2008 Vol 17 No. 4

SCIENTIFIC

PHYSICAL THERAPY

Low Back Pain in Space and Proposed Countermeasures

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Low back pain in microgravity is one of the most common problems experienced by astronauts (Styf, Hutchinson et al 2001, Thornton, Hoffler et al 1977). The mission-oriented mental focus of astronauts and their ability to perform challenging tasks could potentially be affected by disruption of restful sleep and reduced mental concentration if back pain is perceived. It is not uncommon that low back pain is an occurrence in the astronaut corps but to date, there is a paucity of research addressing back pain before, during and after spaceflight. There is also a strong indication that NASA's astronaut population has experienced a higher rate of Herniated Nucleus Pulposus (HNP) per 1000 person years when compared to the general population and to an Army aviation population (Johnston 1998). Of all the possible spinal structures that could potentially be the source of low back pain and debilitation, it appears that the lumbar intervertebral disk is most likely involved in its pathophysiology (Sayson & Hargens 2008). Therefore, the mechanism of low back pain during exposure to microgravity in relation to the disk will be discussed as well as its possible countermeasures.

Data analysis of a retrospective study using medical records of 58 astronauts from the Flight Medical Clinic at NASA Johnson Space Center indicated that sixty-eight percent of astronauts report low back pain during short duration spaceflight (Wing & Tsang et al 1991). Symptom duration varied from 14% to 100% of the flight, and 28% described the back pain quality as moderate to severe in intensity. Also, the reported characteristics of their pain are as follows: a) maximal from Day 1 to Day 6 of microgravity exposure, b) localized to the lumbar spine, and c) pain persistence not a function of age or flight experience.

The cells of the musculoskeletal system normally respond by adapting to load-bearing and muscular contraction to orient the body in an upright position against 1G. Biomechanical energy, in the form of the compressive effect of Earth's gravity as well as the muscular contraction to the dynamic human spine, is an important biological stimulus aside from nutritional, hormonal, and genetic factors. The spine exposed to continued microgravity will result in vertebral column lengthening 2-3 times the diurnal values of 1.5-3 cm (Kimura, Steinbach et al 2001, Krag, Cohen et al 1990) on Earth to 4-6.0 cm (Brown 1977, Styf, Kalebo et al 1994). This length change has been attributed to an increase of disc height due to an increase in fluid volume, as well as to a reduction of the thoracic and lumbar curvatures (Kershner & Binhammer 2004, Lee, Hargens et al 2003, Styf, Kalebo et al 1994). In the microgravity of space, there is an obvious reduction in the necessary biomechanical energy concurrent with the significant reduction of load-bearing and the typical muscular responses supporting the spine. The end-result is most likely hypotrophy to the cells comprising the musculoskeletal system including the disk as well as alteration in its fluid hydrodynamics (Sayson & Hargens 2008). There is likely a spinal adaptation to prolonged microgravity but which becomes maladapted upon return to a 1 G environment.

Inter-vertebral Disk components and hydrodynamics:

A concise review of the lumbar inter-vertebral disk cellular components is needed to understanding its potential as a pain generator. Fluid, proteoglycan (PG), and glycosaminoglycan (GAG) are the biochemical contents of the lumbar disc while cartilage cells, fibroblasts, and collagen fibers comprise the histological contents. These components are in varied proportions between the inner nucleus pulposus and the outer annulus fibrosus, including the vertebral endplates above and below the disk. PG has a high electronegative charge and as a result, has a high swelling pressure which resists compressive loading to the spine. The hydrodynamics of normal disk fluid and nutrient inflow and outflow occurs by two processes: convection and diffusion (Hargens & Akeson 1986). Convection, especially for macromolecules, is a more rapid transport and involves bulk flow through a porous medium such as the interstitium and intervertebral endplates due to hydrostatic pressure gradients and sufficiently large channels. Diffusion, which is dependent on temperature, is the tendency of a solute to reach uniform distribution in the presence of a concentration gradient. When the spine is unloaded in 1G supine sleeping, transport of fluids into the discs occurs via repulsive forces within a matrix of high anionic charge density which exerts large negative fluid pressures resulting in disc imbibition (Hargens 1986). Thus, fluid imbibition occurs when negatively charged proteoglycan macromelocules in the nucleus pulposus repel each other causing fluid inflow.

