The Biomechanics of Vibration and Low Back Pain

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This work is a review of the mechanical factors related to low back pain production in a vibration environment. The sitting posture is an extreme orientation for the lumbar intervertebral disc that 1) increases its internal pressure, 2) increases its anteroposterior shear flexibility, while: 3) decreasing its resistance to buckling instability and 4) stressing the posterior region of the disc. Vibration is an additional mechanical stressor. Several studies suggest that the following preventive measures be taken to reduce the risk of low back pain due to driving: 1) minimize the vibration reaching the driver, 2) avoid lifting or bending immediately following driving, and 3) walk around for a few minutes following driving.   © 1993 Wiley-Liss, Inc.

Key words: whole-body vibration, instability, sitting, truck driving, vehicles, disc herniation, prevention, repetitive motion disorder, cumulative trauma, unexpected loads, pregnancy

INTRODUCTION

Controlling the environment associated with the production of disabling low back pain is a challenge involving anatomic, industrial, behavioral, and environmental factors. This work focuses on the mechanical factors associated with low back pain in a vibration environment that could result in easily implemented accommodations. This is important because low back pain is one of humanity's most disabling conditions [Kelsey et al., 1979] and has a significant economic impact on society. The cost of low back pain annually in the United States ranges from $16 billion to $50 billion [Frymoyer, 1990].

All materials, whether they are man-made or biological, are sensitive to their load exposure history. Engineers and trauma surgeons are especially aware of this concept. Load history can take many forms for low back pain as its risk factors include: heavy lifting, use of jackhammers or machine tools, operation of vehicles, and pregnancy [Frymoyer et al., 1983; Andersson, 1990].

Epidemiologic work [Frymoyer et al., 1983; Hulshof and van Zanten, 1987; Bongers and Boshuizen, 1990] indicates significant association of the low back complaint with exposures to both industrial and nonindustrial (particularly vehicular) vibration. The Centers for Disease Control [1983] concur that back pain and verte-

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brogenic pain may be associated with whole-body vibration. Heliovaara [1987] and Kelsey et al. [1984] found an increased incidence of herniated discs with long-term exposure to automobiles and trucks. In a study of 3,920 patients [Frymoyer et al., 1980], it was determined that the complaint of low back pain was more common in individuals exposed to vibration, e.g., truck and tractor driving and heavy construction equipment operation. In the New York City subway system, lateral vibration was associated with a high prevalence of low back pain [Johanning et al., 1991]. This corroborates the effects on the spine found in other railroad environments, effects which were attributed to vertical and horizontal vibration [Arnautova-Bulat, 1979; Louyot et al., 1954].

MECHANICAL CHARACTERISTICS

Reviews of mechanical characteristics of the lumbar motion segment [Burns et al., 1984; Kaleps et al., 1984; Kazarian, 1972, 1975; Panjabi and White, 1978; Schultz, 1974; Tencer and Ahmed, 1981] show that it is viscoelastic, absorbs energy, moves with six degrees of freedom (three translations and three rotations), exhibits coupled motion (motion in one direction affects motion in others), has limited fatigue tolerance, and depends upon its bony and ligamentous components for mechanical tasks.

Early work concentrated on the effects of single loads or torques applied to the motion segment. Researchers have been studying the three dimensional effects of loads and torques applied [Panjabi and White, 1978] in three dimensions [Edwards et al., 1983; Laborde et al., 1981; Panjabi et al., 1976, 1977; Pope et al., 1977; Schultz et al., 1979; Berkson et al., 1979; Tencer et al., 1982; Tencer and Ahmed, 1981; Tencer, 1981; White, 1969]. Testing of this type is important, as it is difficult to assess directly all the loads and torques experienced by the motion segment in vivo [Dimnet et al., 1984]. If the stiffness characteristics of the motion segment are known, this task is simplified. The forces ([F]) can be obtained by applying the motion segment's stiffness characteristics ([k]) to its in vivo motion ([Δx]) characteristics: [F]-[k][Δx]. Fortunately, six degree of freedom movements of the in vivo motion segment are easily obtained by biplanar or stereo radiography [Brown et al., 1976; Pope et al., 1977; Frymoyer et al., 1979; Stokes et al., 1980, 1981].

