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Is vibration truly an injurious stimulus in the human spine?

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ABSTRACT

Epidemiological data at one time was taken to suggest that chronic vibrations—for example operating vehicles with low-quality seats—contributed to intervertebral disc degeneration and lower back pain. More recent discussions, based in part upon extended twin studies, have cast doubt upon this interpretation, and question how much of the vibration is actually transmitted to the spine during loading. This review summarizes our recent survey of the current state of knowledge. In particular, we note that current studies are lacking a detailed factorial exploration of frequency, amplitude, and duration; this may be the primary cause for inconclusive and/or contradictory studies. It is our conclusion that vibrations are still an important consideration in discogenic back pain, and further controlled studies are warranted to definitively examine the underlying hypothesis: that chronic vibration can influence IVD cell biology and tissue mechanics.

1. History and background

The relationship between vibrations and low back pain has been studied since the 1950s (Hulshof and van Zanten, 1987; Cardinale and Pope, 2003). The main goal of those early studies was to mitigate low back pain often experienced by workers sitting and driving for long periods of time. However, the results of subsequent epidemiological studies have been somewhat mixed. When healthy (asymptomatic) individuals were compared with operators of heavy earth-moving machinery in an age-matched cohort, no differences were found with respect to water content, disc height, viscoelastic behaviour, strength of the vertebrae as indicated by water content (MRI), or bone density (QCT) (Drerup et al., 1999). Similarly, when clinical and MRI assessment was performed on asymptomatic tractor driving farmers and a matched cohort, no difference was found in the degeneration of the spine (Kumar et al., 1999). In contrast, professional drivers have an increased risk of being hospitalized due to spinal disorders, with bus and long-haul truck drivers having more frequent spinal disorders than other truck drivers, potentially due to their increased exposure (Jensen et al., 2008).

Further confounding the issue, recent developments in therapeutic devices have suggested that some vibrations may actually have a beneficial effect. Various studies have indicated a reduction of spine-related pain (Desmoulin et al., 2007; Foundation, 2009) and an increase in disc height (Holguin et al., 2009).

The intervertebral discs (IVDs) are the flexible elements of the vertebral column, permitting mobility and providing space for radiating nerves and arteries (Bogduk and Endres, 2005; Raj, 2008). Degenerative disc disease is a progressive condition wherein the biochemical composition and morphology of the discs change, resulting in reduced disc height, herniation, and/or stenosis of the cord space (Wiesel and International Society for Study of the Lumbar Spine, 1996; Raj, 2008). There is ample evidence that a significant fraction of low back pain patients have concurrent disc degeneration and that these discs are a root cause of pain (Zhou and Abdi, 2006; Edgar, 2007; Raj, 2008). It is worth noting, however, that not all degenerative discs are symptomatic, and vice-versa (Bogduk and Twomey, 1987; Griffiths, 1991; Wiesel and International Society for Study of the Lumbar Spine, 1996; Bogduk and Endres, 2005). Therefore, any general consideration of low back pain should pay close attention to the discs, but not exclusively. For the purposes of this report we will focus on 'discogenic' back pain, i.e. those symptomatic individuals with a clear disc-related cause. Hence, degeneration of the disc becomes the critical factor in our consideration and the effect(s) of mechanical vibration on these discs is our focus.

It is imperative that we better understand the potentially harmful or helpful effects of vibrations on IVD health. It has been suggested that further research on the subject be abandoned (Lings and Leboeuf-Yde, 2000; Battie et al., 2009) (also personal communications with various researchers), as prophylactic techniques (such as modified seats) are diminishing the importance of the effects of vibrations, but this report will show that there is still substantial confusion surrounding the effects of vibrations in the IVD. Epidemiologically, it is important to understand whether

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mechanical forces can influence disc health. From a therapeutic perspective, we must understand whether vibrations can have a long-term biological effect. Finally, we must understand the dynamic mechanical properties of natural and engineered discs, as every effort should be made to minimize adverse effects on the adjacent tissues (i.e. by transferring dynamic loads).

Therefore, the aim of this report is to summarize the critical findings to date, indicate existing deficiencies in the state of knowledge, and argue that further careful study of vibration in the IVD is of vital importance to progress on numerous fronts.

2. Regulatory guidelines

The resonance frequency is the frequency at which there is the least attenuation of applied vibrations; this frequency is considered the most dangerous to structures, as the highest anatomical displacements are experienced here. Several studies have established widely accepted resonant frequencies of the human body in the vertical direction. Notable values include: human body, 3–7 Hz (Kumar et al., 1999); human trunk, 4–8 Hz (Kumar et al., 1999); and lumbar vertebrae, 4.4 Hz (Panjabi et al., 1986; Broman et al., 1991; Kumar et al., 1999).

