LOWER EXTREMITY INJURY CAUSATION IN FRONTAL CRASHES

Chris Sherwood
Brian O'Neill
Insurance Institute for Highway Safety

Shepard Hurwitz
University of Virginia Health Sciences Center
Department of Orthopedic Surgery

ABSTRACT

Data from 37 frontal crashes in which drivers or right-front passengers sustained lower extremity fractures at or below their femoral condyles were obtained from an ongoing study of real-world crashes in a 7-county region in central Virginia, U.S.A. Information obtained from the crash-involved vehicles included crush and intrusion measurements; for each injured person, injury details including the related medical records and radiographs were reviewed. Injuries were classified according to the mechanism of fracture. The most common fractures involved the ankles (36 percent), followed by the knees (33 percent). The most frequent causes of ankle fractures were axial loading and external rotation. Intrusion was common (83 percent) in below-knee fractures, though such fractures sometimes occurred in the absence of intrusion. Patella fractures typically did not involve intrusion and appeared to result from direct loading of vehicle structures in front of the knees, indicating that the risk of these fractures may be reduced with improved design of knee impact areas.

LOWER EXTREMITY INJURIES are a frequent and serious consequence of motor vehicle crashes. The lower extremities are the second most common site of Abbreviated Injury Scale (AIS) 2+ injuries for belted occupants (Morgan et al., 1991). According to National Automotive Sampling System Crashworthiness Data System data for all crash types combined, front-seat occupants sustained more than 190,000 moderate or higher (AIS 2+) injuries to the lower extremities in 1996. Insurance loss data indicate that weight-bearing bone fractures account for $2.6 billion every year (Werner, State Farm Insurance Companies, personal communication, June 1999; Insurance Research Council, 1994). The introduction of airbags and increased levels of seat belt use in the United States are reducing the number of life-threatening injuries in serious motor vehicle crashes. However, many of these "new" survivors will sustain lower extremity injuries that now will require medical treatment, so the costs associated with these injuries are likely to increase.

In addition to direct medical treatment costs, lower extremity injuries can have serious effects on long-term impairment and disability. MacKenzie (1986) found that only 56 percent of patients with lower extremity injuries had returned to work after 1 year. In another study of patients at 6 months after a lower extremity injury, the average level of dysfunction or disability was rated as moderate (MacKenzie et al., 1993). However, the reported effect of the injury on work was severe. Even among patients who have no serious short-term effects, osteoarthritis, which may not be in evidence until years later, can be another direct consequence of these injuries.

To better understand the mechanisms that cause lower extremity injuries in automobile crashes, researchers have conducted biomechanical studies attempting to link injuries to cadaveric specimens and dummy injury measures with loading patterns similar to those caused by contact with vehicle interiors. Begeman and Prasad (1990) tested the ankles of cadavers and Hybrid III dummies in response to dorsiflexion and produced a variety of fracture patterns. Begeman et al. (1993) tested the ankle's response to inversion and eversion. Fractures occurred as the ankle reached its full range of motion in both of these studies. Parenteau et al. (1998) reported that when the ankle reaches these limits of motion, ankle injury (fracture or dislocation) can occur with bending moments as low as 40 Nm. Yoganandan et al. (1996) published a study on the response of the foot-ankle complex to axial loading. Specific injuries were not enumerated but were described as including "extra/intra-articular fractures of the distal tibia/calcaneus with or without extensions into the anatomic joints." Age and dynamic axial force were the best injury predictors. Atkinson et al. (1997) studied the effect of padding on direct loads to the patella. All knees struck with a rigid surface sustained injuries, whereas knees struck with a padded surface (but with additional energy to give approximately the same axial load) did not sustain injuries.

Studies with cadavers suggest that muscle loading conditions during a crash are important, but the effect of these conditions are not well understood. Crandall et al. (1996) tested entire cadavers in a vehicle buck that simulated longitudinal intrusion of the toepan. Only 1 of the 12 cadavers sustained an injury. Kitagawa et al. (1998) tested below-knee cadaver legs with dynamic axial loading but simulated braking force by loading the Achilles tendon. With tibia loads similar to those reported by Yoganandan et al. (1996), the authors were able to produce tibia pylon fractures, which previously had not been produced consistently in the laboratory. They attribute this to the loading of the Achilles tendon. Klopp et al. (1997) tested cadaver legs including the knee joint and simulated bracing of the leg by using a harness at the knee joint that provided a knee extension moment, which was calibrated to provide a tibia axial load of one-half body weight. No consistent injury patterns were produced, and fractures occurred in only 11 of the 50 specimens.