A limitation in the use of the flexibility matrix for reporting the mechanical characteristics of the motion segment is that it is specific to the point at which the load was applied to obtain it. Therefore, it is possible to obtain different flexibility matrices in response to different load rates, magnitudes, and point of application. Using a consistent load range and load rate allows the use of a linear flexibility matrix. A way to solve the problem of load application location is to find a point which demonstrates a consistent mechanical response [Dimnet et al., 1984]. Both Rolander [1966] and Lin et al. [1978] found these points and called them the "balanced position of the load" and an "operational centroidal axis," respectively. They were both defined as that point, where, when a vertical load was applied, the segment would move only vertically.

Three groups have studied the six degree of freedom (three translations and three rotations) response to applied loads and torques of the minimally constrained vertebral body [Tencer, 1981; Tencer and Ahmed, 1981; Panjabi et al., 1977; Tencer et al., 1982; Berkson et al., 1979; Schultz et al., 1979]. These studies have defined

the mechanical response by means of main and coupled stiffness characteristics. Loads and torques applied to motion segments along or about the anteroposterior, lateral, and axial axes have produced main and coupled translations and rotations with which to generate the motion segment's complex flexibility characteristics. Using the main and coupled flexibility characteristics, it was presumed that a generalized stiffness matrix could be developed (by inversion of the flexibility matrix) which would describe the behavior of the segment. Determining this matrix would be of great benefit as it would permit comparison of segment properties as affected by loading, environmental, or disease history. One limitation of these works is that there is no description of a mechanically based reference at which the specimens are loaded. Except for the point of application of preload in the study by Panjabi et al. [1977] and the description of the balance point in the work by Tencer [1981] and Tencer and Ahmed [1981], loads are applied to the motion segment over geometrically based reference locations. All of the above-mentioned unconstrained testing applied loads either in line with the geometric center of the upper vertebral body or along an axis collinear with the line segment connecting the geometric centers of both centra of the upper and lower vertebral bodies of the motion segment.

Wilder [1985] and Wilder et al. [1987, 1988a, b, c, 1989] have loaded specimens at the balance point where both coupled flexion-extension and coupled lateral bend rotations are minimized. The balance point offers a good, mechanically based loading reference. Loading a specimen at its balance point allows the determination of a flexibility matrix at a unique, mechanically based reference, and may have bearing on trunk musculature control strategies.

ETIOLOGY

The seated vibration environment is associated with the production of low back pain [Sandover, 1981; Bongers and Boshuizen, 1990]. Several mechanical factors contribute to stressing the posterior portion of the intervertebral disc in the lumbar spine when one sits.

1. Sitting is an extreme posture for the lower back. It flattens the lumbar lordosis and shifts the line of force of the spine to a point posterior to the effective pivot point of the ischial tuberosities [Chaffin and Andersson, 1984]. In a vibration environment, the load transmitted by the spine, applied along the moment arm created by the anterior offset of the ischial tuberosities, may induce an additional rocking motion in the pelvis and may amplify the vibration motion transmitted to the spine.

2. Sitting also causes an increase in the posterior disc height which may mechanically strain the posterior and posterolateral collagen fibers of the anulus fibrosus where they are thinner and fewer in number [Farfan, 1973; Krag et al., 1987; Panjabi and White, 1978; Galante, 1967].

3. Additional strains are created in forward flexed motion segments because the facets disengage and allow an increase in the anteroposterior translation compliance [Panjabi et al., 1977; Schultz et al., 1979; Tencer et al., 1982].

4. Lumbar intradiscal pressures are significantly greater in the seated posture. This has a tension increasing effect on the disc collagen fibers analogous to increasing the tension in a taut wire by pushing on it from the side [Andersson, 1974; Nachemson and Morris, 1964; Okushima, 1970; Schultz et al., 1979; Belytschko et al., 1974; Nachemson, 1960].

5. Polymers such as rat and human medial collateral ligaments [Fung, 1981] have been shown to become softer and weaker due to vibration loading [Weisman et al., 1980], a fatiguing type response [Hertzberg and Manson, 1980; Riddell et al., 1966].

