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Nonlinear dynamics of the human lumbar intervertebral disc

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ABSTRACT

Systems with a quasi-static response similar to the axial response of the intervertebral disc (i.e. progressive stiffening) often present complex dynamics, characterized by peculiar nonlinearities in the frequency response. However, such characteristics have not been reported for the dynamic response of the disc. The accurate understanding of disc dynamics is essential to investigate the unclear correlation between whole body vibration and low back pain. The present study investigated the dynamic response of the disc, including its potential nonlinear response, over a range of loading conditions. Human lumbar discs were tested by applying a static preload to the top and a sinusoidal displacement at the bottom of the disc. The frequency of the stimuli was set to increase linearly from a low frequency to a high frequency limit and back down. In general, the response showed nonlinear and asymmetric characteristics. For each test, the disc had different response in the frequency-increasing compared to the frequency-decreasing sweep. In particular, the system presented abrupt changes of the oscillation amplitude at specific frequencies, which differed between the two sweeps. This behaviour indicates that the system oscillation has a different equilibrium condition depending on the path followed by the stimuli. Preload and amplitude of the oscillation directly influenced the disc response by changing the nonlinear dynamics and frequency of the jump-phenomenon. These results show that the characterization of the dynamic response of physiological systems should be readdressed to determine potential nonlinearities. Their direct effect on the system function should be further investigated.

1. Introduction

The mechanical response of the intervertebral disc (IVD) is due to the interaction, composition and structural organization of its components at different scales. This provides unique load bearing abilities to the disc and a flexibility that is often referred to as nonlinear, i.e. progressive stiffening (White and Panjabi, 1978). In particular, the uniaxial quasi-static response resembles the mechanics of stiffening systems, where the stiffness increases with the deformation. Several studies have investigated the disc response for different loading scenario. In particular, past studies were focused on the quasi-static and low frequency (<10 Hz) response to pure and combined cyclic loading (Costi et al., 2008; Koeller et al., 1986; Walsh and Lotz, 2004). However, such loading conditions are only partially representative of the in-situ loads that the IVD normally experiences. During occupational whole body vibration (WBV), a combined static and dynamic load acts on the spine. The internal static load is determined by the body mass, posture and the load bearing due to the task-specific payload or equipment. The dynamic load is caused by the high frequency stimuli of the body due to machine vibrations or schocks from the environment (Seidel et al., 1998). Low back pain disorders are often related to WBV, with a direct influence on the IVD. Long-term exposure was seen to be detrimental to normal disc metabolism (Bovenzi and Hulschof, 1999; Urban et al., 2004), whereas short term exposure to high frequency and large amplitude hydrostatic stress was reported to be beneficial for protein synthesis and reduction of protein degradation (Kasra et al., 2003). Although the guidelines proposed by the International Organization for Standardization (ISO-2631-1, 1997; ISO-2631-5, 2005) establish threshold values for daily vibration dose, the precise relationship between vibration dose values and risk of injuries is unclear (Mansfield, 2005). Further, comparison of evaluations and assessments methods, suggested by these standards, reveals discrepancies in the chosen evaluating parameters, and proposed daily exposure limits (Griffin, 1998). Since in-vivo studies evaluate the risk based on the individual perceived parameters (i.e. level of discomfort, perception of vibration) (Thamsuwan et al., 2013), potential vibration-induced injuries could be not perceived if they do not involve nervous receptors. Studies have suggested fatigue failure of vertebral endplates by WBV as cause of subsequent degenerative changes of the lumbar spine, and in particular of the

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IVD (Huber et al., 2010; Sandover, 1998; Schwarze et al., 1998). Therefore, the objective characterization of IVD dynamics is extremely relevant to reduce the risks of degenerative processes triggered by exposure to high frequency loading. However, these studies which have investigated the IVD dynamics provided different outcome with respect to the frequency range of the vertical mode (Izambert et al., 2003; Kasra et al., 1992). This could be due to nonlinearities of the system oscillation which normally affects the dynamic of systems with similar nonlinear quasi-static response. The aim of this experimental study was to investigate the nonlinear dynamic response of human IVDs. The influence of the amplitude of the stimuli and the preload on the oscillation was a specific focus of the study.

2. Material and methods

2.1. Cadaveric material and its screening

Twelve male human cadaver lumbar spines (T12-S1) were harvested at autopsy (Institute for Forensic Medicine, University Medical Center Hamburg-Eppendorf, Hamburg, Germany). They were sealed in plastic bags and stored at -20 °C. Frozen specimens were scanned by computed tomography scanner (Brilliance 16, Philips Healthcare, Hamburg, Germany, settings: 120 kVp; 1 mm slices). The CT-images of the tested specimens were segmented to evaluate the area of the inferior and superior disc boundary, and the volume of the disc. The disc height was calculated by dividing the volume by the mean boundary area. Mean gross morphology data, age, and classification of each specimen are reported in Table 1.

2.2. Specimen

Before testing, each spine was thawed overnight at room temperature. On the day of testing muscle tissue and posterior elements were removed. The anterior and posterior longitudinal ligaments were kept intact. Superior and inferior vertebra were accurately clean to expose the cortical bone. To improve fixation between the vertebrae and the mould, screws were inserted into the vertebrae. The specimen was then embedded cranially and caudally in two steel cups with polymethylmethacrylate (Technovit® 7100, Heraus Kulzer GmbH, Wehrheim, Germany). The specimen position was adjusted to align the disc's longitudinal axis to the vertical direction of the test fixture. IVDs were kept moist by spraying with Ringer solution and by wrapping with wet gauze. After the mechanical testing, the specimens were cut in the mid sagittal plane, photographed, and degeneration degree graded (Thompson et al., 1990). The disc was then scraped off the vertebra to reach the endplates and macroscopically assess them for fracture.