Other research has attempted to determine the mechanisms that cause lower extremity injuries in real-world crashes by combining post-crash vehicle investigations with analysis of the relevant medical records. Lestina et al. (1992) studied 23 frontal impacts, finding that inversion or eversion was the most frequent ankle injury mechanism and that intrusion existed in more than half the cases. Portier et al. (1993) analyzed 42 occupants and determined ankle injuries were most frequently associated with inversion or eversion, whereas forced dorsiflexion caused most metatarsal injuries. Dischinger et al. (1994) reported that inversion or eversion (with or without other loads) contributed to 65 percent of ankle fractures. Taylor et al. (1997) reported that intrusion was an important cause of below-knee injuries, accounting for a majority of the injuries and the most severe ones. Although interaction with foot pedals appeared to be responsible for many injuries, these were less severe.

Despite controlled testing in laboratory conditions and retrospective studies of real-world crashes, data still point to many different possible mechanisms that might be involved in real-world leg injuries. It is the combination of loading mechanisms that can cause these injuries and makes this area of research challenging. The present study focuses on a set of lower leg injuries in real-world crashes that have been studied in detail and provides information on the injury mechanisms.

METHODS

Since 1987, the Insurance Institute for Highway Safety has been conducting in-depth investigations of a sample of towaway crashes of recent model passenger vehicles occurring near Charlottesville, Virginia, U.S.A. Any crash occurring in the city of Charlottesville plus those in Albemarle, Buckingham, Fluvanna, Greene, Louisa, Madison, and Orange counties in which at least one passenger vehicle was towed from the scene was a candidate for the study. Crashes were identified by police reports, collected regularly from the Charlottesville Police Department, the Albemarle County Police Department, or the Virginia State Police. Vehicles usually were examined within 3 to 5 days of the crash at the locations to which they were towed. Data were collected using forms generally similar to those used in collecting National Automotive Sampling System data (Lestina et al., 1992); vehicle damage was described using the Collision Deformation Classification, a seven-digit coding system for vehicle damage. Intrusion typically was measured at several locations in the vehicle. The reported intrusion values used in this analysis are the highest values measured at locations in the areas of the specific injuries, i.e., intrusion measures at the instrument panel for patella fractures, or footwell intrusion measures for all other injuries. In some crashes, intrusion was noted but could not be measured. For this study, an occupant is considered belted if he or she was determined to have been using at least a lap belt. This determination was made from inspection of the belt/webbing and from police and hospital reports of belt use.

The University of Virginia Health Services Center, a level 1 trauma center, treats the vast majority of those injured in vehicle crashes in the study region. To identify occupants of selected vehicles, the university hospital's emergency department log was checked daily, and hospital records were obtained. Vehicle occupants who did not go to the emergency department were interviewed by telephone to determine whether they sustained injuries or whether medical care was obtained elsewhere (Lestina et al., 1991). Follow-up data (e.g., long-term recovery status) were not collected.

The subjects included in this study were drivers or right-front passengers who were not ejected and who sustained fractures to the legs at the knee or below in frontal crashes (10 o'clock to 2 o'clock) with no subsequent rollover, and whose radiographs were available. Ligamentous injuries were not recorded on a consistent basis. Using the study's database, these criteria resulted in 37 crashes with 37 injured occupants and a total of 45 injuries. More than one injury per occupant was counted only if it represented a distinct injury; for example, fractures to both malleoli in the ankle were considered to be one injury, but a calcaneus fracture and a medial malleolus fracture on the same leg were identified as two injuries. This scheme was used for two reasons: first, in order not to overstate certain fractures, such as counting fractures to three of the metatarsals as three injuries; second, to identify injuries as separate if they could have a different causal mechanism. Thus, for example, fractures to the medial malleolus and the fibula shaft are caused by one loading combination of external rotation/inversion, not by two separate external loads.

Radiographs for each of the injuries were studied by an experienced orthopedic surgeon. The fractures were coded according to the Orthopedic Trauma Association (OTA) classifications (except for patella fractures). Determination of the injury mechanism involved comparison with other images considered as standard reference, such as OTA or AO (Arbeitsgemeinschaft für Osteosynthesefragen (Switzerland)) classification schemes. Thus, the mechanism of injury is an inference, not a conclusive determination. Using the medical records and information about the crash, the most likely injury mechanism was determined for each fracture. Anatomical motions of the lower extremity are shown in Figure 1.

