

VALIDATING LOWER LIMB INJURY MECHANISMS IN SIDE IMPACT CRASHES

Naomi Arndt
Raphael Grzebieta
Roger Zou

Department of Civil Engineering, Monash University
Australia
Paper No. 448

ABSTRACT

Lower extremity (LE) injuries sustained in side impact car crashes are debilitating due to the loss of weight bearing function and long rehabilitation times. In Australia such injuries rank third in terms of Harm after the head and thorax. Moreover, it is estimated around 20% of the total annual motor vehicle trauma treatment costs are devoted to rehabilitation of such injuries.

Regulatory design rules protecting the knee, lower leg and ankle/foot in side-impact crashes do not exist. However, in order to adopt sensible mitigation strategies and appropriate design rules, it is essential to identify and validate injury mechanisms.

While considerable work has been carried out identifying lower limb injuries occurring in frontal crashes, little work has been carried out regarding side-impacts. Three injury mechanisms, identified from a real-world side-impact case-study analysis carried out at Monash University were proposed at a Melbourne crashworthiness conference in 2002 [2]. MADYMO computer models simulating near- and far-side occupants in three typical crash scenarios were constructed. Occupant kinematics and force outputs from the models were compared with the injuries and hence the mechanisms identified in the study.

Results from the simulations were compared to published, known injury tolerances and are presented in this paper. Injury countermeasures for these three side-impact configurations are also discussed.

INTRODUCTION

Side-Impacts

Side-impacts are the second most significant cause of serious injury and death after frontal-impact [16]. The cost of injury from side-impacts is high: 25% of vehicle casualties are from side-impacts and account for one third of occupant Harm on Australian roads [12]. Stolinski et al. [39] state that the annual cost of side-impacts in Australia has been estimated at around \$870M per annum.

Side-impact crashes are often segregated into near-side and far-side crashes because the injury mechanisms in these crash types differ. Most side-impact research and regulations are based on near-side occupant injuries, but far-side occupants (Figure 1.B) can also incur serious harm. Near-side occupants are those which are situated on the same side as the impacted side of the vehicle (Figure 1.A). Moreover, side-impact regulatory crash tests in Australia are limited to one crash configuration (90°) and at one speed, 50 km/h.

In this study based on real-world crashes, injury mechanisms in three crash configurations were investigated.

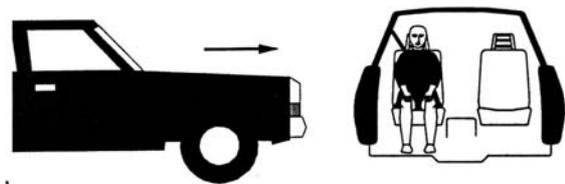


Figure 1.A A near-side occupant is on the struck-side of the target vehicle. After [40].

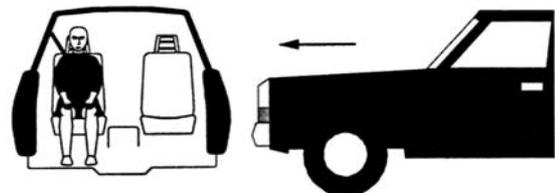


Figure 1.B A far-side occupant is on the non-struck side of the target vehicle. After [40].

Near-Side Occupant Injuries

Researchers have found that near-side occupants are at greater risk than far-side occupants. There is little space between the occupant and the impacting object; i.e. there is a shorter vehicle exterior to occupant distance [42]. “A (near) side-impact collision is violent because the occupant is immediately struck by the door and the incoming car” [36].

The causes of near-side occupant injuries are varied and complicated. Injuries are dependent on the dynamic crush characteristics of the side door

structure, occupant interaction and occupant response. “The door velocity history, occupant location relative to the door and the stiffness and the shape of the door interior all affect the injury outcome” [17].

Far-Side Occupant Injuries

Injuries to far-side occupants in Australia account for 40% of occupant Harm in side-impact crashes [12]. This is significant and worth considering in automotive safety research. Thomas and Frampton [44] found more casualties died in side-impacts than in frontal impacts in their UK in-depth study. They also found that one third of those injured or killed were seated on the far-side.

