LOWER LIMB INJURIES TO PASSENGER CAR OCCUPANTS

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ABSTRACT

A detailed examination was undertaken of hospitalised car occupants who sustained a lower limb injury in a frontal crash. The assessment included an analysis of the type, severity and causes of these injuries and mechanisms involved in lower limb fractures. The findings showed that fractures and dislocations occurred in 88% of lower limb injury cases, that more than half were from crashes below 48km/h and that the number of fractures was directly proportional with delta-V. Ankle dislocations and foot fractures from the floor and toe pan were the most common injury-source combination overall. The most frequent mechanisms of lower limb fracture were compression, perpendicular loading of the knee and crushing or twisting of the foot. The study points to the need for further regulation to reduce lower limb fractures in frontal crashes and highlights a number of possible countermeasures.

LOWER LIMB INJURY to front seat occupants in frontal crashes is still a major source of passenger car occupant trauma, occurring in around one in every three severe crashes (Rastogi, Wild & Duthie 1986; States 1986; Fildes, Lane, Lenard & Vulcan 1994). While not necessarily life threatening, they do cause considerable pain and suffering to the individuals involved, frequently require long-term treatment and rehabilitation and can often result in permanent disability (Bull 1985, Pattimore, Ward, Thomas & Bradford 1991). Furthermore, they are extremely costly to the people involved and to the community generally (Ward, Bodiwala & Thomas 1992).

Apart from specifying acceptable femur loads in regulations such as FMVSS 208 and the Australian ADR 69, there is no other more stringent lower limb injury requirement anywhere in the world that vehicle manufacturers are expected to meet (the offset test procedure currently under development is expected to include some lower limb injury criteria, although this has not been proclaimed at this time).

A study was undertaken on behalf of the Federal Office of Road Safety in Australia to undertake a detailed examination of lower limb injuries to front seat occupants in frontal crashes involving current generation passenger cars. The study set out to identify the frequency and types of lower limb injuries and their contact sources as well as assess the mechanisms of lower limb fractures. This information was to help guide future efforts to develop suitable crash dummies and acceptable crash performance criteria.

METHOD

The Monash University Accident Research Centre has been routinely examining vehicles involved in crashes in and around Melbourne, Australia since 1989. These investigations utilised the NASS crash investigation format (NHTSA 1989) and included details of the type, severity and sources of injury to vehicle occupants and change of velocity during impact (delta-V). Details of this procedure have been thoroughly documented in previous publications (eg; Fildes, Lane, Lenard & Vulcan 1991; 1994) where the entrance criteria required at least one occupant to be either hospitalised or killed and crashes involved all crash configurations in both urban and rural environments. This database (the Crashed Vehicle File) contains details of over 500 crashes and more than 600 injured occupants of which 56% were classified as frontal crashes (full as well as offset frontals). Of these, there were 248 crashes where 280 occupants sustained a lower limb injury and this is fully documented in Fildes, Lane, Lenard, Vulcan and Wenzel (1994).

Mechanism of injury had not been previously recorded in the Crashed Vehicle File, hence it was necessary to re-visit patient files for those sustaining a lower limb fracture. Medical records were accessed at the three major treating hospitals for appropriate cases and relevant additional information from X-rays, surgeons and nursing notes and specialist's comments was gathered to assist in judging mechanism of injury. An expert panel was formed comprising an epidemiologist, a trauma surgeon, a biomechanical engineer and crash investigators to review each case and arrive at a consensus view of the mechanism of injury for each lower limb fracture. Categories of mechanism of injury were developed and these are described in Table 1. Sixty eight out of a possible 98 cases were assessed for mechanism of lower limb fracture (fatalities and unambiguous cases could not be adequately assessed because of lack of sufficient details). Individual case summaries for the 68 cases are available in Lenard, Fildes, Lane, Vulcan and Wenzel (1995).

RESULTS

The average age of the occupants who sustained a lower limb fracture was 38 years, ranging from 18 to 85 years. Fifty-two percent were female and their average age was 6 years older than that for the males. While there were a slight tendency for more cases of lower limb fractures among older women, this was not statistically significant (χ^2=3.04, p=.70).

