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Research Paper

Rate-dependent fracture characteristics of lumbar vertebral bodies

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A B S T R A C T

Experimental testing incorporating lumbar columns and isolated components is essential to advance the understanding of injury tolerance and for the development of safety enhancements. This study incorporated a whole column axial acceleration model and an isolated vertebral body model to quantify compression rates during realistic loading and compressive tolerance of vertebrae. Eight lumbar columns and 53 vertebral bodies from 23 PMHS were used. Three-factor ANOVA was used to determine significant differences ($p < 0.05$) in physiologic and failure biomechanics based on compression rate, spinal level, and gender. Results demonstrated a significant increase in ultimate force (i.e., fracture) from lower to higher compression rates. Ultimate stress also increased with compression rate. Displacement and strain to failure were consistent at both compression rates. Differences in ultimate mechanics between vertebral bodies obtained from males and females demonstrated non-significant trends, with female vertebral bodies having lower ultimate force that would be associated with decreased injury tolerance. This was likely a result of smaller vertebrae in that population. Combined with existing literature, results presented in this manuscript contribute to the understanding of lumbar spine tolerance during axial loading events that occur in both military and civilian environments with regard to effects of compression rate and gender.

1. Introduction

Quantification of lumbar spine vertebral body tolerance to axial compressive loads is important for an understanding of injury biomechanics, for the development of safety enhancements, and for incorporation into finite element models. While fracture tolerance for isolated lumbar vertebral bodies has been outlined experimentally, compressive rates were generally in the quasi-static range (e.g., 5 mm/min) (Alkalay et al., 2008; Belkoff et al., 2001; Hansson et al., 1980; Steens et al., 2007) and effects of spinal level and gender were typically not statistically investigated (Bartley et al., 1966; Bell et al., 1967). However, vertebral body fractures typically occur under dynamic mechanisms such as falls from height,

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high-velocity vehicular impacts (Pintar et al., 2012), and sporting events (Pintar et al., 2012; Cooper et al., 1992; Khan et al., 2008; Larson, 1993). Traumatic mechanisms are particularly relevant for younger populations (Cooper et al., 1992), prior to the onset of osteoporosis. In the military environment, lumbar fractures were demonstrated following aviator ejection, helicopter crashes, and underbody blast events involving improvised explosive devices (Lewis, 2006; Nakamura, 2007; Werner, 1999; Scullion et al., 1987; Shanahan and Shanahan, 1989a; Helgeson et al., 2011; Poopitaya and Kanchanaroek, 2009; Ragel et al., 2009). Vertebral body compression rates during those events are likely to be orders of magnitude greater than quasi-static rates experimentally incorporated to develop injury tolerance limits (Stemper et al., 2011a). Due to the rate-dependence demonstrated for other tissues, including thoracic vertebrae (Kazarian and Graves, 1972), arteries (Stemper et al., 2007), ligaments (Yoganandan et al., 1989), and isolated spines (Pintar et al., 1998), tolerance limits obtained from quasi-static testing may not be applicable for the dynamic loading environment.

Additionally, differing rates of vertebral body fracture between men and women and changing injury distributions as a function of loading rate necessitate the investigation of gender and spinal level on vertebral fracture tolerance. Population-based data have demonstrated that age-adjusted incidence rates for vertebral fractures in women are twice the incidence in men (Cooper et al., 1992). Similar gender discrepancy has been reported in other studies (European Prospective Osteoporosis Study, G. et al., 2002) or has been reported as high as 73% female incidence in an older population (55+ years) (Van der Klift et al., 2002). Whereas higher rates of osteoporosis in post-menopausal women is likely to explain some of this gender difference, studies incorporating wider age ranges have also reported higher incidence rates in women. Loading rate was also shown to influence the distribution of injured spinal levels in a recent review article (Stemper et al., 2011b). Specifically, that study indicated caudally migrating injury locations with higher severity axial acceleration exposures from aviator ejection to helicopter crashes to underbody blast. Although prior experimentation identified a lack of spinal level differences in quasi-static compressive tolerance of vertebral bodies (Hansson et al., 1980; Bartley et al., 1966; Bell et al., 1967), dynamic tolerance may demonstrate spinal level dependence that could partially explain these clinically-identified differences in injury locations.