6. Physical changes and disc herniations have been caused in motion segments by exposure to cyclic and vibration loading [Adams and Hutton, 1983; Brown et al., 1957; Liu et al., 1983; Wilder et al., 1982a].

7. Whole-body vibration studies have established that the seated human has a resonant frequency close to those frequencies produced in common working and vehicular environments. A structure or mechanism vibrating at its resonant frequency is more likely to fail [Bastek et al., 1977; Pope et al., 1987; Seidel et al., 1980; Wilder et al., 1982b, 1985a; Seroussi et al., 1989]. In vitro lumbar motion segment [Wilder et al., 1985b] and in vivo whole-body vibration studies have established the motion characteristics of the lumbar region during vibration exposure [Panjabi et al., 1986; Hagena et al., 1986; Pope et al., 1986a; Kaigle et al., 1991].

8. A vehicle driver's disc is at risk for mechanical damage while unloading the vehicle after driving as back muscles fatigue with some vibration exposure [Wilder et al., 1984; Mangusson et al., 1988]; the lumbar "balance point" locations shift posteriorly following sustained sitting, thereby decreasing the erector spinae moment arm, and increasing the stabilizing load requirements of the erectors and increasing the imposed loads on the disc [Wilder et al., 1987, 1988a, b]; trunk fatigue [Pope et al., 1985, 1986b] results in increased coupled (out of plane) torques [Parnianpour et al., 1988]; and muscles overcompensate for unexpected loads [Marras et al., 1987]; all behaviors which would enhance the motion segment's tendency to buckle after seated vibration exposure [Wilder et al., 1988].

9. The combination of imposed lateral bend vibration and the flexion-extension response due to vertical vibration poses the most severe mechanical environment for the lumbar disc [Wilder et al., 1982a, 1990], due to the greater potential for stretching the posterolateral region of the disc with its subsequent mechanical fatigue.

MATERIALS AND METHODS

The following research on the lumbar spine has evolved from in vivo studies of the motion characteristics of the lumbar spine to studies of the effect of whole-body vibration on the spine of the seated operator and to evaluation of vibration loading of the isolated lumbar motion segment (in vitro). Systematic tests have been performed [Wilder et al., 1987, 1988a, b, c, 1989] to evaluate the effect of the parameters of load rate and load history on the mechanical properties of the motion segment and have demonstrated the sensitivity of the human lumbar motion segment to load application point, load vector, load rate, and load magnitude. Outcome measure data were collected for vibration loaded and statically loaded [Schultz et al., 1982] specimens: 1) before static or cyclic load exposure; 2) after a 1-hour static or cyclic load exposure, simulating sitting in either a static or vibration environment; and 3) after an overload event. The overload event, similar to that used by Adams and Hutton [1982], was applied to simulate a situation where one was compensating for a rapidly shifting load. A bulky package shifting while in the grip of a truck driver unloading the truck at its destination, would be a good example. These tests have shown for the first time a mechanical cause and effect relationship between application of conservative, combined flexion-compression (cyclic or static) loading, as found in static or

vibrating seating environments, and mechanical changes in the motion segment. In addition, experimental observations indicate that the lumbar motion segment is a mechanism with the potential for sudden, short column buckling. Such observations indicate the motion segment depends strongly upon the generalized load and torque provided by the surrounding musculature for its proper support and function.

This work has provided several unique contributions. 1) It has tested and proved the existence and the value of a mechanical balance point (a point where an axial load can be applied and produce minimal coupled flexion-extension and lateral bend rotation) in the in vitro lumbar motion segment. 2) A systematic study was performed of the effect of the new parameters of a) load rate, and b) load history upon the six degree of freedom mechanical response of the L2-3 and L4-5 motion segments. 3) The load history used revealed that a 1-hour duration exposure to the conservative combined compression-flexion loading found in both static and vibration seating environments caused statistically significant changes in the mechanical properties of the motion segment. 4) It exhibited further changes occurring due to an overload of the segment following the 1-hour seating exposure. 5) Data were obtained of the mechanical response of the motion segment, which will be useful to spine researchers and mechanical modellers. 6) The balance point is located posterior to both the geometric centers of the upper vertebral body and the point of intersection of the mid-transverse plane of the disc and the line segment connecting the upper and lower vertebral body centers. It was located near the instant center found by Gertzbein et al. [1984] using a technique analyzing flexion-extension. 7) The balance point changes location in response to load history. 8) The segment exhibits coupled viscoelastic response characteristics.