Table 1 - Summary of mechanism of injury categories used

Code	Mechanism	Direction
01	Axial compression	nil
02	Axial tension	nil
03	Perpendicular loading	medial or lateral
04	Torsion	+ve or -ve (cw or ccw)
05	Shearing	nil
06	Crushing	nil
11	Leg twist	+ve or -ve (cw or ccw)
12	Foot twist	+ve or -ve (inversion or eversion)
13	Ankle twist	+ve or -ve (planaflexion or dorsiflexion))

INJURY ANALYSIS. Table 2 shows that knees were the most common lower limb region injured by front seat occupants in frontal crashes across all injury severities and marginally more so for offset and oblique collisions. Table 3 reveals, however, that most of these knee injuries were relatively minor (81% involved abrasions, contusions or lacerations, predominantly AIS 1 severities). Fractures (dislocations) were more frequent among ankle, leg and thigh injuries. Multiple injuries for each body region were included to ensure that nothing was overlooked in this analysis.

Table 2 - Region of lower limb injury by type of frontal crash

Region of lower limb injury	Full frontal	Offset frontal	Oblique frontal	Total
Ankle/foot	71%	99%	70%	79%
Leg	79%	84%	99%	89%
Knee	130%	111%	100%	111%
Thigh	27%	52%	76%	56%

Multiple injuries were allowed to ensure all injuries were included

Table 3 - Type of lesion by body region injured in frontal crashes

Lower limb lesion	Ankle	Leg	Knee	Thigh
Abrasion	10%	46%	49%	18%
Contusion	70%	46%	50%	62%
Fracture	83%	63%	19%	60%
Laceration	11%	35%	60%	20%

Multiple injuries were allowed to ensure all injuries were included

Table 4 - Source of injury for lower limb fracture or dislocation to front seat occupants (drivers and front-left passengers) in frontal crashes

	Ankle/Foot	Leg	Knee	Thigh	TOTAL
Steering Wheel				5	**5**
Steering Column		1	6	1	**8**
Instrument panel		9	6	16	**31**
Glove Compartment					**0**
Side Panel		2		4	**6**
A-Pillar		1		1	**2**
Floor & Toe Pan	38	19			**57**
Foot Controls					**0**
Parking Brake					**0**
Ground & Exterior	1	1			**2**
Add-On Equipment					**0**
Other/unknown		1			**1**
TOTAL	**39**	**34**	**12**	**27**	**112**

Figures show the injury/source rates per 100 front seat occupants. Only one fracture per contact source was permitted.

Table 4 shows the body region by contact source analysis for front seat occupants who sustained a lower limb fracture or dislocation. The six most common combinations were ankle/foot with floor and toepan (38%), leg with the floor and toepan (19%), thigh with the instrument panel (16%), leg with the instrument panel (9%), knee with the instrument panel (6%) and knee with the steering column (6%). While seating position has obvious implications for injuries and countermeasures, the number of cases was too small for a detailed and meaningful analysis here.

FRACTURES AND INTRUSIONS. Intrusions into the occupant compartment involving the floor and toepan or lower instrument panel were reasonably common among these lower limb fracture or dislocation cases (79%). Table 5 shows the distribution of driver and front left passenger (FLP) lower limb fractures with and without intrusion. The total number of cases is more than the total injured occupants as an occupant could have a leg & foot fracture or dislocation as well as a knee or thigh fracture.

Table 5 - Lower limb fractures with and without intrusion

	Leg/Foot Fractures		Knee/Thigh Fractures	
	Driver	FLP	Driver	FLP
With Intrusion	29	7	27	6
Without Intrusion	5	3	7	0

More than 82% of fractures to the leg and foot were associated with intrusion of the floor or toepan. In many of these cases, foot fractures among drivers (especially right foot fractures) seemed to be associated with use of the pedals, although there were still a sizeable number of leg and foot fractures involving the left foot of drivers and front left passengers where pedal involvement was unlikely. In cases without intrusion, some of the leg and foot fractures seemed to be the result of extreme axial loads in compression (when the knee is locked into the lower part of the instrument panel and the foot is loaded against the floor.

