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Simulation analysis for effects of bone loss on acceleration tolerance of human lumbar vertebra

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Abstract

The purpose of the present study was to analyze and predict the changes in acceleration tolerance of human vertebra as a result of bone loss caused by long-term space flight. A human L3–L4 vertebra FEM model was constructed, in which the cancellous bone was separated, and surrounding ligaments were also taken into account. The simulation results demonstrated that bone loss has more of an effect on the acceleration tolerance in x-direction. The results serve to aid in the creation of new acceleration tolerance standards, ensuring astronauts return home safely after long-term space flight. This study shows that more attention should be focused on the bone degradation of crew members and to create new protective designs for space capsules in the future.

Keywords: Space flight; Human vertebra; Bone loss; Acceleration tolerance

1. Introduction

The landing impact is one of the most important environmental factors when a spacecraft returns to the Earth, as it has the most influence on the safety of the astronauts. If the acceleration level experienced by the crew members is greater than human tolerance, fatal injuries may occur. Therefore, human skeleton dynamic response and tolerances to impact are some of the key constraints in space capsule design since the onset of space flight.

Currently, the most popular acceleration tolerance to impact used in manned space flight is the standard in NASA-STD-3000 (Standard of National Aeronautics and Space Administration). However, the effect of bone loss in long-term space flight is not considered in this standard. There have been many reports in literature that long term spaceflight (Lang et al., 2004; LeBlanc et al., 2000) or simulated microgravity experiments (Whedon and Rambaut, 2006; Meck et al., 2009; LeBlanc et al., 2007) resulted in a reduction in bone mass of the skeleton system and mechanical strength, which ultimately degraded the acceleration tolerance (Lang, 2006; Gozulov and Frolov, 1969). Compared to short-term space fight, the astronauts from long-term space flights were more vulnerable to injury under the same space landing impact loads. The quantitative relationship between bone loss and the acceleration tolerance, however, was still unclear.

Lumbar spine is very vulnerable to fatal injuries during space capsule landing impacts due to the fact that bone loss occurs more frequently here than anywhere else in the spine. The objective of this study was to analyze and predict the relationship between bone loss and the acceleration tolerance of human lumbar vertebra. This information would useful in designing new manned spacecraft for long-term space flight.

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2. Methods

2.1. Model description

The geometry of the L3 and L4 vertebrae was reconstructed from 0.6-mm-thick CT-scan slices of a healthy male with no recent back complication, and remodeled by Mimics 10.0 Software (Materialise, Belgium). The two vertebrae were chosen because the directions of the compressive and shear forces on the two vertebrae are nearly parallel to the directions of the loading. The vertebral bodies were modeled by taking into account the separation of cortical bone using 3-nodes shell and cancellous bone using 4-nodes solid elements. Only the density of cancellous changed due to microgravity. There was intervertebral disc between the intervening endplates, which was subdivided into nucleus pulposus using 4-nodes-solid elements and annulus fibrosus 4-nodes-solid elements. The surrounding ligaments, the anterior (ALL) and posterior (PLL) longitudinal ligaments, intertransverse (ITL), flavum (FL), interspinous (ISL) ligaments, capsular (JC) and spinous spinous (SSL) ligaments, were represented by envelopes of 1 mm uniform thickness. All ligaments were modeled with 4- and 3-nodes (JC) shell elements. There were 743,861 total elements and 119,043 total nodes in this model.

The material properties used for spinal modeling has been described in literature (Marwan et al., 2009; Shim et al., 2005). In this model, the elasto-plastic constitute equation was used for cortical bone, while the visco-elastic and hyper-elastic constitute equation was used for ligaments and discs, respectively. The tied contact interfaces were used to ensure that the disc and ligament were attached to the vertebrae and to prevent any relative movement during the simulation. Frictionless contact interfaces were assumed between the diverse parts of the model to avoid any possible penetration. According to NASA-STD-3000 (vol1/REV.B 3-63), the mass of the body segments acting on the lumbar vertebra was 42.17 kg for a 50th percentile male crew member.

2.2. Dynamic load

The safety acceleration tolerance was listed in NASA-STD-3000 (vol1/REV.B 5-40) as the following table, where peak acceleration was the impact limit. Values under this limit would mean that the occupant would be safe. In this study, the impact load condition was used as the initial load.

During the impact, the acceleration load curve a(t) was fit as the following expression according to experiments (Ma et al., 2008), where a_{p} was acceleration peak, t was time, T_{L} and T_{R} were 22 ms and 47 ms, respectively.

$$a(t)=\begin{cases}\frac{a_p}{2}\left(1-\cos\frac{2\pi}{T_L}t\right), & 0\leqslant t\leqslant\frac{T_L}{2};\\ \frac{a_p}{2}\left\{1-\cos\left[\frac{2\pi}{T_R}\left(t+\frac{T_R}{2}-\frac{T_L}{2}\right)\right]\right\}, & \frac{T_L}{2}<t\leqslant\frac{T_L}{2}+\frac{T_R}{2}\end{cases} \tag{1}$$

The flow path of calculation was done in the following order: firstly, the initial impact limit load was used and got a maximum stress in the vertebra somewhere. When the bone density was reduced, the mechanical properties would change following the constitute equation. Then, the load condition was changed to satisfy the stress in same position, which then yielded the maximum value (Fig. 1).

3. Results

The acceleration load Gx (g in x-direction), Gy and Gz were obtained from this model, which yields the acceleration tolerance. The bone loss was expressed as change in bone density, which was represented in percentage form by using the normalization method. The relationship between bone loss and acceleration tolerance is shown in Fig. 2 by fitting the calculated points (Table 1).

The fitting function is shown as the following:

$$y=ae^{\left(-\frac{x}{b}\right)}+c \tag{2}$$

where the parameters in Eq. (2) are given in Table 2.

From Fig. 2, it can be found that there were obvious declines in three-direction acceleration tolerance. These results are consistent with the hypothesis we made before. Fig. 2 also has shown that the decline rate in the x-direction was faster than the other directions.

4. Discussion

In this study, the effects of bone loss on acceleration tolerance of human lumbar vertebra were simulated by using a finite element model of L3–L4. The results indicate that bone loss has more of an effect on the Gx. Biomechanically, this might result from the movement of the lumbar in the x-direction produced the moment, which results in the stress reaching its maximum value at the front edge of the vertebra quite easily. Physiologically, this might be caused by the variations in bone trabecular microarchitecture. The stability and strength of cancellous bone depends not only the amount of bone trabecular, but also on the trabecular microarchitecture, which includes the three-dimensional orientation and connectedness of trabecular. Thinner trabecular and the decline of connectivity have more negative influences on the shear strength than compressive strength of cancellous bone.

The results in this study would be instrumental for the designers of a new space capsule. The lightweight energy absorption of material and structures, such as metal foams, multilayer metallic sandwich (Wei et al., 2007), and hierarchical woven lattice composites (Zheng et al., 2012) or even polymer-based cellular energy absorbers like the SKYDEX® pad (Zhu et al., 2010), might be novel choices for designers to replace the current polyurethane foam seat liner. In order to reduce bone loss, whole-body vibration and resistance exercise methods are recommended for astronauts (Michael and Sam, 2008). Skylab and Mir station both utilized resistance