Therefore, the current experimental study was designed to quantify the dynamic fracture tolerance of lumbar spine vertebral bodies under compressive loads applied at compression rates designed to approximate military environments. Based on the information outlined above, it is anticipated that biomechanical metrics will be affected by compression rate, specimen gender, and spinal level.

2. Methods

This study incorporated a novel approach of using whole-column and isolated vertebral body specimens obtained from post-mortem human subject (PMHS) donors. Whole column specimens were tested across a range of axial accelerations to quantify vertebral body compression rates under simulated vertical acceleration environments, such as aviator aircraft ejection and helicopter crash using kinematics analysis. Next, isolated vertebral bodies were compressed to failure at compression rates across the range outlined in the first part of this study. Relatively young and non-degenerated specimens were incorporated.

2.1. *Determination of dynamic compression rates using whole column studies*

The first part of this study consisted of analyzing kinematics data from a previously conducted test series to quantify the vertebral body compression rates resulting in fracture during simulated high-rate axial acceleration environments. Dynamic testing of eight PMHS whole lumbar columns (T12-L5) was performed using a novel drop tower apparatus as described in greater detail by Stemper et al. previously (Stemper et al., 2011). The experimental model consisted of two uncoupled platforms attached to a drop tower using guide wheels (Bishop-Wisecarver Corp., Pittsburgh, CA). The caudal fixation of the specimen was attached to the lower platform and mass of the upper platform was 32 kg. The schematic representation of the test setup is shown in Fig. 1. The specimen was pre-flexed with a 5 N m moment and held in place with an initial preload from the upper platform. Both platforms were raised to the specific drop height and released. The specimen was decelerated at the base of the platform using pulse-shaping foam. The foam dimensions were $30 \times 45 \times 65\ cm^3$ (X,Y,Z) and had a density of $16\ kg/m^3$. Acceleration magnitude and shape of the acceleration versus time pulse was controlled by initial drop height and foam characteristics. Acceleration versus time characteristics were measured using redundant accelerometers attached to the lower platform. Digital data were sampled at 20,000 Hz.

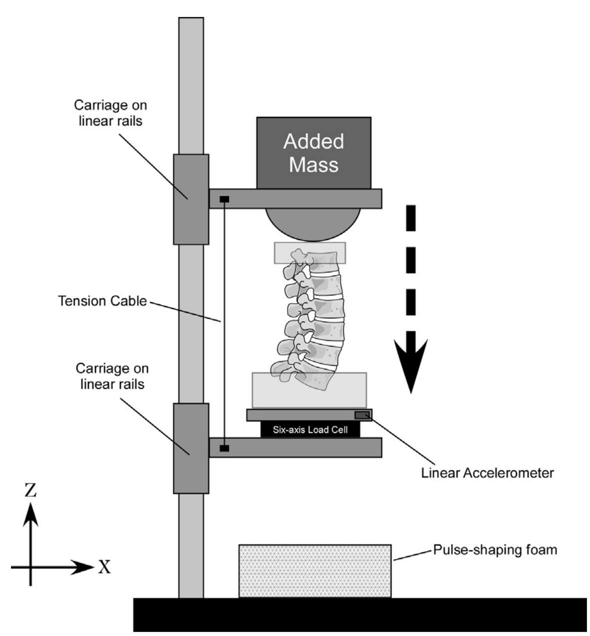

Fig. 1 – Testing apparatus to simulate vertical acceleration of whole lumbar spine columns. Acceleration versus time characteristics were designed to simulate the vertical component of aviator ejection and helicopter crashes.

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