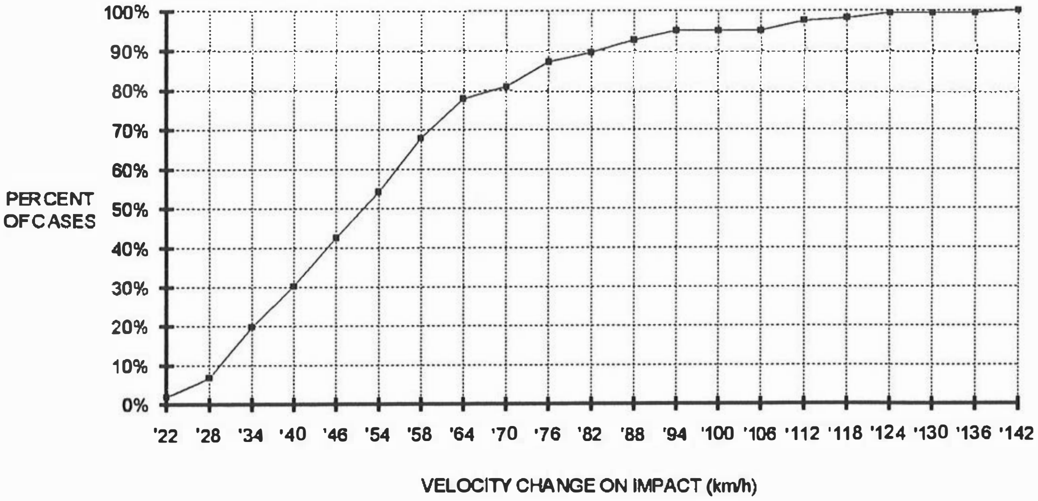

Figure 1 Cumulative percent of lower limb fractures by delta-V.

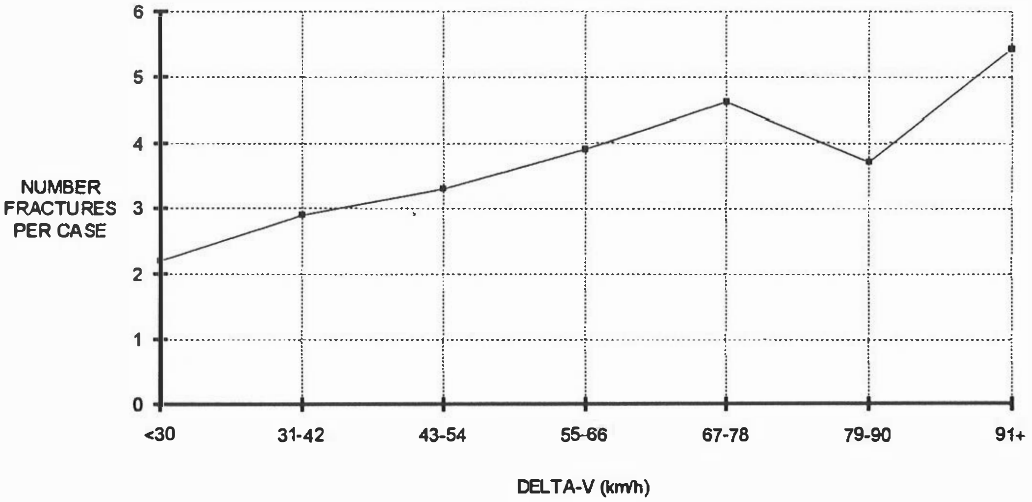

Figure 2 Relationship between delta-V and number of fractures.

Analyses was also undertaken of the rate of lower limb injury by change of velocity during impact (delta-V) and these are shown in Figures 1 and 2. In the first figure, it is apparent that 50% of lower limb fractures occurred at 48km/h or below and that the 80th percentile value of lower limb fractures was 70km/h. Figure 2 shows that the number of fractures per fractured lower limb case was directly proportional to delta-V (the dip in the curve at 79-90 delta-V is probably simply a function of the small number of cases). Although not shown here, lower limb fractures were more common among occupants of smaller than larger cars.

MECHANISM ANALYSIS. The mechanism of injury analysis revealed that compression was the most common mechanism of lower limb fracture or dislocation (42%), followed by perpendicular loading (25%), crushing (13%) and foot twisting (13%). None of the other mechanisms were especially noteworthy. The mechanisms and direction of movement associated with the six most common lower limb fracture by source combinations are shown in Tables 6 and 7 below. Of particular note, dorsiflexion ankle twisting and medial perpendicular loading of the leg seem to be relatively common mechanisms leading to dislocation or fracture of the lower limbs that could be targeted in future initiatives to reduce these injuries.