Weight-bearing and activity deform the intervertebral disks and facilitate fluid and nutrient transport that are essential for tissue viability (Hargens & Akeson 1986). Loading of the spine in 1G results in a 25% of the disk's fluid expressed in an outward flow (convection) and re-imbibed (diffusion) when unloaded in each diurnal cycle on Earth (Sivan, Neidlinger-Wilke et al 2006). Therefore, an intermittent mechanical force to increase and decrease intradiscal pressure cyclically facilitates transport of nutrients, water, and waste products into and out of the nucleus pulposus. The magnitude of disk fluid volume changes in microgravity is presently unknown since the usual loading to the disk is reduced with subsequent reduction of fluid outflow and a relatively increased fluid inflow resulting in disk expansion (Sayson & Hargens 2008).

Possible Pain Mechanisms:

On Earth, the etiology of back pain may be broadly classified as visceral, non-mechanical, and mechanical (attributed to lumbar discs) (Lawrence, Tugwell et al 1992) but the exact cause of low back pain in microgravity is currently unknown. The likely etiology of low back pain in space is therefore, a mechanical classification.

Unloading in microgravity causes the spine to lengthen beyond that of measurements in 1G due to the nucleus pulposus increasing its volume by greater fluid inflow than outflow. There is a reduction in counter forces to return positive pressure (hydrostatic pressure) for fluid transport through the endplates and to the vertebral bodies. As the annulus fibrosus expands, it is possible that a) collagen deformation surpasses the normal physiological collagen deformity of 3-4%, and b) Type IV mechanoreceptors or free nerve endings are stimulated, and the sinuvertebral nerves (recurrent nerve or nerve of von Luschka) continually transmit impulses, thus resulting in perception of low back pain (Sayson & Hargens 2008) (Fig. 1).

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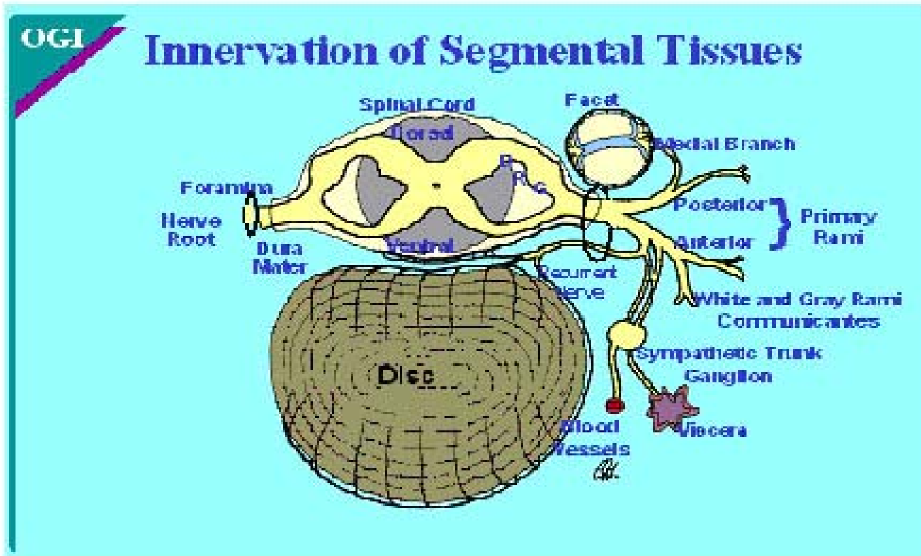

Figure 1: Innervation to the lumbar intervertebral disc. The recurrent nerve (sinuvertebral or nerve of von Luschka) innervates the ipsilateral and contralateral periphery of the lumbar intervertebral discs. It also innervates up to a third into the substance of the annulus fibrosus and the anterior but not the posterior dura mater. (illustration reproduced with permission from the Ola Grimsby Institute).

