MECHANISMS OF LOWER EXTREMITY INJURIES TO FRONT SEAT CAR OCCUPANTS - AN IN DEPTH ACCIDENT ANALYSIS.

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ABSTRACT

An in-depth analysis of 194 fractures of the lower extremity has been performed. The principal aims of the study were to determine the incidence and mechanisms of lower extremity injuries to front seat car occupants in frontal impacts and to resolve the question of which injuries are a priority for prevention based on their potential for causing long term impairment and disability using new injury severity and impairment scales.

The majority of the most severe and impairing below knee injuries were considered to be caused by footwell intrusion. Although pedals were implicated as the cause of over one fifth of below knee injuries, the majority of pedal related injuries were of low severity and not a source of long term impairment.

LOWER LIMB INJURIES TO FRONT SEAT CAR OCCUPANTS are recognised as an important cause of long term disability in survivors of serious crashes (Pletschen, Scheurent et al. 1990; Miller, Pindus et al. 1993). They are the second most frequent injuries after injuries to the head and face (Pattimore, Ward et al. 1991). Whilst improvements in car safety have focused on reducing life threatening injuries to the head, neck and torso, they have had little impact on reducing lower extremity injuries (Dischinger, Cushing et al. 1992; Fildes, Lenard et al. 1995). As a result of a reduction in potentially fatal injuries, fractures of the lower limb will assume a greater relative importance in terms of future developments in vehicle safety.

Despite recent interest in lower extremity injuries, there is still not enough data available from the investigation of real world crashes on the incidence and mechanisms of the injuries that are likely to be a source of long term disability. Important factors influencing injury risk include occupant and vehicle variables as well as crash configuration.

A review of the literature reveals that the following factors are important in determining the risk of injury to front seat car occupants :

1. Injuries to the leg, foot and ankle are common and are a cause of significant long term disability. (Pletschen, Scheurent et al. 1990; Miller, Pindus et al. 1993)
2. Improvements in car safety have not had a significant effect in reducing injuries below the knee. (Dischinger, Cushing et al. 1992; Fildes, Lenard et al. 1995)
3. Older, shorter and female car occupants are at greater risk of lower extremity injury. (Huelke, Compton et al. 1991; Dischinger, Cushing et al. 1992; Dischinger, Kerns et al. 1994)
4. The majority of injuries to the lower extremity occur in frontal collisions. (Dischinger, Cushing et al. 1992) Offset collisions carry a greater risk of intrusion and there is a much higher incidence of foot and ankle fractures in offset collisions compared to full frontal collisions. (Otte, Rheinhaben et al. 1992; Fildes, Lenard et al. 1995)
5. Increasing crash severity increases the risk of injury. (Otte, Rheinhaben et al. 1992; Fildes, Lenard et al. 1995; Thomas, Charles et al. 1995)
6. Footwell intrusion appears to be the most significant indicator of injury risk although the mechanism by which it influences injury remains unclear. (Thomas, Charles et al. 1995)
7. Pedals appear to play an important role in increasing the risk of injury, particularly in relatively low severity crashes. (Morgan, Eppinger et al. 1991; Pattimore, Ward et al. 1991; Otte, Rheinhaben et al. 1992; Fildes, Lenard et al. 1995; Thomas, Charles et al. 1995). Exactly how they influence injuries is not clear.
8. More detailed information about the exact nature of injuries to the leg, foot and ankle is required. In particular, the relative importance of different loading mechanisms is not clear (Lestina, Kuhlmann et al. 1992). The severity of the resultant injuries as well as their potential for long term impairment is not well defined. (Parenteau, Viano et al. 1996)

This last point is of paramount importance in influencing improvements in vehicle safety. It is important to prevent those injuries that have the potential for causing long term disability as well as less impairing but more frequent injuries. Studies that have attempted to address this issue have been hampered by the lack of a detailed assessment and coding of injury severity and impairment. The Abbreviated Injury Scale (1990) is used as to code injuries in terms of "threat to life" and does not indicate the potential for that injury to cause long term impairment. The Injury Impairment Scale (IIS) (1994) was developed as a measurement of impairment. It has not been validated for pelvic and lower extremity fractures (Massoud and Wallace 1996) . The work of Parenteau et al. (Parenteau, Viano et al. 1996) highlights the inability of the IIS coding to discriminate between the different levels of impairment that occur as a result of different injuries to the foot and ankle.