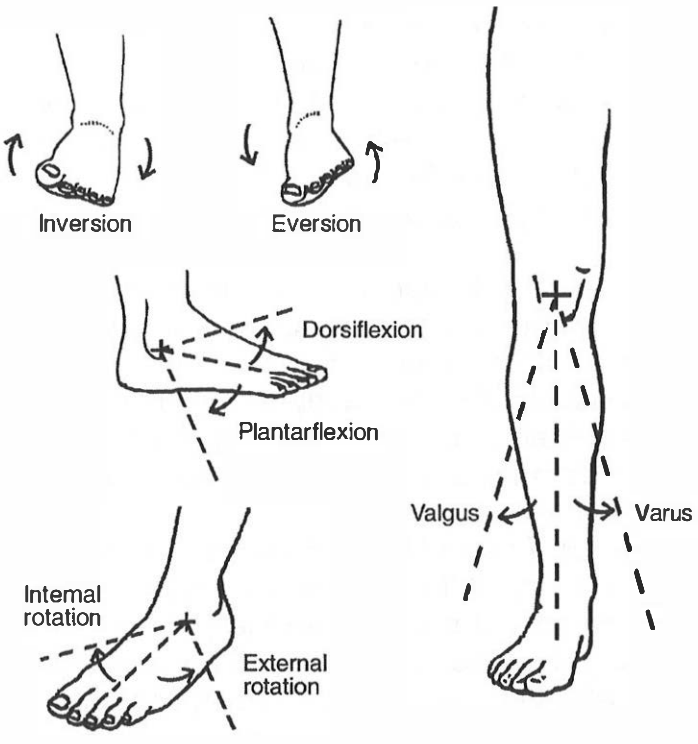

Fig. 1 – Anatomical motions of lower extremity joints

RESULTS

The average age of the 37 occupants was 46 years old (range 17-74 years); 20 (54 percent) were female, and 17 (46 percent) were male. Thirty-three (89 percent) of the occupants were drivers, and 4 were right-front passengers. Three of the 4 injuries to the passengers were patella fractures. Sixty-seven percent of the injuries (75 percent of ankle fractures) were to the right leg. The average velocity change (delta V) was 42 km/h (range 18-80 km/h) for the 31 vehicles for which delta V could be estimated. Most (84 percent) of the occupants sustained only 1 lower leg fracture. One 74-year-old female driver in a severe crash (delta V=80 km/h) sustained 4 injuries. Statistics for delta V and age were calculated on the basis of the 37 occupants, not the 45 injuries. The injuries and other relevant data are listed in Table 1 and shown in Figure 2.

Ankle fractures were most common, accounting for 16 of the 45 injuries (36 percent). Table 2 lists the distributions of the specific ankle fractures. The average delta V was 46 km/h for the crashes in which an occupant sustained an ankle fracture. The average intrusion in these vehicles was 13 cm (range 0-35 cm).

