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Case series analysis of hindfoot injuries sustained by drivers in frontal motor vehicle crashes

Xin Ye [a,*], James Funk [a], Aaron Forbes [b], Shepard Hurwitz [b], Greg Shaw [a], Jeff Crandall [a], Rob Freeth [c], Chris Michetti [c], Rodney Rudd [c], Mark Scarboro [c]

[a] Center for Applied Biomechanics, University of Virginia, 4040 Lewis and Clark Drive, Charlottesville, VA 22911, USA
[b] School of Medicine, University of North Carolina, 400 Silver Cedar Court, Chapel Hill, NC 27514, USA
[c] National Highway Traffic Safety Administration, 1200 New Jersey Avenue, SE, West Building, Washington, DC 20590, USA

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ABSTRACT

Improvements to vehicle frontal crashworthiness have led to reductions in toe pan and instrument panel intrusions as well as leg, foot, and ankle loadings in standardized crash tests. Current field data, however, suggests the proportion of foot and ankle injuries sustained by drivers in frontal crashes has not decreased over the past two decades. To explain the inconsistency between crash tests results and real world lower limb injury prevalence, this study investigated the injury causation scenario for the specific hind-foot injury patterns observed in frontal vehicle crashes. Thirty-four cases with leg, foot, and ankle injuries were selected from the Crash Injury Research and Engineering Network (CIREN) database. Talus fractures were present in 20 cases, representing the most frequent hind-foot skeletal injuries observed among the reviewed cases. While axial compression was the predominant loading mechanism causing 18 injuries, 11 injured ankles involved inversion or eversion motion, and 5 involved dorsiflexion as the injury mechanism. Injured ankles of drivers were more biased towards the right aspect with foot pedals contributing to injuries in 13 of the 34 cases. Combined, the results suggest that despite recent advancement of vehicle performance in crash tests, efforts to reduce axial forces sustained in lower extremity should be prioritized. The analysis of injury mechanisms in this study could aid in crash reconstructions and the development of safety systems for vehicles.

1. Introduction

Lower extremity injuries are the most common injuries involved in frontal motor vehicle crashes, and within this body region, the foot/ankle complex is the most frequently injured [1]. Previous studies have documented the high incidence of lower extremity injuries with associated consequences and cost [2]. In addition, a recent study found that the relative proportion of lower extremity injuries has continued to increase and now accounts for 45% of all Abbreviated Injury Scale (AIS) 2+ injuries for frontal occupants in frontal crashes [3]. The relative importance of below-knee lower extremity injuries has increased in frontal crashes as seatbelt usage and airbag availability has improved [4]. Since the late 1980s and the early 1990s, considerable changes have occurred in terms of the composition of the vehicle fleet, crashworthiness of the vehicles, and restraint systems. Improvements to vehicle frontal crashworthiness have led to reductions in toe pan and instrument panel intrusions as well as leg, foot, and ankle loads in standardized crash tests. However, the effects of these changes in mitigating the incidence of lower extremity injuries are not clearly understood. While frequency is one measure for prioritization, the long-term impairment and disability associated with a particular lower limb injury varies greatly depending on its location, the involvement of articular surfaces, and the fracture pattern.

Classification schemes for lower limb injuries rely heavily on hypotheses supplemented with laboratory studies in which relatively simple loading were applied. Rational treatment of lower limb injuries and rigorous classification requires extensive knowledge. In addition to the variability associated with the direction, rate and magnitude of the external loading, the lower extremities of occupants in actual crashes vary in their initial position and level of muscle bracing. Given the detailed injury and

* Corresponding author. Tel.: +1 434 466 8342; fax: +1 434 296 3453.
E-mail addresses: xy3vp@virginia.edu (X. Ye), jfunk@virginia.edu (J. Funk), aaronlforbes@gmail.com (A. Forbes), shurwitz@abos.org (S. Hurwitz), cgs5w@virginia.edu (G. Shaw), jrc2h@virginia.edu (J. Crandall), Robert.Freeth@inova.org (R. Freeth), Christopher.Michetti@inova.org (C. Michetti), Rodney.Rudd@dot.gov (R. Rudd), Mark.Scarboro@dot.gov (M. Scarboro).

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crash information, cases from the Crash Injury Research and Engineering Network (CIREN) could demonstrate these complex conditions as injury patterns do not identically match with existing classification schemes that are predominantly based on experimental testing conditions. A recent study reviewed the biomechanics of ankle injuries from mechanical testing of human cadavers, and summarized the injury mechanisms based on the principle axis of force or torque applied to injured foot segment [5]. The proposed diagram deciphered experimental data for identifying injury mechanisms given an injury pattern and was referred in current study. The resulting flow-chart of initial foot and ankle positions along with the loading components provided a valuable tool for understanding injury mechanisms and associated injuries with contributing factors, including vehicle intrusions and foot panel contacts. The motion of the foot by a three-dimensional coordinate system in this study was illustrated using the Society of Automotive Engineers (SAE) sign convention (Fig. 1), with terminology describing the ankle kinematics [6].

The objective of this study is to analyze the current patterns and causes of lower extremity injuries sustained in moderate to severe frontal crashes, as a tool to provide forensic evidence and reference for crash reconstruction and injury mechanism analysis.