More recently, injury severity and injury impairment scales have been proposed by the trauma committee of the American Orthopaedic Foot and Ankle Society (Levine, Manoli et al. 1995) . These have greater "face validity" than the IIS in that they differentiate between displaced and undisplaced fractures and fractures that disrupt the joints of the lower limb or alter the foot biomechanics. Each injury is given a single score for severity and impairment. A major disadvantage is that the score can not be implied from the AIS codes, unlike the IIS (Parenteau, Viano et al. 1996). Each injury must be coded separately from the initial x-rays and close co-operation between crash researchers and trauma surgeons is required.

Despite the fact that these injury severity and impairment scales are still the subject of validation studies, the authors believe that it is the best tool available for the purposes of determining the relative importance of different types of foot, ankle and leg injuries.

AIMS

This study is the first part of a co-ordinated programme of research to reproduce lower extremity injuries, quantify injury risk and evaluate new dummy designs. The principal objectives of this study were to:

1. Identify the types of lower limb fractures and serious soft tissue injuries sustained by front seat occupants in frontal crashes.
2. Identify the source of each injury from the vehicle.
3. Judge which injuries are a priority for prevention due to either their high incidence or their potential for causing severe and long term disability and recommend methods of reproducing the injuries observed in "real-world" situations in the laboratory setting.

METHODS

The data used in this study are from an on-going study of vehicle crash performance and occupant injury (the Co-operative Crash Injury Study) which commenced in the UK in 1983. The database holds information on approximately 13,000 vehicles involved in crashes containing 20,000 occupant who sustained between them about 85,000 injuries.

Each vehicle in the study was inspected within a few days of the collision. The general sampling criteria of the CCIS study are;

(i) that the vehicle involved was towed away from the scene of the accident to a garage or recovery yard;

(ii) that the vehicle was less than six years old at the time of the collision (although some older vehicles are included in the sample);

(iii) that there was an injury in the vehicle according to the UK Police system of injury classification.

About 80% of serious and fatal accidents in each study area were investigated along with 10-15% of slight accidents according to the UK Police system of injury classification. The resulting sample represents all levels of injury outcome while being biased towards more serious injuries.

Medical data concerning each occupant was obtained from hospitals and each occupant was also requested to complete a questionnaire which provided additional data several days after the crash. Injuries were coded according to the Abbreviated Injury Scale, 1985 revision (American Association for Automotive Medicine; 1985).

A more comprehensive overview of the Co-operative Crash Injury Study can be attained in Mackay et al (1985).

The criteria used to obtain data for the current study were as follows:-

(i) All vehicles which had sustained crashes in the Midlands of England.
(ii) From these, all vehicles which sustained a frontal impact in which the principle direction of force (PDoF) was between 1 o'clock and 11 o'clock (i.e. within 45 degrees of 'head-on') were selected. Any vehicles involved in a "rollover" were excluded.
(iii) Of these, only front seat occupants who sustained an Abbreviated Injury Score of 2 or above to the lower extremity were selected.
(iv) Of these occupants it was only possible to undertake an in-depth examination of the lower extremity injuries of those occupants whose X-Rays were still available.

The injuries were classified according to the most likely mechanism of injury (e.g. direct blow, bending or twisting). The objective was to define the mechanism of injury by the *principal direction of force* applied to the injured segment in relation to the standard anatomical position of the body.
This classification is based on x-rays of the lower limb injuries with additional information being obtained from the patient's medical records. The understanding of fracture mechanisms of the lower extremity is based on biomechanical experiments on cadaver lower limbs as well as clinical observations. (Lauge 1948; Lauge-Hansen 1950; Lauge-Hansen 1952; Lauge-Hansen 1953; Lauge-Hansen 1954; Aitken and Poulson 1963; Neer, Grantham et al. 1967; Kennedy and Bailey 1968; Nummi 1971; Wiley 1971; Main and Jowett 1975; Melvin and Nusholtz 1976; Peterson and Romanus 1976; Protzman and Burkhalter 1976; Viano, Culver et al. 1978; Pennal, Tile et al. 1980; Yde 1980; Johner and Wruhs 1983; Rasmussen and Kroman-Andersen 1983; Tile 1984; Nyquist 1986; Young, Burgess et al. 1986; Kress and al 1995)

Each injury was given a severity score and impairment score according to the Injury Scale developed by the American Orthopaedic Foot and Ankle Society (Levine, Manoli et al. 1995) ranging from 0 (No impairment) to 6 (Completely incapacitated). Detailed descriptions of each category are included below. Its primary function is as a tool for car crash researchers to determine which injuries are a priority for prevention.

