Expanded Combined Lumbar Injury Criterion Due to Underbody Blast

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Introduction

Improvised Explosive Devices (IEDs) are an increasingly frequent source of injury and mortality for U.S. soldiers[1, 2]. The lumbar spine is particularly vulnerable in underbody blast (UBB) events due to rapid underbody loading and bending moment experienced by vehicle occupants. Lumbar spine injury ranks 2nd most common among injuries sustained by vehicle occupants killed in action and 4th most common among U.S. soldiers wounded in action[1-3]. Injury prevention relies on understanding the lumbar spine injury tolerance when subjected to UBB.

Recent studies determined an injury tolerance for lumbar vertebral body fracture due to axial compression alone[1]. However, injury risk is highly dependent on the complex geometry of the spine and the loading path, which is rarely purely axial in realistic scenarios. Ortiz-Paparoni et al. (2021) established a combined loading injury criterion[4], considering both axial force and bending moment for postures seated nominally and within one standard deviation, determined through the UMTRI seated solider study[5]. However, a criterion is needed that considers postures with increased bending moment to fully capture realistic injury risks. The objective of this study is to improve the previously established lumbar injury risk criterion by expanding its application range to higher dynamic bending moments relative to axial force. Ultimately, use of this criterion should lead to more effective injury mitigation efforts.

Methodology

This study uses results from 75 high-rate lumbar compression tests from Ortiz-Paparoni et al. 2021 along with 15 additional tests positioned in one of four more extreme postures. Lumbar spine components (T12-S1) from human cadavers were fixed on the superior end in the mechanical test system (MTS) with the lumbar column positioned in postures with increased flexion or extension[5]. The inferior end was subjected to a high-rate, inferior/superior force, that produced a force/moment profile. A six-axis load cell measured the axial compression forces and bending moments during loading. Injury events were assessed through acoustic sensors secured to vertebral bodies and high-speed video. Post-test, fractures were confirmed though computed tomography (CT) and necropsy.

Results and Discussion

Out of 90 specimens tested, 77 experienced fracture of at least one vertebral body, and 13 did not sustain vertebral body fractures. The expanded combined injury metric (EXL_{ic}) was developed using prismatic beam failure analysis. The US Department of Transportation used similar analyses for assessing the Hybrid III ATD neck[6]. For a given test, there exists a peak (EXCOMB), but this peak depends on $F_{r,crit}$ and $M_{y,crit}$, which are not known. To optimize, the Anderson-Darling fit coefficient was iteratively minimized for the given distribution. The recommended injury risk curve follows a loglogistic distribution, shown in Figure 1.

Postures tested represent real-world exposures within military vehicles[5], expanding the applicability of the injury criterion. Including these 15 additional tests, positioned in a wider range of postures, resulted in a higher bending moment contribution, illustrated by a smaller optimized $M_{y,crit}$ value relative to the previously established metric[4]. This study focused on single vertebral body fracture risk. Additional studies are desirable to address risk of multiple vertebral body fracture, intervertebral disc failure, or posterior element injury.

$$EXL_{ic} = \frac{1}{1 + \exp\left[-\frac{ln(EXCOMB) - \mu}{\sigma}\right]}$$

where

$$EXCOMB = \frac{F_r}{F_{r,crit}} + \frac{M_y}{M_{y,crit}}$$
$$F_{r,crit} = 6011\ N$$
$$M_{y,crit} = 904\ Nm$$
$$\mu = 0.0$$
$$\sigma = 0.1797$$

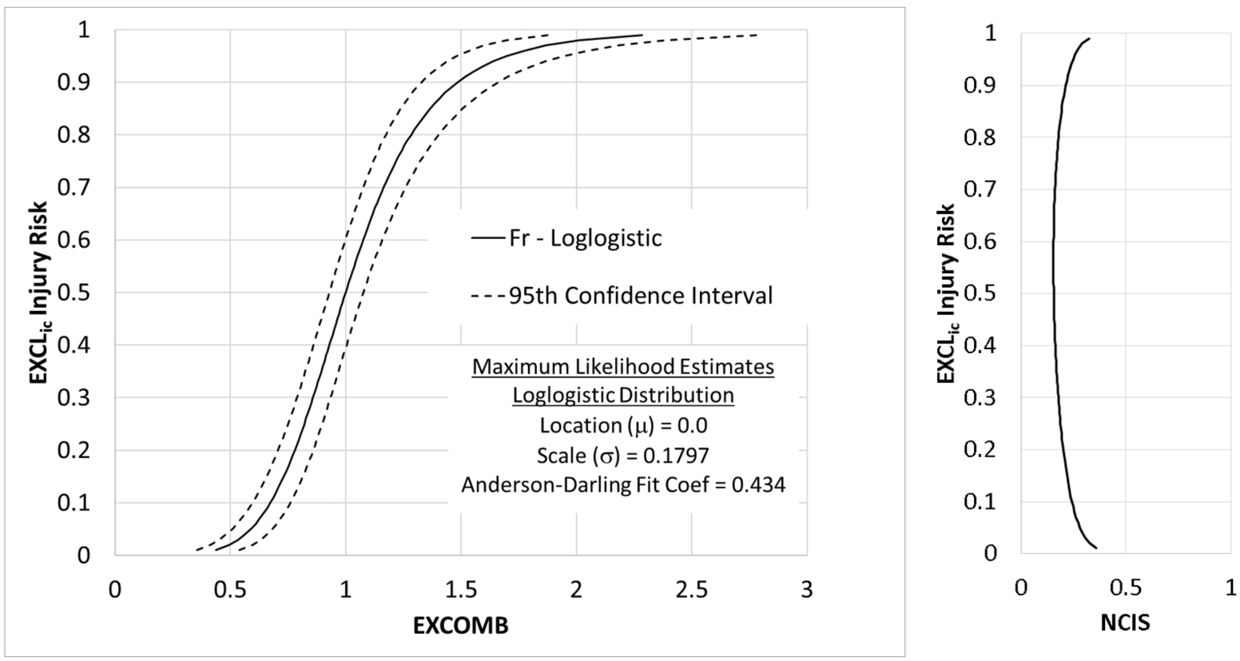

Figure 1: Lumbar spine human injury probability curve for single-level vertebral body fracture for a combined loading metric with 95% confidence intervals (dashed).