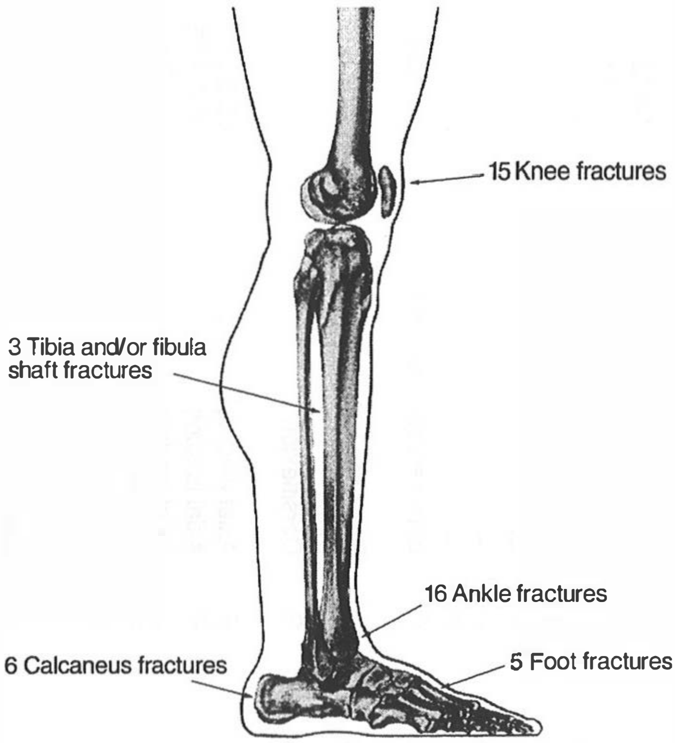

Fig. 2 – Skeletal locations of injuries

Table 1 – Lower leg injuries and driver and crash characteristics

Injury	Aspect	Mechanism	OTA code	Age	Gender	Seat position	Belt use	Delta V (km/h)	Maximum intrusion (cm)*
Ankle Fractures									
Bimalleolar fracture	R	External rotation/inversion	44-B3.2	74	F	D	B	—	32
Bimalleolar fracture	R	Medial force and inversion	44-A2	74	F	D	B	80	27
Bimalleolar fracture	L	External rotation/inversion	44-B2	47	F	D	U	31	None
Medial malleolus fracture	R	—	—	32	F	D	U	68	15
Medial malleolus fracture	R	—	—	28	M	D	U	55	35
Medial malleolus fracture	R	—	—	26	M	D	B	51	Yes
Medial malleolus fracture	R	—	—	32	F	D	U	—	9
Medial malleolus fracture	R	—	—	31	F	D	U	37	None
Medial malleolus fracture, fibula shaft fracture	R	External rotation/eversion	44-C2.2	36	F	D	B	—	4
Medial malleolus fracture, fibula shaft fracture	L	Posterior force and external rotation	44-C1.33	24	M	D	U	43	17
Medial malleolus fracture, talar neck fracture	R	Dorsiflexion	—	57	M	D	U	61	Yes
Pylon fracture	R	Axial loading/inversion	43-B2.2	38	F	D	U	27	8
Pylon fracture	R	Axial loading	43-B3.25	72	F	D	—	41	Yes
Pylon fracture	L	Axial loading	43-A3.1	74	F	D	B	80	12
Pylon fracture	R	Axial loading/inversion	43-B2	60	F	D	B	30	None
Pylon fracture	L	Axial loading/inversion	43-C3.2	49	M	D	B	28	7
Knee Fractures									
Patella fracture	R	Direct loading	—	47	M	D	B	36	—
Patella fracture	R	Direct loading	—	54	F	D	B	69	13
Patella fracture	L	Direct loading	—	67	F	D	B	—	—
Patella fracture	R	Direct loading	—	61	M	D	B	26	—
Patella fracture	R	Direct loading	—	38	F	P	—		None
Patella fracture	L	Direct loading	—	45	F	D	U	30	None
Patella fracture	R	Direct loading	—	32	M	D	U	47	None

cont'd

Table 1 – Lower leg injuries and driver and crash characteristics (cont'd)

Injury	Aspect	Mechanism	OTA code	Age	Gender	Seat position	Belt use	Delta V (km/h)	Maximum intrusion (cm)*
Patella fracture	L	Direct loading	—	63	F	P	U	18	None
Patella fracture	R	Direct loading	—	40	M	P	B	22	None
Patella fracture	R	Direct loading	—	58	M	D	B	61	None
Patella fracture	L	Direct loading	—	58	M	D	B	61	None
Tibia plateau fracture	L	Axial loading/valgus	41-B2.1	39	M	D	U	39	None
Tibia plateau fracture	R	Axial loading/varus	41-C1.2	47	F	D	B	51	Yes
Tibia plateau fracture	L	Axial loading/valgus	41-B3.1	44	F	D	U	34	None
Femoral condyle fracture	R	Axial loading	33-C1	47	F	D	B	51	Yes
Calcaneus Fractures									
Calcaneus fracture	R	Vertical compression	73-C1	47	M	D	B	55	None
Calcaneus fracture	R	Inversion	73-A1.2	40	M	D	U	31	None
Calcaneus fracture	R	Vertical compression/eversion	73-C1	52	M	D	B	39	27
Calcaneus fracture	L	Vertical compression	73-C2	54	F	D	B	69	33
Calcaneus fracture	L	Vertical compression	73-C2.1	51	F	D	B	36	13
Calcaneus fracture	R	Vertical compression/inversion	73-C2	50	F	D	B	29	9
Foot Fractures									
Metatarsal fracture	R	Dorsiflexion	81-D1	25	M	D	B	—	34
Metatarsal fracture	R	Axial loading/dorsiflexion	81-A3	38	F	D	U	27	8
Metatarsal fracture	L	Dorsiflexion	81-B1.1	74	F	D	B	80	12
Metatarsal fracture	R	Axial loading/valgus	82-C1.3	49	M	D	B	28	5
Navicular fracture	L	Axial loading	74-B2	33	F	D	B	50	Yes
Tibia and/or Fibula Shaft Fractures									
Tibia/fibula shaft fracture	L	Axial loading/rotation	42-A1.2	17	M	D	U	47	—
Tibia/fibula shaft fracture	R	Axial loading/varus	42-B1.2	74	F	D	B	80	27
Fibula shaft fracture	R	External rotation/inversion	44-B1	68	M	P	U	32	Yes