The following tables contain the definitions for the Ankle Foot Injury Scales (AFIS) as developed by the Trauma Committee of the American Orthopaedic Foot and Ankle Society. The scales and definitions were developed using AIS as the basic model. The following are the definitions for Injury Severity (AFIS-S) Scale:

0	No Injury
1	Minimal Injury
2	Mild Injury
3	Moderate Injury
4	Severe Injury
5	Very Severe Injury
6	Currently Untreatable

Similar terminology was used for the impairment scale (AFIS-I), a scale that gives the expected permanent considering as the average permanent impairment of 100 patients treated by an average orthopaedic surgeon. If an injury had a high probability of complications, such as, a displaced talar neck fracture dislocation, the complication rate was factored in when determining the average outcome for the group of one hundred patients with the listed injury.

0	No impairment
1	Minimal impairment
2	Mild impairment
3	Moderate impairment
4	Severe impairment
5	Very severe impairment
6	Total impairment

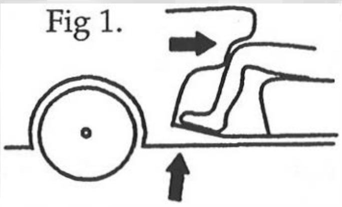
The following explanations were used to define each impairment level:

1. **No impairment** .
   Patient has no residual signs or symptoms associated with the injury.
2. **Minimal impairment.**
   Able to do all desired activities but may be slightly limited at impact sports. May have occasional discomfort requiring and OTC medication. Able to wear any type of footwear.
3. **Mild impairment.**
   Unable to do impact activities, for example, unable to participate in sports such as tennis, basketball, etc. Has some limitations at work. Cannot do a job requiring constant standing, walking, and climbing. Regularly uses OTC medication to control discomfort.
4. **Moderate Impairment.**
   Walking is limited. Can do most activities but unable to walk for long periods. Can do normal shopping but excessive walking impossible. May occasionally use cane for support. May need occasional non-opioid prescription medications for pain relief. Can do work requiring some walking but needs to be able to sit. Cannot do job requiring weight bearing. May need orthotics to control pain.

5. **Severe impairment.**
   Able to walk about living quarters. Usually can weight bear but often needs to use a single walking aid (cane). Can do work requiring minimal walking and standing but needs to sit most of the time. Cannot participate in sports requiring weight bearing. Regularly uses non-opioid medications to control pain.
6. **Very Severe Impairment.**
   Can barely get a round living quarters without walking aids. Must use walking aids or wheelchair when out house. Usually can be partially weight bearing but at times has to be non weight bearing. Able to do sedentary work without any standing, walking, or climbing. Regularly uses non-narcotic medications for pain control and may occasionally need OOP's to control pain. Only able to work in limited jobs requiring no standing, walking, or climbing.
7. **Total impairment.**
   Unable to weight bear - must use walking aids or wheelchair at all times. Unable to perform any type work activities and/or household chores. Needs opioids on a regular basis. Pain very poorly controlled.

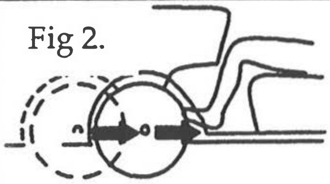
The information obtained from the medical records was combined with the report of the crash investigator and photographs of the car interior and analysed by Orthopaedic specialists, vehicle safety experts and crash investigators. From this analysis, a consensus was reached as to the most likely mechanism of injury from contact with the car interior, the Principal Injury Source. These were coded to entrapment between the floor and facia, intrusion of the footwell, foot trapped under the pedal, foot roll off the pedal, foot blow from a pedal and contact with the floor without intrusion. The details of each mechanism are detailed below and are adapted from Morgan et al. (1991) .

Fig 1.



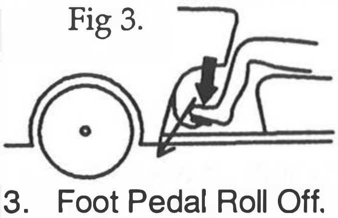
1. Entrapment of leg between instrument panel and footwell. Significant footwell intrusion in association with evidence of pocketing of knee.

Fig 2.

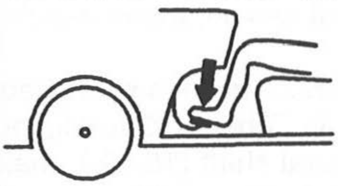


2. Intrusion of Footwell (Wheel well/ Fire wall / Floor)
Significant intrusion in the region of injured leg in the normal driving position.

Fig 3.

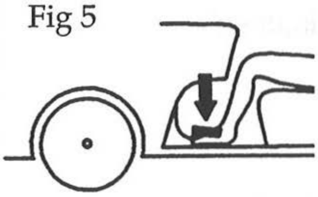


3. Foot Pedal Roll Off.
Evident from distortion and bending of the pedals, scuffing or displacement of the pedal rubber and reporting of the accident circumstances.