Few studies ([10], [40], [41]) have reflected on the nature and causes of LE injuries resulting from far-side crashes. There are no far-side occupant protection regulations. However, “real-world crash evidence has shown that occupants seated away from the struck side are still subject to a risk of injury...Relatively little research literature is available that addresses the protection of far-side occupants” [41].

LE Injury

LE injuries cause high levels of impairment and require costly rehabilitation and treatments. They are debilitating due to the loss of weight bearing function. About \$80M in Harm is caused by LE injuries incurred in side-impacts in Australia [Fildes et al. cited in [39]]. The most commonly injured body regions of survivors in the study by Thomas and Frampton in the UK [44] included the LE (55% of MAIS 3+ injuries). Thomas and Bradford (cited in [44]) showed that most injuries to survivors of side-impacts involved the tibia (Figure 2) (about 23% of survivor injuries and 49% of fatality injuries). Pattimore et al. [33] in a study of frontal and side-impacts found that skeletal injuries of the lower limb were more common in side-impacts.

Side-impact regulations (FMVSS 214 and ECE Regulation No. 95) have helped reduce LE side-impact Harm by about 25% (\$20M pa in Australia) [Fildes et al. cited in [39]]. However, there is still a significant cost incurred by occupants in side-impact as seen by the high frequency of LE injuries [44]. Neither EuroSID nor US-SID (side-impact dummies) have the capability of measuring the risk of injury to the LE below the pelvis. Hence improving the capabilities of these dummies to measure LE loads and displacements may help firstly to gain a better understanding of how LE injuries occur and secondly to mitigate these injuries.

Even though injuries of the knee and below are common and debilitating, few studies detailing how injuries occur to the lower leg in side-impacts exist. “While there have been numerous fracture tolerance studies conducted on the femur there has been relatively little emphasis on tibial strength” [30]. Morgan et al. [26] reported that injuries of the thigh have been reduced to around 10% but knee injuries still account for 20% to 30% of LE injuries in frontal-crashes. In a study by Thomas and Bradford (cited in [44]), the LE was the most frequent site of severe injuries of survivors. Fractures of the tibia and femur (Figure 2) were most common. According to Crandall and Martin [7], “more than half the more severe LE injuries occurring in frontal-crashes were of regions below the knee”. Pattimore et al. [33] reported, lower leg fractures accounted for 38% of LE fractures in side-impacts. The AAAM [1] and Fildes et al. [13] concluded that injuries of the lower parts of the LE were the most common types of injuries.

Hence, it is clear that further work on understanding injuries of the knee and below and how they occur in side-impact crashes is required.

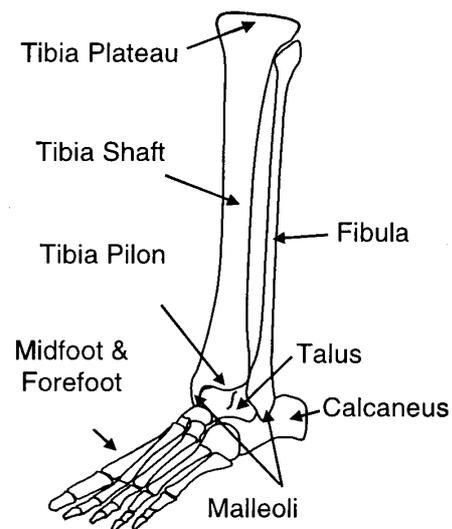


Figure 2. The lower leg bones. (After Funk et al. [14]).

Previous LE Injury Studies

A number of vehicle-crash injury studies have been carried out to date where some LE injury mechanisms have been identified. In a study by Fildes et al. [12] the main causes of injury in side-impacts were contact with the door, an external impact object or to a lesser extent the dashboard (instrument panel/knee bolster). In impacts with a frontal component, inertia carries the driver forward striking the dashboard resulting in disruptive knee injuries including the tibial plateau (Figure 2) [9]. Impact of the knees with the dash

with entrapment and interaction with the toepan from intrusion causing axial loading in the lower leg have also been reported as injury mechanisms in several other frontal studies [19], [25-27]. Hoglund et al. [19] and Schreiber et al. (cited in [19]) reported that a combination of axial loading and bending moments in the tibia decrease its strength.