The sinuvertebral nerves are unmyelinated with a slower conduction of nerve impulses (0.5-2 m/s) than that for myelinated nerves A delta (5-15 m/s), and B fiber (3-14 m/s) (Wyke 1979). Stimulation of the sinuvertebral nerves by deformation will therefore result in a progressively slow, dull, achy, gnawing, scalding or burning sensation and which could also be termed as neuropathic pain (Bowsher 1991). During spaceflight, astronauts complain of pain localized to the lower back and the nature of the pain is described as "dull" pain (characteristics of sinuvertebral nerves) without any intense or incapacitating nature (Wing, Tsang et al 1991).

On Earth, loading of the spine produces biomechanical factors which act in synergy with physicochemical factors to regulate intervertebral disc cellular activity and tissue morphology (Hargens & Akeson 1986). In Microgravity, these factors are altered without the compressive loads provided by activity in 1g where muscle contraction and cyclic changes alter disc hydrostatic pressures. Alteration of mechanical loading with disruption of fluid equilibrium may then result in disk hypotrophy or degeneration. Subsequently, the structural morphology of the disk may weaken, potentially increasing the incidence of HNPs reported in astronauts upon return to 1G loading conditions post-flight.

Pain relief and proposed countermeasures:

Astronauts claim that a "fetal tuck position" described as curling the spine or the knees to chest position relieves low back pain (Thornton, Hoffler et al 1977, Wing, Tsang et al 1991) (Fig. 2). Also, other techniques reported by astronauts to ease low back pain include stretching, taking acetaminophen, treadmill exercise, and deliberate compression of the spine (Wing, Tsang et al 1991). The underlying rationale for pain relief appears to be two-fold, a biomechanical and a neurophysiological mechanism.

In biomechanics, spinal flexion moves the instantaneous axis of rotation from the center toward the anterior lumbar discs producing a compressive load via muscle contraction of the spine flexors (in the absence of gravitational load). At the same time, there will be stretching and tensioning of the posterior ligamentous soft tissue and nervous structures which may result in additional spinal compressive load (White & Panjabi 1990).

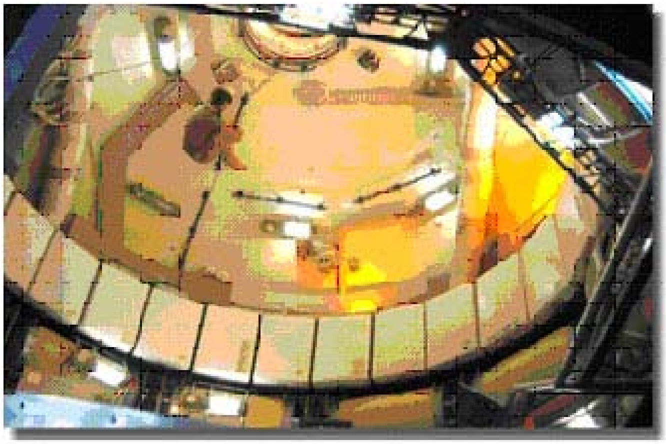

Figure 2: Astronaut assuming a fetal-tuck position in Skylab (undated photo NASA archives)

The *biomechanical mechanism* of low back pain relief using the fetal tuck position may be due to lumbar disk compression which in turn, re-establishes hydrostatic pressure, facilitates disk fluid outflow through convection, decreases disk fluid volume, and finally, reduces annular deformation and stimulation of the sinuvertebral nerves. On the other hand, the *neurophysiological mechanism* of low back pain relief aside from reduced stimulation of the sinuvertebral nerves, may be due to the mechanical stretching of the posterior soft tissues to include the apohyseal joint capsules and ligaments, which stimulates Type I and Type II mechanoreceptors (Sayson & Hargens 2008). The spinal reflex response to this episode is an inhibitory effect whereby the pre-synaptic neurotransmitters substance P and neurokinin A are neutralized by naturally occurring enkephalins in the dorsal horn of the spinal cord. Enkephalins together with endorphins are a class of naturally-occurring opioids (also known as endocoids) that have analgesic actions (Korr 1986).