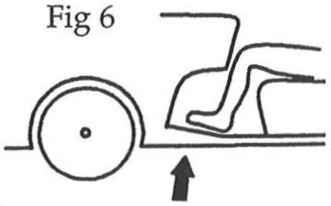
4. Contact With Foot Pedal
Evident from depression of the pedals, reporting of the accident circumstances and an isolated injury consistent with loading concentrated over a small surface area.

Fig 5



5. Foot Trapped Under Pedal
Evident from shoes trapped under pedals or reporting by the occupant or rescue services that the feet were trapped by the pedals.

Fig 6



6. Contact With the Floor
No significant intrusion identified, no damage to the pedals and no other contact source identified. Often seen in unrestrained occupants.

RESULTS

A total of 194 AIS 2+ injuries to 145 limbs have been analysed. The overall sample was 114 out of a potential 527 occupants (virtually all of whom were restrained by a 3 point seat belt), or a sample size of 22%. This introduces a potential sampling error and so a comparison of the occupant characteristics from the CCIS and in-depth analysis databases was performed. This demonstrated that there were no significant differences between the databases in terms of the frequency of AIS injury codes, the mean crash severity, mean age, gender distribution, mean weight and heights.

The frequencies of the different AIS 2+ injuries sustained in frontal collisions to front seat occupants are given in Table 1. Overall, the most frequently encountered fractures were femoral shaft (18.6%), malleolar ankle fractures (11.9%), patella fractures (10.3%), fractures of the talus (8.2%) followed by fractures of the tibial shaft, pilon ankle fractures and forefoot fractures (all 6.7% each).

The analysis of injuries has been subdivided into two sections. These are:
1. AIS 2+ above the level of the tibial plateau. For ease of reference, these will be referred to as “above knee injuries”.
2. AIS 2+ injuries to the tibial plateau and below. For ease of reference, these will be referred to as “below knee injuries”.

Table 1. Distribution of AIS 2+ lower extremity injuries to front seat car occupants analysed in this study.

Injury Region / type	Frequency (N)	%
Pelvis	2	1.0
Acetabulum	6	3.1
Hip dislocation	6	3.1
Femoral neck	3	1.5
Femoral shaft	36	18.6
Supracondylar	7	3.6
Patella	20	10.3
Knee ligament	2	1.0
Tibial plateau	11	5.7
Tibial shaft	13	6.7
Pilon Fractures	13	6.7
Ankle Fractures (malleolar)	23	11.9
Talus	16	8.2
Calcaneus	6	3.1
Midfoot	6	3.1
Lisfranc's joint	5	2.6
Forefoot	13	6.7
Phalanges	6	3.1
Total	**194**	**100**

Above Knee Injuries

The most frequent injuries seen above the knee were femoral shaft fractures (30% of above knee injuries) and patella fractures (16% of above knee injuries). (Table 2)

Table 2 Frequency of all above knee injury mechanisms by anatomical site.

	N	Primary Mechanism
Acetabulum	6	Internal/external Rotation
Hip Dislocation	6	Posterior (axial load to femur)
Femoral Shaft	35	Bending +/- Compression
Femoral Shaft	1	3 Point bending
Supracondylar Femur	4	Axial Load
Patella	19	Direct Blow
Other	11	Other Mechanism
Total	82	

For virtually all femoral shaft fractures, a well defined knee contact was identified in the facia region (Table 3). The fracture pattern varied from simple transverse to more complex multifragmentary types. The more complex fracture patterns are an indication of greater energy absorption by the bone and surrounding soft tissues and these fractures were most commonly associated with a knee contact against the intruding facia.

Like femoral shaft fractures, patella fractures were caused by a direct blow to the knee from the facia or associated structures (Table 3). For patella fractures, the facia cladding itself was often found to be protecting narrow, stiff objects such as structural cross-beams and brackets associated with the steering mechanism. However, for the majority of knee contacts, the surface contact was identified only because inspection of the vehicles by the crash inspectors does not include stripping of the vehicles. Only if there was a defect in the facia was it possible to identify the underlying structures.

Table 3. Principal contact and injury source for above knee injuries by site of injury.

	Principal Contact Source			
	Facia/knee Contact	Facia & Bracket/ knee Contact	Entrapment	Column Bracket
Pelvis	1	1		
Acetabulum	4	2		
Hip Dislocation	6			
Femoral Neck	3			
Femoral Shaft	32	2		2
Supracondylar	3		2	2
Patella	16	2		2
Knee Ligament	2			

Femoral shaft fractures were not usually associated with AIS 2+ injuries to the knee although loading through the knee was the principal load pathway for femoral shaft fractures. A fracture of the ipsilateral patella was identified in only 6 of the 36 (17%) femoral shaft fractures.