The most common situation in which vibrations are applied to the human spine is driving but building vibrations and vibrations from ground reaction forces are also transmitted to the spine through connective tissues (Yamazaki et al., 2002). The resonant frequencies mentioned above fall within the average range of vibrations produced in common environments:

- 0.1–0.6 Hz causes motion sickness (Safety, 1998)
- Forklifts/bulldozers/tractors: 1–7 Hz (Kumar et al., 1999) (0.4–2.3 m/s^2; Safety, 1998)
- Ford focus: 2–30 Hz (Qiu and Griffin, 2004)
- Stationary equipment and buildings: >20 Hz (Seidel et al., 1986)
- Physiotheraphy systems 18–180 Hz (Rittweger et al., 2002a; Abercromby et al., 2007a, 2007b; Desmoulin et al., 2007)

The International Standards Organization (ISO) has established a standard for evaluating human exposure to whole-body vibrations (ISO 2631). In general, the standard addresses the evaluation of translational whole-body vibrations for standing, sitting, or recumbent humans between 0.5–80 Hz (Griefahn and Brode, 1999). Accelerations in the inferior–superior, medio-lateral, and anterior–posterior directions are combined and the resultant acceleration is evaluated. The standard presents comfort contours for separate vertical and lateral vibrations, as well as for simultaneously applied vertical and lateral vibrations. This standard also addresses the Reduced Comfort Boundary, the Fatigue Decreased Proficiency Boundary, and the Exposure Limit. The Fatigue Decreased Proficiency Boundaries indicate the frequency, amplitude, and exposure duration wherein job performance becomes impaired due to fatigue from vibrations. To determine the Exposure Limit, the value of the Fatigue Decreased Proficiency Boundary (the maximum tolerable duration of exposure) is multiplied by 2 (Inc., 2003). As of 1986, the exposure limits suggested by this ISO regulation were above frequencies shown to cause injury in humans (Seidel and Heide, 1986). A separate validation study also suggests that the ISO regulations are qualitatively correct but require further quantitative refinement (Griefahn and Brode, 1999). There does not appear to be any regulations regarding rotational vibrations. However, rotational vibrations are not functionally experienced by humans; rather they are the secondary result of vibrations applied in other directions.

3. The scientific basis for vibrations as harmful stimuli

Large population studies of workers exposed to vibrations were very popular in the 1980s. Unfortunately, these studies often neglected control groups, making it very difficult to extract credible results from them (Seidel et al., 1986; Seidel and Heide, 1986; Lings and Leboeuf-Yde, 2000). More recent epidemiological studies have either retro-actively re-evaluated prior data or performed new studies to include controls, and have provided more insight regarding the effects of long term exposure to vibrations in the workplace on the IVD (Lings and Leboeuf-Yde, 2000).

The most common types of computational models used to predict the behaviour of the IVD under vibrations are 3D FEM models. These models typically correlate well with results obtained from measurements on cadaveric motion segments. However, many simplifications are often made to render the model computationally feasible; the influence of surrounding soft tissues is almost always neglected and posterior elements (including ligaments and facet joints) are usually removed. While these studies provide a general understanding of the effect of vibrations on the IVD, their results are currently not truly representative of in vivo behaviour.

The effects of a wide range of vibrations at the cellular level have recently been well investigated. Several disadvantages of in vitro studies are that the influences of the anatomic structures of the disc (i.e. annulus lamellar structure) are lost, and that cellular studies are most often done on animal models. However, these studies often give insight into the potential cellular mechanisms of degeneration and biosynthesis in the disc.

In vivo studies are the most physiologically relevant but are also most difficult to perform. Very few of these studies have been performed, due in part to ethical considerations around internally measuring accelerations of the spine. Some studies classified as in vivo in this report actually measured body or spine accelerations outside of the spine, but differ from epidemiological studies in that they did not have a very large sample population. The recent trend towards measuring accelerations externally makes these in vivo studies much more feasible.

4. Effects of vibration parameters

In order to fully understand how/whether vibrations affect the human IVD, the individual effects of vibration and subject parameters must be isolated. There are at least three key parameters that characterize any simple vibration: frequency, amplitude, and duration of exposure, plus related factors including axis of loading and the state of surrounding anatomical structures. Therefore, let us examine each in turn.

5. Frequency

Virtually all vibration frequencies to which humans may normally be exposed have been investigated using one of the 4 types of studies discussed above. Combined together, these studies suggest that frequencies close to the resonant frequency of the human spine (4–5 Hz) should be avoided, as these are the most damaging vibrations. Fluid volume fluctuations (Cheung et al., 2003) and viscous damping (Izambert et al., 2003; Guo et al., 2005, 2009b) are significant in this range suggesting significant mechanical energy transfers to the disc.

Mid-frequency vibrations (18–30 Hz) applied in vibration exercise programs have been shown to decrease low back pain (Rittweger et al., 2002b). Damping decreases in this range