2. Methodology

Crash Injury Research and Engineering Network (CIREN) is a U.S.-based research program designed to gather detailed records necessary to conduct multidisciplinary analysis on crash reconstruction and attribution of injury causation. Individual CIREN cases consisted of extensive information including crash summary, vehicular damage, countermeasure information, and injury biomechanics, with supporting radiology files. The crash investigation utilized physical evidence such as skid marks, vehicular damage measurements, and occupant contact points coupled with the investigator's expert knowledge and experience of vehicle dynamics and occupant kinematics in order to determine the pre-crash, crash, and post-crash movements of involved vehicles and occupants. Medical experts and engineers went over the evidence for each case, and analyzed the documented photographs, X-ray films and CT scans of the patient's injuries. Cases with complete CT scans and Digital Imaging and Communications in Medicine (DICOM) files were selected for 3-D reconstruction of injuries to examine more specific patterns and locations, adding detailed information on postulated injury causation and severity. Injury severity ranking and attribution was also conducted based on medical notes and relevant injury radiology files.

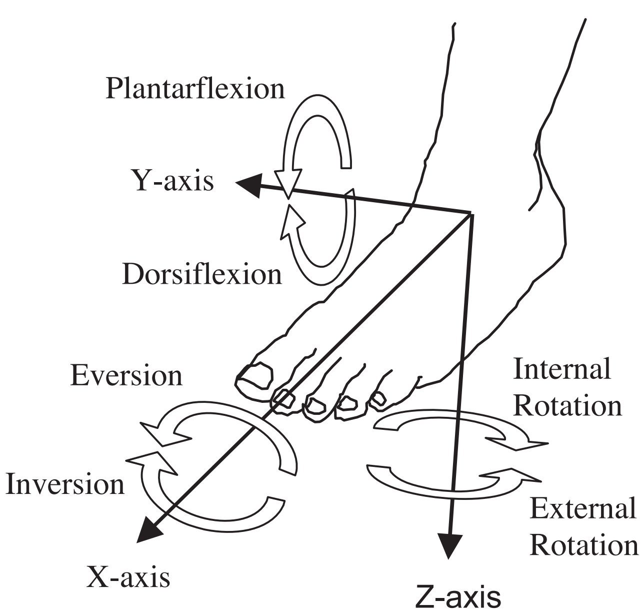

Fig. 1. Diagram of terminology used to describe ankle kinematics.

Eligibility and criteria for case inclusion in this study consisted of drivers older than 16 years of age that were involved in a single event, frontal plane crash during the years 2005 to 2010. Frontal collisions was determined by occurrence of most severe vehicle crash damage (i.e., Rank 1) in the frontal plane with principal direction of force (PDOF) ranging between positive and negative 20 degrees. Collision Deformation Classification (CDC) was also tracked for crash type identification as per the CIREN coding guidelines. All case occupants must contain at least one ankle of hind foot injury with moderate or greater severity of injury, as defined by the Abbreviated Injury Scale (i.e., AIS2+) [7].

An in-depth analysis, using crash, occupant, and medical information, was performed on the selected cases to identify each hind foot injury: specifically, the injury mechanisms, contributing factors, involved vehicle components, injury causation scenarios, and applicable injury trauma codes. Fracture classification was conducted and each injury pattern was coded using the AIS codes. Additionally, the lower extremity injuries were further classified based on existing OTA classification developed by Orthopaedic Trauma Association to standardize the characterization of injury severity and potential associated impairment [8]. The Lauge–Hansen classification was not included in the injury summary results, as the classic classification system was not fully prognostic to represent all hind-foot injury mechanisms, including supination and external rotation injuries [9,10]. Involved physical components (e.g., instrument panel, toe pan) and initial foot orientation were then deduced based on the injury results coupled with crash statistics and kinematics knowledge. Vehicle intrusion and contacts for each injury were labeled with an injury causation scenario. The long term consequences of each injury was also analyzed based on post-injury observation notes and invasive procedures, in terms of their impact on cognitive, physical, psychosocial and economic factors.

Decisions for each case were justified via utilizing the BioTab method to determining and documenting injury causation and injury mechanisms, which leveraged information available to develop evidence-based assessment and to improve the quality and accuracy of the findings [11]. Complete review of the crash scenario was performed in consideration of an extensive literature review of hind foot injuries for similar injury patterns. For cases involving multiple injury mechanisms, both primary and secondary attributing factors were documented. Consensus was reached with all judgments confirmed by biomechanical engineers, medical doctors, orthopaedic surgeons, and epidemiologists through case review sessions.

3. Results

The case inclusion criteria resulted in 34 cases with detailed information in terms of driver characteristics and lower limb injuries to further investigate the mechanisms of injuries to the foot/ankle complex (Table 1).

A statistical summary of demographic information showed that female drivers accounted for 62% of queried cases, with passenger cars attained the highest proportion in vehicle types (Table 2).

Injury with the highest AIS code was assigned with Rank 1 injury, and if two or more injuries meet the criteria of the highest AIS, ranking was based on the source of injury and confidence of data from CIREN database. As a result, lower extremity injuries accounted for 50% of Rank 1 injuries in these cases, with hind foot and ankle injuries contributed to 38% of Rank 1 injuries (Table 3).