The average crash severity for femur fractures was significantly higher than that for patella fractures ($p < 0.001$) (Table 4). Although the crash severity for all other lower extremity injuries were lower than for femoral shaft fractures, the differences observed did not attain statistical significance.

Table 4. Mean and median crash severity expressed in terms of EES for different AIS 2+ lower extremity injuries.

Injury Group	Mean EESC3 (km/hr)	Median EESC3 (km/hr)
Femur # (N=6)	60.7	58.5
Patella # (N=6)	32.3	29.0

In general, femoral shaft fractures were uncommon in the absence of intrusion of the facia. Two thirds of femoral shaft fractures occurred in the presence of 25 cm. or more of intrusion. In contrast, there was no associated intrusion in 50% of patella fractures. (Table 5)

Table 5. Percentage of injuries associated with level of intrusion for patella and femoral shaft fractures.

	Intrusion Banding (At Facia Level)				
	None	1-9 cm	10-24 cm	25-49 cm	50 + cm
All Above-Knee Injuries(N=76)	17%	12%	20%	47%	4%
Femoral Shaft # (N=32)	3%	3%	28%	59%	6%
Patella # (N=20)	50%	5%	10%	30%	5%

What is even more striking is the distribution of patella fractures between the left and right legs of drivers. 63% of drivers' patellae occurred on the left side and 37 % were on the right side ($p<0.001$). This was highly significant and not affected by intrusion, crash severity or the principle direction of force.

Below Knee Injuries

A total of 112 "below knee injuries" to 88 legs in 78 occupants (65 drivers and 13 front seat passengers) were analysed. Injuries to the ankle joint accounted for one third of below knee injuries. Although the majority of these were malleolar fractures, one third of the ankle fractures were "pilon" fractures (Table 6).

By frequency alone, injuries to the ankle (32%), talus (14%), tibial shaft and forefoot (both 12%) and tibial plateau (10%) would appear to be the most important injuries. However, this does not take into account that many of these injuries are of low severity and are associated with a good outcome and also that several injuries that occur relatively infrequently account for a large proportion of the most disabling injuries.

Table 6 Injury frequencies by site for all below knee AIS 2+ injuries.

Injury	N	%
Tibial Plateau	11	9.8
Tibial Shaft	13	11.6
Ankle Pilon #	13	11.6
Ankle Malleolus	23	20.5
Talus	16	14.2
Calcaneus	6	5.4
Midfoot	6	5.4
Lisfranc's Joint	5	4.5
Forefoot	13	11.6
Phalanges	6	5.4
Total	112	100

Table 7 lists the principal injury source for below knee injuries. Contact with an intruding surface was perceive to be the primary injury mechanism in almost half of injuries below the knee. Intrusion also played a significant role in the 19 cases where entrapment between floor and facia occurred. The entrapment would be likely to increase the risk of injury or to increase the severity of injuries that may have occurred in the presence of intrusion alone.

Injuries attributable to contact with a foot pedal or the foot rolling off a pedal accounted for 25% of below knee injuries. The "foot roll-off pedal" injuries were almost exclusively ankle-malleolus fractures. This mechanism accounted for 8 of the 23 (34%) malleolar fractures.

The majority of forefoot injuries attributed to foot pedal contact were fractures of the distal metatarsals.

Table 7 Principal injury source for all below knee AIS 2+ injuries.

	Entrapment between Floor & facia	Foot Pedal Contact	Roll-off Pedal	Foot Trapped Under Pedal	Intruding Firewall/ Wheel-well	Floor Contact
Tibial Plateau #	5				3	3
Tibial Shaft #	8				3	2
Pilon #	3	1			9	
Malleolus #		2	8		10	3
Talus #	2	2	1		11	
Calcaneus #	1				5	
Midfoot #				1	5	
Lisfranc's #		2		1	2	
Forefoot #		10			3	
Phalanges #		2		2	2	
Total	19	19	9	4	53	8

A separate analysis of left and right leg injuries is detailed in table 8. The frequency of driver's right lower leg injuries is twice that of the left leg but for front seat passengers the ratio of left to right is almost one to one. In the United Kingdom, the driver's right leg is also the outboard leg and so it is difficult to separate the possible increased risk of injury to the right lower leg due to the influence of pedals from the influence of being on the outboard side which is more frequently the 'struck side' in frontal and offset collisions.

Table 8. Frequency of injuries by site and side (left or right) for drivers and front seat passengers.

