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Analysis of crash parameters and driver characteristics associated with lower limb injury

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ABSTRACT

This study aims to investigate changes in frequency, risk, and patterns of lower limb injuries due to vehicle and occupant parameters as a function of vehicle model year. From the National Automotive Sampling System-Crashworthiness Data System, 10,988 observations were sampled and analyzed, representing 4.7 million belted drivers involved in frontal crashes for the years 1998–2010.

A logistic regression model was developed to understand the association of sustaining knee and below knee lower limb injuries of moderate or greater severity with motor vehicle crash characteristics such as vehicle type and model years, toepan and instrument panel intrusions in addition to the occupant's age, gender, height and weight. Toepan intrusion greater than 2 cm was significantly associated with an increased likelihood of injury (odds ratio: 9.10, 95% confidence interval 1.82–45.42). Females sustained a higher likelihood of distal lower limb injuries (OR: 6.83, 1.56–29.93) as compared to males. Increased mass of the driver was also found to have a positive association with injury (OR: 1.04, 1.02–1.06), while age and height were not associated with injury likelihood. Relative to passenger cars, vans exhibited a protective effect against sustaining lower limb injury (OR: 0.24, 0.07–0.78), whereas no association was shown for light trucks (OR: 1.31, 0.69–2.49) or SUVs (OR: 0.76, 0.28–2.02).

To examine whether current crash testing results are representative of real-world NASS-CDS findings, data from frontal offset crash tests performed by the Insurance Institute for Highway Safety (IIHS) were examined. IIHS data indicated a decreasing trend in vehicle foot well and toepan intrusion, foot accelerations, tibia axial forces and tibia index in relation to increasing vehicle model year between the year 1995 and 2013. Over 90% of vehicles received the highest IIHS rating, with steady improvement from the upper and lower tibia index, tibia axial force and the resultant foot acceleration considering both left and right extremities. Passenger cars received the highest rating followed by SUVs and light trucks, while vans attained the lowest rating.

These results demonstrate that while there has been steady improvement in vehicle crash test performance, below-knee lower extremity injuries remain the most common AIS 2+ injury in real-world frontal crashes.

1. Introduction

The most common injuries sustained in frontal motor vehicle crashes involve the lower extremities. The socioeconomic burden of these injuries is high, due to protracted recovery time and related health care costs. Several studies have examined potential occupant and vehicle factors for increasing the risk of lower extremity injuries. Lower extremity injuries were observed more frequently in frontal collisions compared to other crash modes, and seatbelts were not effective restraints in preventing these injuries (Dischinger, 1996; Dischinger et al., 2005). In addition, sex was noted to affect lower limb injury risk, with female drivers having a higher likelihood of ankle and foot fractures than male drivers when height was explicitly considered as a covariate, as height has also been shown to correlate with injury risk (Crandall et al., 1996). In a field study using Folksam Insurance data over the years 1985–

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1991, age was found to be less significant of a predictor for Abbreviated Injury Scale (AIS) 2 and 3+ foot/ankle injuries than seating position and impact location (Parenteau et al., 1996). Rudd (2009) investigated lower limb injury risk and associated factors, and compared the risk and severity of injury based on crash characteristics and vehicle specifications from NASS-CDS data 1994–2007. Results indicated that the incidence of foot and ankle injury increased despite structural improvements to vehicles.

Austin et al. (2012) examined NASS-CDS data from 1997 to 2009 to assess whether intrusion causes lower extremity injuries. For Maximum AIS (MAIS) 2 and greater lower limb injuries, 68.0% of the injury sources originated from the floor including the toepan, while foot controls including brakes accounted for 25.2%, instrument panel and knee bolster for 5.7%, and other injury sources resulted in the remaining 1.1% of injuries. While toepan intrusion is often considered to be a significant contributor in lower extremity injury risk, an updated analysis of the influence of recent vehicle changes to lower limb injuries has yet to have been established.

This study aims to investigate the prevalence and patterns of lower limb injuries in relation to vehicle and driver parameters. In addition, this study evaluates and contextualizes results from real-world lower limb injuries against improvements made in standardized crash testing outcomes over a similar period of time.