Nyquist et al. [30] reported that “lower leg bending loads can occur to occupants as a result of contact with lower portions of the instrument panel (in frontal collisions) as well as other contacts during uncontrolled flailing of the LEs in a broad cross section of collision modes”. “Regardless of the initial position of the heel, contact between the heel and floorpan is inevitable during a severe crash” [Pilkey et al. cited in [14]] and hence entrapping the lower leg between the floor and the instrument panel.

Forces perpendicular to the proximal tibia can cause tibial plateau fractures. Nagel et al. [27] reported these injuries to occur when the knee impacted a rigid steering column support or instrument panel.

Lau et al. [23] reported the effect of door intrusion in side-impact on the LE. In a side-impact, the struck door encroaches into the occupant compartment and strikes the occupant directly and the impact object punches the dummy. In a side-impact a stiff armrest or other protrusions on the trim can produce concentrated loads. Door buckling induced by barrier impact can also present a non-uniform surface to the occupant.

Previous Injury Threshold Studies

Again, a number of studies have been carried out to determine injury tolerances of the LE. Impact tests have yielded the following injury tolerances.

Kajzer et al. [20] conducted lateral impacts to determine shearing and bending effects of the knee joint. The injuries incurred were upper tibial fractures. Kajzer et al. stated that the injury mechanism is directly related to the knee impact (contact) force. The mean peak force values which corresponded with the injuries were **1.8 (± 0.38) kN** (at 15 km/h) and **2.57 (± 0.45) kN** (at 20 km/h).

For the ligaments in the knee: the ultimate tensile load for the anterior cruciate ligament (ACL) is **1.9 kN** for younger people and **0.6 kN** for older people according to Silver [35]. According to Melvin et al. (cited in [18]) the posterior cruciate ligament (PCL) can be avulsed at a peak contact force of **7 kN**. Arnoux [3] found the cruciate ligaments to fail at loads between **0.17 kN** and

0.5 kN and the collateral knee ligaments to fail at between **0.15 kN** and **0.3 kN**. They conducted high-velocity stress tests (2m/s). Kajzer et al. [21] found knee ligaments to fail at **1.4 kN** shearing force at the knee joint.

According to Kramer et al. (cited in [29]) in pendulum catapult impacts perpendicular to the long axis of the tibia, the forces required to fracture the upper tibia ranged between **1 kN** and **4.3 kN**. The difference in force values corresponding to different injuries is due to the behaviour of bone under different loading rates. According to Viano et al. (cited in [29]) the forces for tibia fractures ranged between **3.28 kN** (females) and **6.89 kN** (youngest and male) (from Table 4 in [29]). They impacted seated subjects' proximal tibias below the joint centre.

For the fibula, Levine [24] reported the following fracture tolerances. In bending, the forces required to fracture are between **0.35** to **0.54 kN** for males and between **0.21** and **0.39 kN** for females. In compression along the long axis, a fibula can fail under loads of between **0.24** to **0.88 kN** (males) and between **0.2** and **0.83 kN** (females).

OBJECTIVES

The objectives of this study were to:

- Understand the significance of LE fractures/dislocations in side-impacts.
- Simulate the injury mechanisms identified from real-world side-impact crashes where typical LE injuries occur using MADYMO.
- Discuss the results of these models and compare them to injury tolerance data reported in other impact studies.
- Discuss some injury countermeasures reducing LE injuries in side-impacts.

THE DATA

Real-world crash information was extracted from the crash files, namely the Crashed Vehicle Files (CVFs) and the Australian Crash Injury Study (ANCIS). Data were collected between 1989 and 2002 and supplied by Monash University Accident Research Centre (MUARC) for analysis. Twenty-four side-impact crashes involving twenty-five injured occupants were analysed including four far-side crashes.

The injuries described in the data included severity, location and description where possible, contact sources of injury (e.g. knee contacting dash or door), angle of impact (Figure 3), speed of crash and impact object. Information about the vehicles included types (make, model, year) (in the CVF

cases only). The occupant information included height, weight and age. Injury data were obtained from hospital records and x-ray reports. Variables like positioning of the seat (forward, middle, rearward) were not recorded in the CVFs but this was estimated from the occupant height. Foot positioning on pedals was also not recorded as it was difficult for occupants to recall.