	Driver		Passenger	
	Right leg	Left leg	Right leg	Left leg
Tibial Plateau	4	5	1	1
Tibial Shaft	8	1	4	0
Malleolus	12	6	0	3
Pilon	10	3	0	0
Talus	10	3	1	2
Calcaneus	2	2	1	1
Mid-foot	3	2	1	0
Lisfranc's Joint	0	3	1	1
Forefoot	8	4	0	1
Phalanges	3	2	1	0
Total	60	31	10	9

Tables 9 and 10 detail the injury severity score (AFIS-S) and injury impairment scores (AFIS-I) respectively for the different types of below knee injuries observed in this study.

Table 9. Injury Severity by site for below knee AIS 2+ injuries.

	1	2	3	4	5	6
Tibial Shaft #				4	7	2
Malleolus #	10	5	5	3		
Pilon #			1	5		7
Talus #	1	1	8	1	4	1
Calcaneus #			1		5	
Mid-foot #			6			
Lisfranc's #					5	
Forefoot #		2	7	4		
Phalanges #		2	4			
Totals	11	10	32	17	21	10

From table 9, the most severe of the lower extremity injuries are tibial shaft fractures, pilon fractures, fractures of the talus and calcaneus and injuries of Lisfranc's joint. Table 7 demonstrates that these severe types of injury are associated with footwell intrusion and entrapment of the lower limb between the intruding footwell and facia. If injury severity is plotted against primary injury mechanism, this association becomes more obvious. (Figure 1). From this graph, it is clear that pedal related injuries constitute over 50% of the minimal and mild severity injuries (Severity Score = 1 or 2). However, as the Severity of the injuries increases to moderate through to very severe (Severity Score = 3 or above), pedal related injuries form a smaller proportion of the injuries and intrusion and entrapment are responsible for the majority of injuries seen. For the most severe injuries (Severity Score of 6), the primary mechanism of injury was intrusion in 90% of cases.

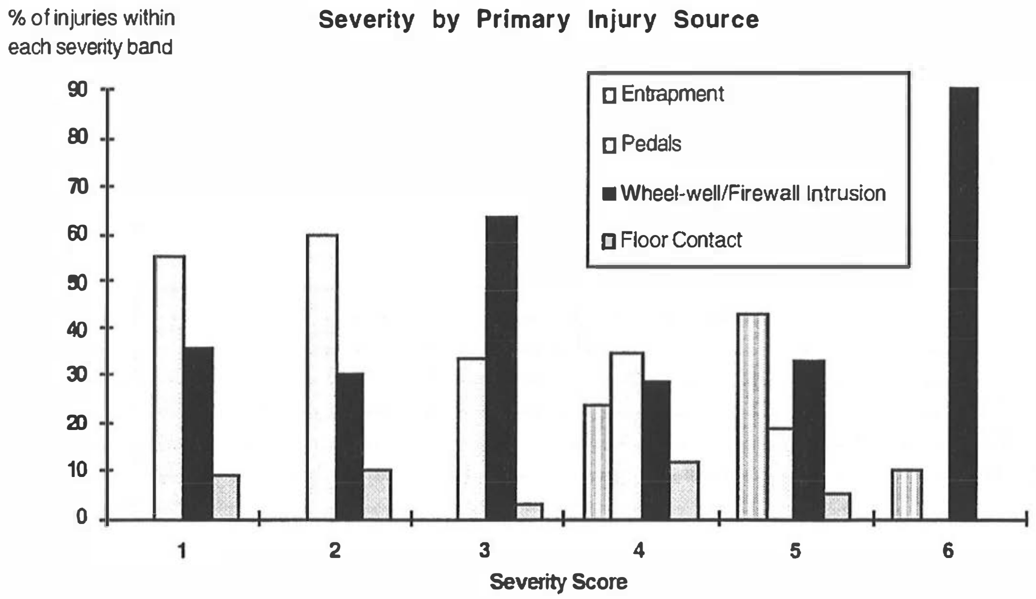


Figure 1. Graph demonstrating percentage of injuries of a given severity score (1-6] attributed to different primary mechanisms (entrapment, pedals, intrusion or contact with the floor).

Performing a similar analysis for impairment scores (AFIS-I) by site of injury and by primary mechanism, the ranking of importance of each injury alters slightly but the influence of intrusion becomes even more apparent (Table 10 and Figure 2). Considering the expected long term impairment, the most important injuries in descending rank are :

1. Pilon Fractures.
2. Fractures of the Talar Neck, Calcaneus.
3. Lisfranc's joint injuries.
4. Fractures of the Tibial Shaft and Tibial Plateau. Although tibial plateau fractures are not included in the AOFAS-IIS, the authors recognise that these injuries are potentially more impairing than tibial shaft fractures due to the fact that they disrupt the joint surface and can result in premature arthritis of the knee.
5. Malleolus Fractures.
6. Forefoot (Metatarsal) Fractures.