2.3. Setup dynamic test

A test fixture was designed to duplicate a base excitation model, where the upper part of the body was simulated by a dead weight, referred to as the preload (m), and a cyclic displacement (y) was applied at the bottom of the specimen (Fig. 1a–c). The preload was applied by weights ($m/4$) fastened to a four-arm crossbar fixed to the top embedding cup. Four pillars structurally coupled the motion of the bottom embedding cup to the top mounted actuator of a servo-hydraulic machine (MTS® Bionix, USA). To limit the vibrational degree of freedom to the longitudinal direction, a guiding cylinder was mounted on the top embedding cup, and its oscillation was constrained by eight Teflon holders fixed on the pillars. Silicone lubricant was sprayed on the contact surfaces to reduce friction. Accelerometers (4508 B 004, Brüel & Kjaer, Nærum, Denmark) recorded the acceleration (sampling frequency 11 kHz) of the disc ($\ddot{x}$) and the frame ($\ddot{y}$). A camera system (VICON®, Oxford, United Kingdom) tracked the displacement of markers on the disc (two markers) and on the frame (one marker). The volume of view was adjusted to achieve 400 fps.

2.4. Test protocol

Before the dynamic test, a quasi-static compression-tension test was performed to precondition the specimen and to obtain the nonlinear quasi-static response (five cycles, compression 1000 N, tension 200 N, displacement rate 0.09 mm/s). The setup for the test is illustrated in Fig. 1d.

According to the base excitation model, the dynamic test was performed by applying a sinusoidal displacement to the lower embedding cup (y). The displacement amplitude (y_i) was kept constant and the system was driven by a sinusoidal sweep function:

$$y = y_i \ \sin(2\,\pi\, f(t)\, t)$$

The frequency was set to increase linearly from a low frequency to a high frequency boundary (Increasing Frequency Sweep, IFS) and back down (Decreasing Frequency Sweep, DFS). The frequency sweep rate was set to 0.1 Hz/s, after verifying that it was low enough to have a transient steady response of the system. The frequency range was defined by the analysis of the last cycle of the quasi-static test, which was force-averaged. For small stimuli the dynamic of nonlinear system can be approximated with linear model, hence, assuming a linear undamped model, the ideal resonant frequency would be given by:

$$f_{id} = \frac{1}{2\pi}\sqrt{\frac{k_{\text{preload}}}{\text{preload}}}$$

The initial frequency range was defined by $f_{id} \pm 6$ Hz (value defined during the pilot study). The influence of the preload was investigated by repeating the dynamic test with different weights, from 16 kg to 56 kg in steps of 10 kg. For each preload, different y_i were used: 0.1 mm, 0.1 mm, 0.15 mm, 0.2 mm 0.15 mm, 0.1 mm, 0.1 mm. After the test with 56 kg-preload, a test with 16 kg-preload and y_i of 0.1 mm was repeated three times. Tests were coded [preload]kg–[y_i]mm, e.g. 36 kg–0.1 mm. Three minutes were allowed for creep to occur after the application of each load increment.

Table 1
Characteristics of the tested specimens with the classification based on the comparison of the quasi-static test before and after the dynamic tests (specimen status, I=*intact*, F=*failed*, FE=*failed-endplate*), and on the dynamic response exhibited in the test sequence (*H*=*hardening*, *S*=*softening*).

No.	Age (yr)	Disc level	Disc grade	Volume (mm^{-3})	Height (mm)	Status	Dynamic response
1	21	L2L3	1	12,921	8.5	*F*	H+S
2	21	L4L5	1	16,261	10.7	*I*	*S*
3	28	L1L2	1	14,491	9.8	*I*	H+S
4	31	L1L2	1	14,504	9.9	*F*	H+S
5	31	L4L5	1	16,565	11.1	*I*	H+S
6	34	L2L3	3	9,794	6.4	*F*	H+S
7	34	L4L5	3	11,367	7.1	*I*	H+S
8	35	L2L3	1	14,319	8.7	*F*	H+S
9	35	L4L5	1	17,208	9.6	*I*	H+S
10	39	L2L3	2	15,052	10.5	*F*	H+S
11	39	L4L5	2	16,717	10.8	*I*	*S*
12	47	L2L3	2	22,739	10.8	*FE*	H+S
13	47	L4L5	2	20,974	10.2	*FE*	S
14	56	L2L3	3	13,284	8.7	*FE*	H+S
15	56	L4L5	3	9,839	6.4	*F*	H+S
16	61	L4L5	2	12,095	7.4	*I*	H+S
17	63	L2L3	3	18,926	9.6	*FE*	H+S
18	63	L4L5	3	20,185	10.2	*I*	*S*
19	67	L2L3	2	14,099	8.5	*FE*	H+S
20	67	L4L5	2	17,407	9.6	*FE*	S
21	69	L2L3	3	10,399	7.9	*FE*	H+S
22	69	L4L5	3	10,184	7.1	*F*	H+S