*Instrument panel Intrusion was measured for patella fractures, and left or right footwell intrusion was measured for all other injuries.
— not available

Table 2 – Distribution of knee and ankle fractures

16 Ankle fractures	5 Pylon fractures 5 Medial malleolar fractures 3 Bimalleolar fractures 2 Medial malleolar/diaphyseal fibular fractures 1 Medial malleolar/talar neck fractures
15 Knee fractures	11 Patella fractures 3 Tibia plateau fractures 1 Femoral condyle fractures

Injury mechanisms were not identified for the 5 isolated medial malleolar fractures. These injuries can occur from dorsiflexion, adduction, intemal rotation, or direct contact. A clinical examination of the injury site at the time of the injury is necessary to accurately determine the mechanism. Inversion or eversion was involved in 7 of the other 11 ankle fractures; however, neither was ever the sole injury mechanism, and these fractures did not appear to result from exceeding the inversion/eversion limits of motion. Rather, the fracture pattems indicate that inversion/eversion merely describes the position of the ankle when the injury force (axial load, extemal rotation) was experienced. Axial loading was a mechanism in all 5 of the pylon fractures but not a mechanism in any of the other ankle fractures. Extemal rotation was a mechanism in 4 of the injuries.

Knee injuries (fractures to the femoral condyle, patella, or tibia plateau) accounted for 15 (33 percent) of the 45 injuries. Although these fractures occurred in the same anatomical joint, they have different injury mechanisms and thus will be discussed separately.

Patella fractures were very common, accounting for 24 percent of the injuries. Eight fractures (5 right and 3 left patellas) were to drivers, and 3 fractures (2 right and 1 left patella) were to passengers. Of the 10 patella fractures in which occupant belt use was known, 70 percent involved belted occupants. The average delta V for all crashes in which belt use was known was 39 km/h, but the average for the belted cases (43 km/h) was considerably higher than for the unbelted cases (31 km/h). All of the patella fractures were caused by direct contact with the instrument panel, knee bolster, or steering column. Intrusion was present for only 1 patella fracture.

Femoral condyle or tibia plateau fractures accounted for 4 (9 percent) of the injuries. One of the occupants suffered both fractures in the same leg. The delta Vs in these crashes were 34 km/h, 39 km/h, and 51 km/h. Only 1 of the injuries occurred in a vehicle with intrusion. All injury mechanisms were axial loading accompanied by either varus or valgus motion.

Calcaneus fractures accounted for 6 (13 percent) of the injuries, with 4 of the fractures to the right foot. The average delta V for these crashes was 43 km/h (range 29-69 km/h). Five of the 6 occupants were belted, and the average vehicle intrusion was 14 cm (range 0-33 cm). These calcaneus fractures were caused almost exclusively by vertical compression, with inversion or eversion accompanying the vertical compression in 4 of the 6 fractures.

Five of the 44 injuries were foot fractures (4 metatarsal fractures and 1 navicular fracture). The average delta V was 46 km/h (range 27-80 km/h), and the average vehicle intrusion was 15 cm (range 5-34 cm). Four of the 5 occupants were belted. Foot fractures were caused primarily by dorsiflexion and/or axial loading. It is interesting that 3 of the 5 foot fractures occurred in subjects who had multiple lower extremity injuries.

Three of the 44 injuries were shaft fractures of the tibia (2) and/or fibula (1). The delta Vs in these crashes were 32 km/h, 47 km/h, and 80 km/h. Both tibia/fibula fractures were caused primarily by axial loading, whereas the fibula shaft fracture was caused by inversion and external rotation.