Table 10 Injury Impairment Score by site of injury for all below knee AIS 2+ injuries.

	0	1	2	3	4	5
Tibial Shaft #		3	8	2		
Pilon #			6		7	
Malleolus #	10	6	7			
Talus #		8	2	5	1	
Calcaneus #				5		1
Mid-foot #		2	2	2		
Lisfranc's #				5		
Forefoot #		8	5			
Phalanges #		6				

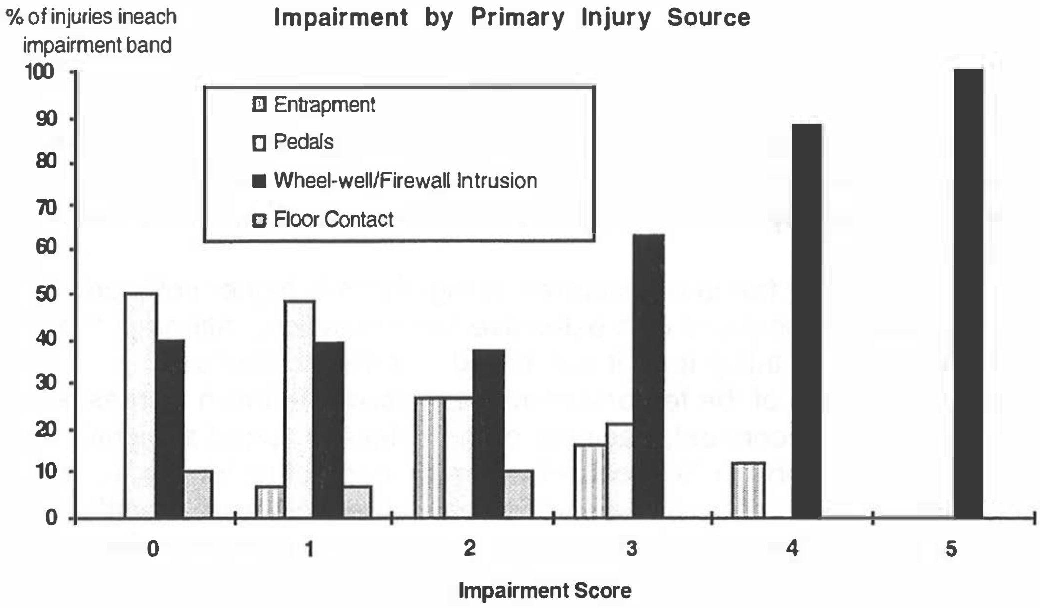


Figure 2. Graph demonstrating percentage of injuries of a given injury impairment score (0-5) attributed to different primary mechanisms (entrapment, pedals, intrusion or contact with the floor).

From these data, footwell intrusion is identified as the mechanism of injury in the most severe and impairing below knee fractures analysed. If this is indeed the case, one would expect to see the majority of the high severity and high impairment injuries associated with high levels of intrusion. A breakdown of the number of fractures within each band of intrusion is given in Table 11. Fractures of the calcaneus, talar neck and Lisfranc's injury are associated with higher levels of intrusion but there is no similar pattem for tibial fractures or pilon fractures.

Table 11. Number of different injury types within different intrusion bands.

	0 cm	1-9 cm	10-24 cm	25-49 cm	50 + cm	Unknown
Tibial Plateau #	4	2	1	4		
Tibial Shaft #	2	2	2	4	1	2
Pilon #	1	3	2	4	2	1
Malleolus #	4	7	6	4	4	
Talus #		2	1	8	5	
Calcaneus #	1		1	3	1	
Mid-foot #		1	2	2		
Lisfranc's #	1		2	2		
Forefoot #	2	3	5	2	1	
Phalanges #			1	5		

Discussion

This study identifies priorities for the prevention of AIS 2-3 leg, foot and ankle injuries in frontal collisions. The study is based on a retrospective, in - depth analysis of a representative sample of lower extremity injuries from the CCIS database.

The principal injury source for virtually all above knee injuries was identified as a knee contact with the facia and associated structures . The two most frequent injury types in this region were femoral shaft fractures and patella fractures.

Femoral shaft fractures occurred at significantly higher collision severity and were associated with extensive facia intrusion. Although the data was not presented in this paper, it was noted that the incidence of comminuted fractures of the femoral shaft were associated with increasing levels of intrusion. In contrast, fractures of the patella occurred at significantly lower crash severity and 50% occurred in the absence of residual intrusion of the facia. However, hard contact sources behind the facia were identified for many of the patella fractures. In only two cases was the steering column identified as the injury source. The majority of patella fractures were associated with a definite knee contact in front of the steering column. This would indicate that despite the fact that the steering column and its associated fixtures is potentially a "hostile" contact for the knee, it is not the cause of many of the above knee fractures seen in this study.