The longer the exposure to microgravity without the normal 1g stresses, the more likely that the annuli hypotrophy or degenerate as the nucleus pulposus swells, the disk expands, and adapts to abnormally low-load conditions. Disc stiffness may be lost (termed segmental instability) which may cause pain, disk deformity, or risk neurological structures when normal external loads in 1g are reapplied. To address low back pain in space, acetaminophen, aspirin, and ibuprofen are taken orally by astronauts (Putcha & Berens 1999, Wing & Tsang et al 1991).

To date, the U.S. space program has no other non-pharmacologic countermeasures in use during microgravity exposure specific to low back pain utilizing biomechanical principles. Countermeasures will have to rely on reproduction or simulation of Earth-like biomechanical loading to the spine in microgravity to prevent or delay potential disc hypotrophy that may cause HNPs post-flight.

Spinal loading during microgravity with exercise combined with axial spine compression may reduce disc expansion and subsequent pain by re-establishing the normal hydrodynamics of the disk. Spine loading using elastic bungee cords that tether astronauts onto a treadmill produce insufficient mechanical loads equivalent only to 60-70% that of terrestrial values as well as with a disadvantage of producing extreme discomfort where it compresses the shoulders and pelvic region (Whalen 1993). A promising alternative to the bungee cord may be with the use of a treadmill exercise within a lower body negative pressure (LBNP) device (Cao, Kimura et al 2005). A treadmill enclosed in a LBNP chamber avoids localized high pressures of bungee cord harness systems that cause discomfort by distributing the differential air pressure uniformly over the surface of the body sealed at the waist by a kayak-type skirt. However, the LBNP treadmill is still in need of a redesign for spaceflight and crew habitability. A form of compression garment called the penguin suit has been used by the Russian space program but no peer-reviewed study is available to document spine biomechanics or back pain relief with its use. The closest possible maneuver used to date may be spine rotation with compression using a hammer throw exercise used against elastic cords in conjunction with a penguin (61, 67). This may have decreased back pain in cosmonauts due to physiological loading of the spine.

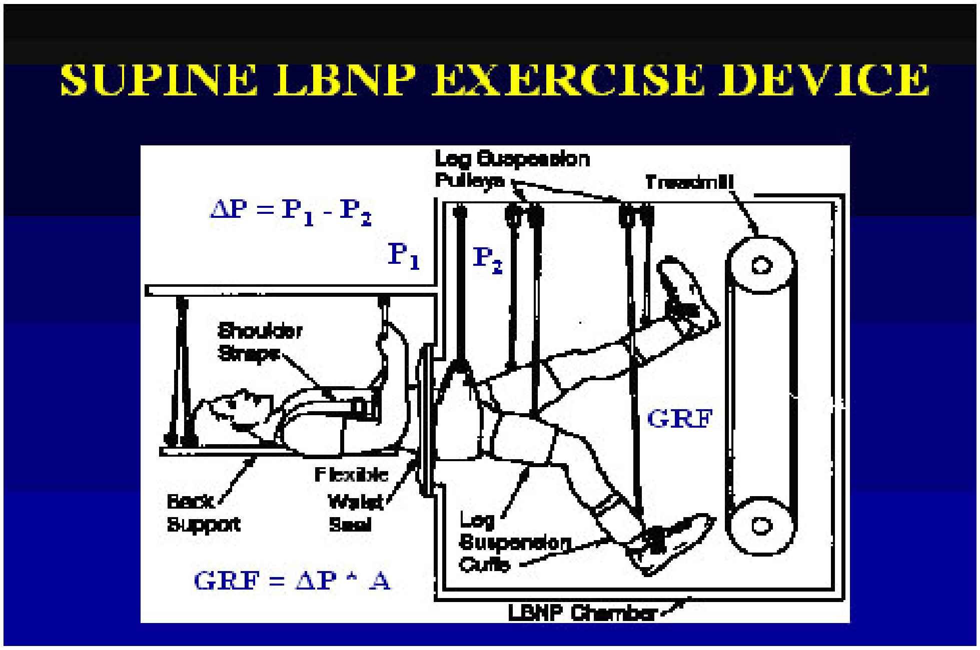

Fig 3. The Lower Body Negative Pressure (LBNP) Treadmill Exercise. (Cao P, Kimura S, Macias B., Ueno T, et al. Exercise within lower body negative pressure partially counteracts lumbar spine deconditioning associated with 28-day bed rest. J Appl Physiol 2005; 99: 39-34)

