrated that spine diseases, such as scoliosis and spine injuries, denucleation and capsular ligament removal, have further altered the frequency of the spine (Guo et al., 2009; Jia et al., 2019). Jia et al. constructed the S1-L1 spine model, which revealed that scoliosis decreased the resonant frequency from 9.2 Hz (healthy spine) to 3.9 Hz (Jia et al., 2019). A reduction in resonance frequency was also observed for the injured spine, where the fundamental resonant frequency in the vertical direction decreased from 7.68 Hz for an intact model to 6.65 Hz for injured models (Guo et al., 2009).

Experimental studies revealed that the resonant frequency (F-E and axial mode) of the spinal column was measured in the range between 1–6 Hz (Jia et al., 2019; Meyer et al., 2004; Wilder et al., 1982). In these studies, however, the subjects were excited with seated vertical sinusoidal vibration and impact. The modal parameters were extracted from the amplitude ratio or transfer function of the spine vibration to the vibration of the seat. The experimental setup can be costly and complex. Hence, this limitation motivated the present study. We examined the efficacy of OMA to predict the fundamental resonance frequency of the lumbar spine from an actual loading condition of the subject, such as jumping activities. The accelerometers only measured the output vibration of the lumbar spine. The excitation was assumed to be generated by stochastic loads from the noisy ambient condition (Storti et al., 2021). The resonant frequency of the L4–L5 lumbar spine was acquired in the range between 1–5 Hz for the first to fifth vibration modes, respectively. The computed resonant frequency in the F-E direction was 1.31 Hz, which is in agreement with that of Meyer et al. (1.4 Hz) (Meyer et al., 2004).

By contrast, for the axial mode, the resonant frequency was 2.63 Hz, which is far less than the previous findings (4–6 Hz) (Panjabi et al., 1986; Pope et al., 1987; Sandover, 1988). This discrepancy may arise due to the different body masses of the test subjects; the FE models have revealed that the carrying inertia considerably affected the spine resonant frequency (Guo et al., 2005; Schmidt et al., 2013). To a certain extent, human spine motion is determined by the combined physical properties of the intervertebral discs, facet joints, ligaments, surrounding tissues and muscles (Qiao & Rahmatalla, 2020). These collective physical properties may vary for different subjects. In OMA data acquisition, the quality of modal data is attributed to the signal-to-noise ratio (S/N), where the desired signal level is compared with respect to the unwanted background signal or noise. The desired signal provides essential information to extract the modal parameters compared with the background noise (Anuar et al., 2018). The results showed a decent S/N (80–90 dB) (Figure 3).

The present study encountered several limitations. This study was carried out as a preliminary stage to examine the potential of OMA in extracting the biodynamic properties of the human lumbar spine. Only one healthy subject was tested to study the response of the lumbar spine under ambient conditions. A more significant number of subjects should be tested to measure a normal range of spine modal parameters. In addition, only one actual (exercise) condition was studied. Different actual conditions, e.g. walking or running on a treadmill, can be studied to investigate the robustness of this method. In the future, this method can be performed to study the effect of spinal injuries and implants on the lumbar spine biodynamic characteristics.

5 Conclusion

This study presented an OMA method to measure the fundamental frequency of the human lumbar spine. The dynamic characteristics were obtained using OMA, which revealed that the natural frequencies of the F-E and axial modes were 1.31 and 2.63 Hz, respectively. The findings showed that this method can produce reasonable results based on comparisons with previous experimental works. Further studies study should be conducted to improve this method using various algorithms. This work paves the way for future research on the use of modal analysis techniques for spine health monitoring.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

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