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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 suggesting greater load sharing between the tissues and structures of the spine (Izambert et al., 2003).

These studies further suggest that vibrations at high frequencies (20–300 Hz) encourage biosynthesis in the IVD. In at least one study, high amplitude/high frequency vibrations stimulated collagen synthesis in rabbit annulus cells, while low amplitude/low frequency vibrations had no effect. The high amplitude/high frequency vibrations also increased protein synthesis and decreased degeneration in 3D rabbit nucleus culture. However, the effect of vibration frequency was significant only at high amplitudes (Kasra et al., 2003; Desmoulin et al., in press). Interestingly, at least two clinical treatments use vibrations applied between 18–80 Hz to decrease low back pain; results have shown success comparable to that obtained using conventional physiotherapy (Rittweger et al., 2002a, 2007b; Desmoulin et al., 2007).

6. Amplitude

Several studies suggest that the mechanical behaviour of the IVD when exposed to vibrations is independent of the amplitude of the vibrations. One in vivo study applied vibration amplitudes of 1 and 3 m/s^2 and found no differences in the transmittance of vibrations to the subjects (Panjabi et al., 1986). Similarly, the amplitude of impact applied to the human seat by a pendulum had no effect on the peak transmissibility or attenuation as measured in vivo at *L*3 (Broman et al., 1991).

These accelerations are representative of the accelerations typically studied in vivo. In vitro studies often use 0.1 G ($\sim$1 m/s^2), which is a very functionally relevant amplitude but may not adequately represent the range of accelerations that humans are exposed to. An experiment using rabbit hip and knee articular chondrocytes used 1.4 G vibration ($\sim$14 m/s^2) (Liu et al., 2001) frequencies above 400 Hz suppressed DNA synthesis in the chondrocytes. This suggests that the amplitude of the vibrations may have no effect on the disc's mechanical response. However, vibration amplitude may have an effect on the cellular response of the IVD; an increase in protein synthesis and decrease in degeneration was observed at high loading amplitudes in 3D rabbit nucleus cell cultures (Kasra et al., 2003). Similarly, an increase in mRNA expression for various extracellular matrix genes was found in bovine organ cultures (Desmoulin et al., in press).

7. Axis of loading

Relatively little research has been done on the responses of the spine subjected to vibrations in different (off-axis) orientations. The vast majority of the studies applied vibrations in the vertical (superior–inferior) direction. Some insight into the relationship between vertical and lateral vibrations has been given by studies validating the ISO 2631 regulations surrounding vibrations applied to the human body.

Horizontal and rotational vibrations induced by vertically applied vibrations have been investigated. When sinusoidal frequencies between 2–15 Hz were applied in the vertical direction, both horizontal and rotational accelerations were observed. However, there was no horizontal resonance frequency and rotational accelerations were highly dependent on the individual (Panjabi et al., 1986). In a study during which subjects were asked to match an applied lateral vibration to a previously induced lateral vibration (calculated from an applied reference vertical vibration by ISO 2631 methods), it was shown that sensitivity to lateral vibrations is considerably greater than predicted by ISO 2631 (Griefahn and Brode, 1999). In a study of the effects of whole-body vibration training, often used to increase leg muscle strength, bone density and decrease back pain, it was found that the transmission of vibrations from the feet to the upper body and head while standing was 71–189% greater in vertical vibrations than in rotational vibrations (Abercromby et al., 2007a, b). However, it should be noted that these whole-body vibration studies were quite subjective, as they used a subject's perception of equivalent vibrations to compare vibrations in the vertical and lateral directions.

8. Duration of exposure

The effect of exposure length on degeneration of IVDs has been studied extensively at the whole-body level. Several epidemiological studies have shown a relationship between increased low back pain and long-term exposure to vibrations in the workplace, but clinical evaluation shows no underlying structural cause of this relationship.

Several cell-level studies have shown that increased exposure to vibrations results in inhibitory cellular effects, such as decreased protein synthesis (Kasra et al., 2003), aggrecan expression (Yamazaki et al., 2002), water content (Hirano et al., 1988), and metalloproteinase expression (Yamazaki et al., 2002). However, increased ATP release (Yamazaki et al., 2003) and DNA synthesis (Weinhold et al., 2000) over short periods of vibration exposure would suggest that there is an optimum exposure length which may encourage disc biosynthesis; exposure times beyond this optimum level increase degeneration.

9. Anatomical structures

The effects of various structures in the spine subjected to vibrations are studied by removing them in cadaveric samples and models. Posterior elements, ligaments, and facet joints are usually neglected to simplify computer models of the spine but the effect of a nucleotomy has also been modeled. Removal of the posterior elements decreased the resonance frequency of cadaveric *L*2/*L*3 segments (Kasra et al., 1992). Nucleotomy similarly reduces the resonance frequency in 3D finite element models (Kasra et al., 1992; Guo et al., 2005). Overall, it appears that the discs are the dominant structure in the vertebral column's response to vibrations (Guo et al., 2009a, 2009b).