2. Methodology

2.1. NASS-CDS data analysis

The National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) is a nationally representative database maintained by the U.S. National Highway Traffic Safety Administration for the assessment of traffic safety and evaluation of crash-resultant injuries. In the current study, the NASS-CDS database was queried to obtain sampled data on the following inclusion criteria: frontal crashes during the calendar years 1998–2010 with the principal direction of force (PDOF) between 11 and 1 o'clock (PDOF = $\pm 30^{\circ}$), and no resulting rollover event, ejection or fire. All case occupants were drivers with age greater than 16 years and who were properly belted. Further classification of frontal crashes was performed based on Collision Deformation Code (CDC), and vehicle class. Vehicle model years were restricted to 1998–2011, since significant changes in airbag systems occurred in 1998 with depowering of inflator and reduction of volume (Kahane, 2006). For survey analysis and survey frequency, weighting factors were assigned a range between zero and one million. Cases with survey weighting factors greater than one million were considered outliers and excluded from the analysis.

In the examination of demographic data, height, weight and sex were considered as potential injury predictors. Body Mass Index (BMI) was calculated and categorized based on standard ranges: underweight (BMI $\leq$ 18.5), normal weight (18.6 $\leq$ BMI $\leq$ 24.9), overweight (25 $\leq$ BMI $\leq$ 29.9) and obese (BMI $\geq$ 30) (James et al., 2001). Vehicles were categorized into four body types, namely passenger cars, SUVs, light vans, and pickup trucks (<5000 kg curb weight).

Injury outcomes were coded based on the AIS (AAAM, 1990). The occupant's body was divided into seven anatomical regions based on the AIS coding standards: (1) head/face, (2) neck, (3) thorax, (4) abdomen, (5) spine, (6) upper extremity, and (7) lower extremity. Pelvis contents including soft tissues, vessels, etc. were included in the abdominal region, while musculoskeletal structures (e.g., sacroilium, pubic symphysis, etc.) were included in the lower extremity category. For each body region, selection criteria limited analysis to moderate or more severe injuries (i.e., AIS 2+). Maximum AIS was documented for each anatomical region by counting the most severe injury and excluding concurrent injuries of the same AIS level.

The classification of lower extremity region was applied using a functional approach similar to that of Klinich and Schneider (2003), with the lower limb been categorized into five sub-regions: hip, femur shaft, knee, tibia/fibula shaft, and ankle/foot (Table 1). The functional classification was then mapped with the AIS and queried from the NASS-CDS database. Lower extremity injury codes pertaining to skin, blood vessels, or the nerves were excluded in this anatomical categorization.

A multi-variate logistic regression model was developed for analyzing the associated odds ratios of knee and below knee lower limb injuries in the specified frontal crash conditions(SAS, 2004). NASS-CDS measured the driver toepan and instrument panel intrusion in magnitude ranges (i.e., $\leq$2, 3–8, 9–15, 16–30, 31–46, 46–61, $\geq$61 cm). A preliminary analysis showed the majority of the intrusions occur at lower level with 97.14% of the vehicle's toepan intrusion and 97.56% of vehicle's instrument panel intrusion occurring at less than or equal to 2 cm. As a result, very few observations were included at levels of large intrusion. Therefore, a dichotomous variable was defined to quantify the intrusion level, with less or equal to 2 cm as little/no intrusion or larger than 2 cm as moderate/severe intrusion. Delta-V was included in the regression model as a continuous variable for the measurement

Table 1
Categorization of AIS 2+ lower limb injuries.

Category	AIS 2+ lower limb injuries	
Hip	Femoral head/neck fractures Hip dislocation NFS	Hip NFS laceration into joint
Femur shaft	Femur fractures Femoral vessel injury	Femur fracture Femur supracondylar
Knee (fractures, soft tissue injuries)	Femoral condyle fracture Collateral/cruciate ligament laceration Patellar tendon Patella fracture Popliteal vein NFS	Tibia condyle fracture Joint laceration Dislocation Sprain Popliteal artery NFS
Tibia/fibula shaft	Tibia fracture Fibula fracture	Tibia open/comminuted fracture
Ankle/foot	Dislocation Foot fracture (talus, calcaneus, medial mal., posterior mal.,toe)	Fibula lateral malleolus fracture Achilles tendon Ligament laceration