Table 6 - Mechanisms of lower limb fractures

INJURY SOURCE	ankle/foot floor/toepan	lower leg floor/toepan	thigh inst. panel	lower leg inst. panel	knee inst. panel	knee steering	TOTAL
compression	31%	62%	62%	60%	20%	17%	**42%**
tension							
perp. loading	5%	24%	24%	30%	80%	83%	**25%**
torsion		5%	4%				**1%**
shearing	7%	5%					**4%**
crushing	31%						**13%**
leg twist		5%					**1%**
foot twist	25%		10%	10%			**13%**
ankle twist	2%						**1%**

Table 7 - Directional findings of lower limb fractures

Ankle/Foot Fractures from Floor and Toepan

70%	not applicable		
27%	12 - foot twist	eversion (-ve)	40%
		inversion (+ve)	60%
3%	13 - ankle twist	dorsiflexion	100%
		plantarflexion	0%

Lower Leg from Floor and Toepan

66%	not applicable		
24%	03 - perpendicular loading	lateral	0%
		medial	100%
10%	04 - torsion	positive	50%
		negative	50%

Thigh from Instrument Panel

65%	not applicable		
21%	03 - perpendicular loading	lateral	33%
		medial	67%
14%	04 - torsion	positive	75%
		negative	25%

Lower Leg from Instrument Panel

60%	not applicable		
30%	03 - perpendicular loading	lateral	0%
		medial	100%
10%	04 - torsion	positive	0%
		negative	100%

Knee from Instrument Panel

100%	not applicable		

Knee from Steering Wheel

92%	not applicable		
8%	03 - perpendicular loading	lateral	100%
		medial	0%

Not applicable refers to cases where a direction of force result was not relevant or meaningful (eg; compression is direction neutral).

DISCUSSION

There has not been much research conducted into lower limb injuries to date and only one or two of the papers uncovered reported mechanism of injury results. There are a number of aspects of these findings that deserve further discussion.

As noted earlier, a number of studies from the US, Europe and Australia have reported a high incidence of lower limb injuries in frontal crashes which is consistently around 30 to 40 percent in frontal crashes. There was greater inconsistency in the particular types of lower limb injuries seemingly because of differences in injury severity and belt wearing between these studies. The high incidence of ankle and foot injuries observed in the study reported here was quite different to that reported by Huelke, O'Day and States (1982), although this earlier study involved mainly unrestrained occupants. Of interest, though, the finding in this study that the floor and toepan features highly as the predominant cause of ankle dislocations and foot fractures was also reported by Huelke et al as well as in other restrained population lower limb analyses (Pattimore, Ward, Thomas & Bradford, 1991).

The mechanism of injury results demonstrated that many of the ankle dislocations and foot fractures resulted from dorsiflexion twisting of the ankle and from eversion and inversion movements of the foot. Begeman and Prasad (1990) showed in cadaver studies that abrupt dorsiflexion (bending the foot upwards) past 45 degrees, without eversion, caused malleolar fracture and ligament avulsion which suggests that the occupants observed in the Crashed Vehicle File must have experienced severe loading from underneath. Lestina and colleagues (1992) also found that eversion and inversion loading of the foot beyond the normal limits of rotation were common mechanisms involved in foot fractures, although they did not find evidence of over-involvement of dorsiflexion as was found here.

Clearly, additional effort on the part of manufacturers to provide fewer floor and toepan intrusions and increased energy absorbing padding in these regions are warranted on the basis of these universal findings. The required thickness and type of floor padding for adequate protection is an area still requiring further research (it is understood that Daimler-Benz have introduced 1 inch or 25 mm of honeycomb padding under the floor/toepan area in some of their models, although the effectiveness of this does not appear to have been reported on extensively at this time).

What role the pedals play in these injuries is not clear from the findings of this study as it is practically impossible to determine pedal use objectively in retrospective studies. Estimate of pedal involvement in lower limb fractures in this study were 8% overall (12% for the drivers) and mainly those involving ankle dislocations or foot fractures, although this was not a convincing result.

Others have argued that the pedals play an even more major role (Begeman & Prasad 1990; Bowker 1991; Pattimore et al 1991; Pilkey et al 1994) and estimates have ranged up to 60% for all ankle and foot injuries. This suggests there is merit in designs aimed at developing a safer pedal. The practicality of break-away pedals under extreme loading might also be worth investigating.

Levine (1986) reported that ankle dislocations and bone fractures were usually faster to recover than other types of lower limb fractures (around six to 12 weeks on average), although foot fracture recovery varied greatly, depending on the bones involved. A number of the cases observed in this study involved multiple ankle dislocations and foot fractures and the medical records suggested these people required substantial periods of treatment and rehabilitation. It would be interesting to follow up all these cases systematically to see if Levine's claim is substantiated in other studies.