It has been found that different regions of the spine respond and deform differently when exposed to vibrations. 3D non-linear poroelastic finite element models of an *L*4 and *L*5 lumbar motion segment based on a CT of an asymptomatic healthy subject showed a non-uniform change in anterior–posterior disc height and a decrease in disc fluid volume during vibration. This in turn decreased lordosis, which decreased facet joint loads until 40 min into applied vibrations, when the facet joint loads increased again as the disc started to deform evenly. The decrease in fluid content was 4 times that experienced under static loading, and fluid loss from the nucleus was greater than from the annulus (Cheung et al., 2003). The effects on the facets were somewhat conflicted by a separate study, which found that posterior vibration amplitudes were larger than anterior vibration amplitudes in 3D non-linear finite element model of *L*3–*L*5 (Guo et al., 2005).

Lastly, it is worth noting that the IVD is not the only spinal structure, which may respond to vibrations with biological changes. While this review has focused on the disc and long-term changes, other tissues have been shown to undergo short-term change, which may affect pain. For example, the vertebrae are moved during vibration, in turn stretching the attached muscles, tendons, and ligaments. Previous animal models have shown that cyclic tension of vertebral tendons results in decreases to gamma motor neuron input mediated by Renshaw cells (Pompeiano et al., 1975; Fromm and Noth, 1976; Fromm et al., 1976; Rymer and Hasan, 1981). These studies further indicated that the inhibition increased as vibration frequency increased. The frequencies tested ranged from 100 to 300 Hz. Pompeiano and coauthors discovered that Renshaw cell activity was maximized at frequencies between 150 and 250 Hz (Pompeiano et al., 1975). Pompeiano used amplitudes ranging from 180 μm to 12 mm, none of which showed a difference in Renshaw cell activity; hence the phenomenon may be frequency dependent and displacement independent. Furthermore, as gamma motor neuron input decreases, so does the stretch reflex input for contraction. It has been shown that this reflex activity entering the medial branch of the dorsal ramus at one spinal level causes similar activity across 1 or 2 adjacent levels (Kang et al., 2002).

10. Conclusions

Ultimately, it is clear that the issue is very complex. The axis, frequency, amplitude, duration, and surrounding tissue health can all influence the spine's response to vibration. The time-average of these responses is bound to be intricate, as it would be exceedingly rare for an individual to experience a single vibration over the timeframes involved in degenerative disc disease. Moreover, vibrations that have long-term negative biological effects on the connective tissues could have short-term positive effects on the nocioceptive fibers (or vice versa).

There is a long history of investigations to determine the effects of vibrations on the human spine. However, clinical data has been confusing, with widely mixed results and conflicting conclusions.

Taken collectively, the data surveyed in this report suggest that the effect of vibrations may be highly dependent upon the frequency, amplitude, axis, and duration of exposure, among other factors. Furthermore, the interactions between the IVD and facets may be significant, in that the facets may change segmental dynamics, and vibrations may cause altered loading of the facets.

This is perhaps the most critical factor when considering these epidemiological studies. If we consider the "parameter space" of vibration studies, even the simplest vibration is characterized by at least three parameters: frequency (f), amplitude (a), and duration (t). Most epidemiological studies and many laboratory studies explore only a small portion of this space. If a certain patient population experienced one region of the f–a–t space, while another was somewhere else, and a third in vitro study was in yet another region, how can these studies be effectively compared? Moreover, the actual values of f–a–t were rarely characterize in epidemiological studies; 'truck drivers' were lumped together, independent of whether they experienced the same vibrations. Therefore, a positive effect on one subgroup could have easily masked a negative effect on another resulting in a null result. It is imperative that these complex issues be better explored.

It has been suggested that research in the area be abandoned and resources be focused on "more important" issues (Lings and Leboeuf-Yde, 2000); however, it is clear that the effect of vibrations on the IVD are very complicated and not fully understood. At best, we can conclude that some vibrations are not overtly harmful, in that they do not statistically correlate to the incidence of reported discogenic back pain. However, this does not mean that all vibrations are harmless nor does it eliminate the possibility that harmful effects are being masked by other factors in epidemiological studies.

Therefore, it is our considered opinion that further study is required to isolate the effects—beneficial or harmful—of vibrations in the human spine.

Disclosure

Ms. Hill received no compensation for this work. Mr. Desmoulin is the Associate Research Director of Optima Health Solutions, which produces and distributes the Khan Kinetic Treatment system. Dr. Hunter received a research contract from Optima Health Solutions in 2008–2010.

Conflict of Interest

Christopher J. Hunter hereby affirms that there are no undisclosed affiliations and that there are no conflicts of interest in the study. Christopher J. Hunter affirms that all authors have been involved in the study and preparation of the manuscript, and that it has not and will not be submitted for publication elsewhere.

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