RESULTS
Large Rotation or Buckling Response of the Motion Segment

Under certain conditions of balance point location and load exposure history (regional compliance changes in the disc), the segment would rotate linearly (similar to normal segments up to a point) and then rotate rapidly or buckle (in less than 0.1 seconds) to a new equilibrium position. When this occurred, the segment rotated to its normal limits.

Most significantly, it is possible that, as a result of a regional mechanical change in the disc, a combination of vertical and lateral loading could produce a rapid, combined flexion and lateral bend buckling approaching normal physiological limits. The region of the disc receiving the greatest deflection from the motion is the posterolateral region. Under these conditions, the posterolateral portion of the disc could be subjected to large deflection, high strain rate, and tensile impact loading. If this response were to be assisted by a superimposed axial torque and/or improper loading from fatigued or damaged muscle, then this situation could be a viable mechanism for either sudden disc herniation or subacute fiber failure in the posterolateral region of the disc.

However, more revealing of the segment response to load, was the frequency of buckling responses. In general, the L2-3 segment exceeded the translation (1.0 mm) and rotation (1.0°) limits more frequently than the L4-5 segments. The frequency of buckling responses showed that the L2-3 segment was more sensitive to vibration loading, but that the L4-5 segment was more sensitive to static loading. A review of their average coupled flexion and coupled lateral bend rotation responses indicated

TABLE I. Incidence of Buckling in 82 Lumbar Motion Segments

n	Intervention type	Post intervention (%)	At overload (%)
Normals (n = 67)			
28	Flexion-lateral bend vibration	22/28 (79)	22/28 (79)
21	Static flexion-lateral bend load	2/21 (10)	10/21 (48)
18	No load	—	15/18 (83)
Segments with osteophytes (n = 15)			
9	Flexion-lateral bend vibration	7/9 (78)	9/9 (100)
3	Static flexion-lateral bend load	2/3 (67)	3/3 (100)
3	No load	—	2/3 (67)

L2-3 generally larger in flexion and lateral bend rotation means and standard deviations due to vibration loading.

Effect of an Overload Event

Overloaded motion segments tended to buckle. That showed the balance point is sensitive to load magnitude in addition to the load vector, application point, and load rate. Exposure to an overload increased the compliance of the motion segments, and increased the means and standard deviations of the coupled lateral bend rotation exhibited upon follow-up mechanical testing. This occurred after exposure to a prolonged flexion-compression static or vibration loading environment.

Work on Asymmetric Lumbar Motion Segment Loading

In 82 lumbar motion segments tested, short column buckling continued to be a common response of the segment to vibration exposure and overload events. The 82 specimens tested comprised L2-3 and L4-5 motion segments; 67 of the segments were considered normal and 15 were osteophytic. The 1-hour load interventions used were similar to those previously described, but with one additional component: a lateral bend moment. Another group using the condition of "no load" as the 1-hour intervention was also studied. It is clear from the results of all the lumbar segments tested in this fashion (Table I) that vibrated motion segments are at greater risk of sudden buckling. Specimens that were loaded with a combination of flexion and lateral bend vibration components were especially likely to buckle following the 1-hour intervention.

DISCUSSION

Mechanical properties of an intervertebral motion segment can be obtained at mechanically based references (such as the balance point) in addition to geometrically based ones. This has the possible benefit (although not yet tested) of simplifying the existent stiffness matrices used to describe the mechanical properties of the motion segment. It may also help reduce some of the scatter in mechanical properties reported by Tencer and Ahmed [1981], Schultz et al. [1979], and Berkson et al. [1979]. Testing motion segment properties at a balance point would also provide a reference for obtaining comparable data between researchers.

Clinically, there are several implications of the work.