While the numbers were small, the finding that ankle/foot injuries were more common among those injured in smaller cars seems intuitively sensible, given their smaller mass and therefore less structure ahead of the driver. Morgan, Eppinger and Hennessey (1991) also found a similar trend among the NASS population of crashes in the US. This suggests that efforts to reduce ankle and foot injuries should be especially focussed on smaller cars. Tibia and fibula fractures were the second most common severe lower limb injury recorded in this study and these injuries mainly resulted from contact with the floor or toe pan or the lower instrument panel. The frequent occurrence of tibia fractures in frontal crashes of modest delta-V's was also reported earlier by States (1986).

The principal fracture mechanism observed in this study was from medial perpendicular loading of these bones (bending fractures from intrusions or forward movements), although there were also a noteworthy number of tibia and fibula fractures from torsional (twisting) loading in either a CW or CCW direction. Presumably, this occurred when either the foot or the knee was encapsulated by the floor or instrument panel (States claimed that most tibia shaft fractures were caused by axial loading because of "knee-dash fixation" and rearward movement of the toepan coupled with torsion and/or bending movement). Nyquist (1986) specified acceptable static loads for the tibia from various sources including human volunteer loadings ranging from 233-310 Nm for younger males but only 180-182 Nm for older females. While it might be simplistic to specify a simple standard tolerance load for axial compression of the tibia and fibula, nevertheless, a specific value is needed for design rule purposes and these values seem appropriate.

A femur fracture was sustained by 27 percent of lower limb fracture cases in this study, predominantly from contact with the instrument panel, the steering wheel or the side panel. The major mechanism involved in these fractures was compression, although perpendicular loading was also involved in approximately one-in-four of these fractures. There have been a number of biomechanical investigations of the femur under dynamic loading with both short (8-18 msecs) and long (30-40 msecs) loading times. Among these, the lowest axial compressive loads resulting in fracture was around 4.4 kN and the highest without fracture 23.7 kN. Rastogi and colleagues (1986) were able to estimate the load on the femur in 14 of their 39 cases of fracture, ranging from 8 kN to 26 kN, with a mean of 18 kN. From the findings reported here, attempts to either reduce the frequency of these contacts or the compressive loads involved would all have injury reduction potential.

Fractures of the patella (knee cap) from contact with steering column and instrument panel were also observed here in approximately 12 percent of cases where someone sustained a lower limb fracture. While those sustaining a fractured patella generally have good outcomes (Levine 1986), a small percentage will sustain some on-going disability from the loss of their knee cap. Viano et al (1978) demonstrated that impacting the knee joint below the centre of rotation (with the knees bent) can often lead to fracture and ligament tear. The placement of injurious components in the direct line of travel of the knees in a frontal crash (ie; switches, fuse boxes, exposed steering column support brackets and solid cross members without adequate coverage) should not be tolerated. The use of kneebars to prevent these contacts could also be encouraged as a prevention measure against knee fractures.

The relationship observed here between delta-V and lower limb injury is most interesting and shows that these injuries can occur in crashes as low as 25 km/h and that the probability of injury rises rapidly up to 70 or 80 km/h. Rastogi et al (1986) reported.that lower limb fracture can occur as low as 15mph (24km/h) which was substantiated in this study, too. In addition, a direct linear relationship observed between the number of fractures and delta-V for the cases observed here. This finding does not seem to have been previously reported and again shows the need for greater attention to reducing lower limb injuries in frontal crashes.

In conclusion, these findings have a number of implications for current and future vehicle design regulations. The current dynamic frontal crash standards FMVSS 208 in the US and ADR 69 in Australia specify acceptable axial loads for the femur as the only lower limb injury criterion. Yet, the thigh was only the third most frequent type of lower limb fracture and compression occurred in only 62 percent of these cases. In short, while femur load criterion is necessary, it is clearly not a sufficient measure of lower limb injury potential in modern passenger cars. Attempts in future to regulate to reduce lower limb injuries in frontal crashes need to include ankle and foot, leg and knee measures with suitable criteria to address the more common mechanisms of injury identified in this study. It is hoped that the test procedure for the new offset test proposed in Europe will include suitable lower limb injury criteria.

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