DISCUSSION

Ankle fractures were the most common injury, accounting for 36 percent of the fractures in this study. Past research (Lestina et al., 1992; Portier et al., 1993) has suggested that inversion or eversion past the normal biomechanical limits of motion is the most common mechanism in ankle fractures. In this study inversion or eversion was present in 7 of the 11 ankle fractures in which an injury mechanism was identified, but typically was not the main component of failure. In these cases, the ankle was either inverted or everted when another motion caused the fracture. For example, in two of the bimalleolar fractures, inversion/external rotation was the mechanism of injury. The foot was partially inverted and, from this position, an external force caused external rotation of the foot, which resulted in the fractured malleoli. The current findings suggest that axial loading and external rotation forces were the most frequent causes of ankle fractures, causing 5 and 4 fractures, respectively. Axial loads tended to cause pylon fractures, whereas malleolar fractures were caused primarily by external rotation.

The conclusion that ankle fractures in this study were not caused by the foot inverting or everting past its maximum rotation limits does not mean that these motions play no role in the fractures. Crandall et al. (1998) reported that the inversion or eversion angle was not related to ankle injuries under axial load, but that “foot and ankle injuries common in automobile crashes can occur due to a combination of axial loading of the foot and high rate of ankle rotation.” This finding is consistent with the 5 pylon fractures in this study; high axial loads were present in each, and inversion also was a mechanism in 3 of these. Although the major failure mechanism was axial loading, high inversion/eversion rates may have increased the likelihood of fracture. Further laboratory research is needed to determine if inversion/eversion angle or angular rate make the ankle more susceptible to injury during external rotation loads.

Vehicle intrusion played a significant role in leg injuries below the knee. The average amount of vehicle intrusion for those injuries below the knee was 14 cm (range 0-35 cm), and 83 percent (24) of these injuries occurred in crashes with intrusion. This is remarkably similar to the 79 percent reported by Fildes et al. (1995) and the 68 percent reported by Crandall et al. (1995). The ankle, calcaneus, and foot fractures occurred in crashes with similar average intrusion amounts (13-15 cm).

Past research indicates that intrusion, even if it produces small forces or deflections, can raise the risk of injury to the lower extremities, especially the foot and ankle. Sakurai (1996) has shown that intrusion can occur in all directions, causing severe ankle rotations. Footwell intrusion can put the lower extremity in positions that make it more susceptible to injury. An initially plantarflexed foot is more susceptible to injury than a dorsiflexed foot (Klopp et al., 1997). Inversion/eversion angular rates increase likelihood of injury (Crandall et al., 1998). Thus, vehicle modifications to reduce intrusion in the footwell region should reduce the risk of lower leg injuries.

Intrusion played a much smaller role in injuries to the knee area. Of the 8 patella fractures with recorded intrusion measures, only 1 injury occurred in a vehicle with intrusion of the knee bolster/instrument panel. Two of the 4 tibia plateau and femoral condyle fractures had footwell intrusion. Every patella fracture was attributable to direct loading of the knee by structure in front of it, presumably as the occupants moved forward toward those structures. The tibia plateau and femoral condyle fractures were more complicated, resulting from axial loading of the joint through the tibia while the lower portion of the leg rotated inward or outward about the knee. The higher average delta V for the crashes with belted occupants who sustained patella fractures (43 km/h) versus unbelted occupants (31 km/h) suggests that belt use reduces the rate of patella fracture. Still, most patella injuries involved belted occupants (70 percent). Thus, better designs of potential knee impact areas are required to reduce such injuries. For example, the biomechanical research of Atkinson et al. (1997) indicates that improved padding of knee contact areas could be greatly protective of the patella. It could be that deployable knee bolsters would be effective for both types of fractures by limiting the forward motion of the occupant at an earlier stage.

Recently, some manufacturers have introduced energy-absorbing padding in the footwell to reduce foot and ankle injuries. Such padding could be effective in reducing those injuries that involve axial loading through the tibia as well as reducing calcaneus fractures, for which compressive loading was the primary injury mechanism. This study cannot address the effectiveness of these countermeasures, but the ubiquity of intrusion for foot and ankle injuries suggests that limiting footwell intrusion is still important for reducing those injuries.

Currently, no U.S. safety standards address lower leg injuries. However, most automakers are working to improve the structural performance of vehicles in serious frontal offset crashes to obtain good ratings in consumer testing programs in the United States (Insurance Institute for Highway Safety), Europe (EuroNCAP), and Australia (Australian NCAP). These improvements, which include reduction of footwell intrusion, should reduce the incidence and severity of lower leg injuries.

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