1. Simulated sitting causes significant changes in the mechanical properties of the motion segment. This may indicate seat and job task redesign, but more work is needed to evaluate the long-term mechanical changes.
2. Neuromuscular control systems may use a balance point concept for applying loads properly to the spine. Due to the mechanical sensitivity of a balance point, it is important that the muscles apply the loads properly. A small mismatch (due to chronic or acute, trauma, or disease processes) between the way the load is applied and the way it "should be applied," as dictated by the segment's properties, may lead to a condition where the muscles may enhance damage of the segment.
3. Because the lumbar motion segment is sensitive in several directions to load application rate, low back pain sufferers should not rapidly change complex postures. For instance, one should get in and out of a car seat slowly, using simple posture changes.
4. After driving, it is not wise to bend over, lift rapidly, and twist as the rotational compliance of the L4-5 motion segment increases (gets softer) due to vibration.
5. It is a good idea that upon leaving the vehicle, one should walk around for 5 or 10 minutes before bending or lifting. This should allow the lumbar motion segment to reorient itself.
6. The work supports the assertion by Bongers and Boshuizen [1990] that the ISO 8-hour Fatigue, Decreased Proficiency (FDP) level is not conservative enough and should be lowered in order to prevent long-term damage to the lumbar disc in whole-body vibration environments.

From the existing epidemiologic and etiologic literature, it is evident that the lumbar motion segment is particularly at risk in both static and vibration seating environments which:

1. increase its internal disc pressure and
2. increase its anteroposterior shear flexibility, while:
3. decreasing its resistance to buckling,
4. stressing the posterior region of the disc, and
5. loading it in the form of static or vibration load environments.

It is also evident that there is a risk associated with lifting [Damkot et al., 1984] and unexpected loads [Marras et al., 1987]. These findings suggest that a systematic study is needed of the effect of load history upon the trunk musculoskeletal system soundness. If lumbar region response characteristics could be obtained from this sort of work, the cause and effect relationship between seating environments and mechanical response changes in the trunk could be established. This would be a valuable contribution as there is now no such firm relationship.

Future work will study the in vivo effects of common loading environments on the mechanical response of the seated human. The eventual goal of this line of work is to evaluate and control the occupational health hazard of low back pain, by establishing an "envelope" of loading conditions which should not be exceeded if the spine is to experience minimal mechanical damage. Proceeding from prior in vitro findings of short column buckling in the lumbar spine following vibration exposure, future studies will evaluate how the supporting trunk musculature responds to an

unexpected load application after a 1-hour load intervention (seated vibration or sitting still). This will simulate the sudden and unexpected shift of an object in the hands of the car or truck driver, who has driven for 1 hour. Normal walking (as a break) for 5 or 10 minutes, prior to an unexpected load application, will also be tested to determine if it would be a reasonable control, allowing lumbar discs to return, via creep behavior, to the upright posture orientation where the facets are more firmly engaged.

CONCLUSIONS

A method and an apparatus have been developed and tested which allow the testing of the main and coupled motion, compliance, and viscoelastic response of a spinal motion segment to pure axial compression loading applied at or away from the specimen's balance point. The device allows testing of the effects of complex load environments or structural alterations of the motion segment.

A point has been found where coupled flexion-extension and lateral bending rotations are minimized. This balance point is a reliable and repeatable indicator of the characteristics of the specimen. It exhibited significant changes in location only in response to sustained static, cyclic, or brief overload combined flexion-bending/compressive loading conditions. The specimen also exhibited frank rotations when it was loaded at points away from the balance point.

For the first time, there has been shown a mechanical cause and effect response of the isolated vertebral motion segment to a known load history including a simulated, 1-hour static, seated load exposure, and a 1-hour seated load exposure to the conservative vibration accelerations of the ISO [1985] 8-hour "Fatigue, Decreased Proficiency" limit at the 5 Hz frequency. There was significant softening in the segment's coupled compliance characteristics as a result of static or vibration loading simulations.

For the first time, coupled viscoelastic mechanical characteristics have been demonstrated in the unconstrained lumbar motion segment.

Under certain conditions, the motion segment exhibited a sudden, large, combined (flexion and lateral bend) rotation response to axial loading. This reorientation may be a mechanism for a rapidly occurring posterolateral disc herniation.

Vibration loading increased the magnitude of the final lateral bend and flexion-extension rotation, more often, in the L2-3 motion segment.

ACKNOWLEDGMENTS

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