Recommendations for future research would have to depend on a logical perspective with regard to the application and approximation of defined loading conditions to the spine to include cyclic variances in lumbar disk hydrostatic pressure. Further research should include: a) muscle specific conditioning exercises and equipment for the spine pre-flight, in-flight, and post-flight to provide normal physiological disk loading and compression, b) spine compression by a penguin suit or another device for comfortable but high spinal loads and c) repetitive spine rotation which accurately reproduces activities on Earth.

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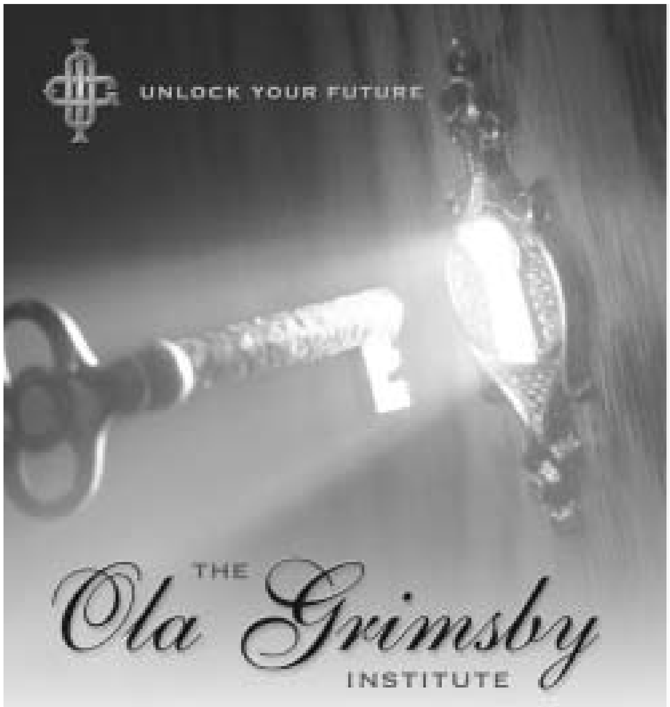

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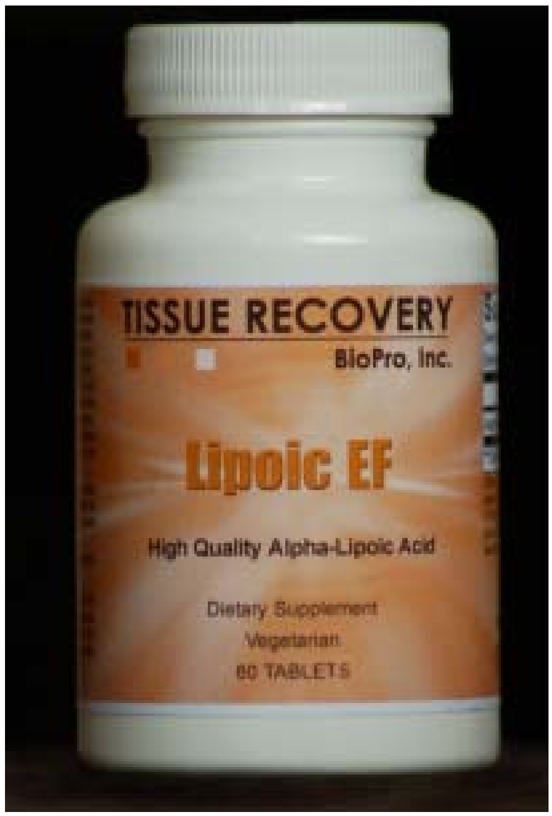

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