Fractures of the patella in the same leg occurred in only 17% of femur fractures. These findings indicate that a different mechanism of loading is responsible for causing these two injuries and are consistent with observations made by Viano that the patella can tolerate very high loads if they are well distributed (Viano, Culver et al. 1978).

The most striking feature in above knee injuries was the significantly increased risk of fracture of the left patella compared to the right side. This is not explained by the direction of impact, the crash severity or the level of intrusion. The most likely explanation is the presence of stiff, unyielding structures with a small contact surface area on the left side of the steering column.

Patella fractures are often difficult to treat and are a cause of significant long term disability (Bostman, Kiviluoto et al. 1983). It is important that the different mechanisms of injury are taken into consideration when assessing knee-bolster impacts and that the frontal crash test dummy is capable of detecting risk of injury to the patella as well as to the femoral shaft.

The results of this study suggest that by minimising intrusion at the facia level, it might be possible to reduce the risk of femoral shaft fractures. However, this may be at the expense of increasing the risk of patella fractures, which, unlike femoral shaft fractures, are not a potential threat to life but do lead to long term impairment and disability due to painful degeneration of the patello-femoral compartment of the knee joint.

A unique feature of this study is that it has used the American Foot and Ankle Orthopaedic Society's Injury Severity and Impairment Scales to determine priorities for the prevention of below knee injuries in frontal collisions.

By frequency alone, injuries to the ankle malleoli and metatarsals are the most important injuries. However, when the severity of the different injury types are taken into account, the priority for injury prevention changes. Ankle pilon fractures, fractures of the talar neck, fractures of the os-calcis and injuries to Lisfranc's joint become the most important injuries. Thus, a better understanding of the exact mechanisms of these different injuries is required and biomechanical experiments should be directed towards assessing the mechanisms and tolerances to injury of the calcaneus, talus, tibial plafond and Lisfranc's joint.

Intrusion was perceived to be the most important principal injury source for below knee injuries. Intrusion was implicated in the majority of below knee injuries. More importantly, intrusion of the footwell was seen to be responsible for the majority of the most severe and impairing injuries.

This retrospective study was unable to determine the relative importance of crash severity and intrusion because of the exclusion of non-injured car occupants. The majority of the important injury groups were judged to be caused by intrusion. Although fractures of the calcaneus, talar neck and Lisfranc's injury were associated with higher levels of intrusion, no similar pattern for tibial fractures or pilon fractures was demonstrated.

This may indicate that residual intrusion is merely a surrogate marker for local crash severity. Alternatively, it may reflect the limitations of intrusion measurement in this study. The intrusion is placed in broad bands and a single, maximum level of residual intrusion is recorded. The residual intrusion may not fully reflect the dynamic intrusion and there is no information available to correlate the crash pulse and intrusion (e.g. a very high load of short duration may cause no residual intrusion or a lower load of longer duration may leave significant amounts of intrusion). More information regarding the shape of footwell and the pattern of footwell deformation is required. The "survival space" available for feet needs to be assessed as well as the risk of contact and crushing.

Foot pedals were implicated in having a direct role in 20% of below knee injuries. The two most frequent ways in which this occurred was by the foot rolling off a pedal causing an ankle malleolus fracture or by a direct blow to the foot causing isolated metatarsal fractures. Although this is a large proportion of the total number of injuries, the majority of these injuries were of relatively low severity.

An additional problem with the retrospective nature of this study is the occupant variables. Information about the occupant weight and height was only available in approximately 60% of cases therefore conclusions concerning anthropometry were not valid and were therefore not included. Furthermore, the seated position of the occupant prior to the crash could not be determined in most cases. More detailed information about the position of individual legs at the time of the crash would perhaps provide an even greater understanding of the fracture mechanisms than this study has allowed and hopefully these issues will be addressed in a prospective accident study which is currently on-going.

Conclusions

1. Significant differences exist between patella fractures and femoral shaft fractures in frontal crashes.
2. Any improvement in techniques aimed at injury mitigation of above-knee injuries need to consider the different mechanisms.
3. With regard to below-knee injuries, the priorities for prevention are pilon fractures, talar neck fractures, fractures of the calcaneus and Lisfranc's fractures.
4. Intrusion is considered to be responsible for the most important below-knee injuries although this study has been unable to determine the relationship between crash severity and intrusion.
5. Injuries directly related to foot-pedals are important in terms of frequency alone. They are unlikely to be a cause of significant permanent impairment.

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