Sixty-two percent of occupants who had LE fractures were females. Hence in the three side-impacts simulated, and reported here, two of the occupants were female.

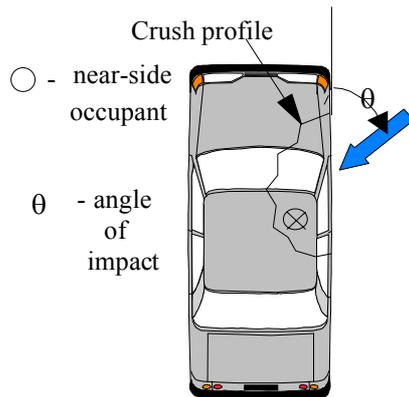


Figure 3. Impact Angle (θ) Definition.

Impact Objects

Impact objects included other cars, 4WDs, poles/trees and trucks/buses. Impacts with fixed objects such as trees/poles and heavier vehicles like buses/trucks and 4WDs commonly cause more serious injuries than those with light vehicles.

According to Ginpil et al. (cited in Stolinski and Grzebieta [38]) 40% of all side-impacts result from impact with a tree or pole. Others reported the following rates of impacts with narrow fixed objects (poles/trees): 22% [15] to 25% [12] of Australian side-impacts, 31% of seriously injured survivors and 16 to 43% of fatalities in the UK [Thomas and Bradford (cited in [44])], [Gloyns and Rattenbury (cited in [43])].

For this study [2] Figure 4 shows the impact object type where a LE fracture was sustained. Of the 24 crashes 37.5% were with poles/trees correlating with the figure given by Ginpil et al. (40%). Fifty-four percent were with other cars and 8.3% were with trucks/buses.

Results from the Previous Study

The earlier analysis of the data described above identified three fundamental injury causation mechanisms. The mechanisms of LE fractures and

dislocations differ according to the type of crash. It was found that they depend on the severity and angle of impact.

The LE fracture and dislocation mechanisms identified were:

- (1) Axial compression and/or bending of the lower leg caused by entrapment resulting from leg area volume reduction and/or a side intrusion force;
- (2) High-energy, side impact, striking force resulting from being in direct contact with the struck portion of the vehicle; and
- (3) Inertial movement of the body causing loading of the lower limbs resulting from interaction with the vehicle interior, where intrusion is not the cause of injury.

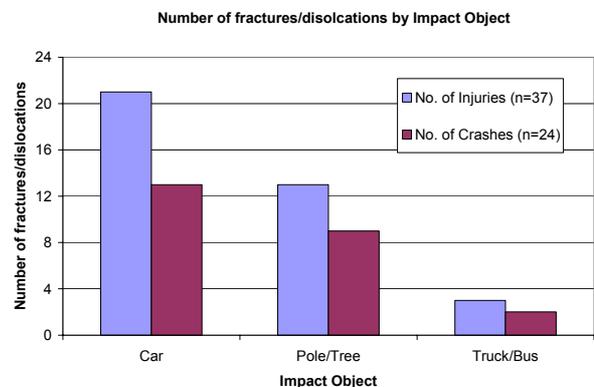


Figure 4. No. of fractures by Impact Object.

CRASH SIMULATIONS

The real-world crash data were accessed at MUARC for this study. Computer simulations were conducted at Monash University’s Department of Civil Engineering. The real-world case studies of the occupant LE fractures and dislocations provided a basis for establishing how each of the three fundamental mechanisms should be simulated. Three crashes were chosen for reconstruction, i.e. one from each of the mechanism categories described above.

MADYMO computer models were used for the crash simulations. “MADYMO allows users to design and optimise occupant safety systems and vehicle designs efficiently, quickly, cost-effectively” [37] and safely and assess injury outcome parameters in different crash configurations. “It is a standard tool for occupant safety analysis and is used extensively in automotive design and safety research centres around the world” [37] with a clear audit path to validated model components.

The three crashes simulated were those in which most variables (details about the injured occupant, crash and vehicles) were available. Occupants had injuries to their lower leg bones (tibia, fibula) and one occupant also had a knee joint disruption. The three cases modelled were:

Mechanism (1): a 30° oblique crash between a medium sized car (1185 kg) impacting a small car (865 kg);

Mechanism (2): a 90° crash between a medium sized car (1141 kg) impacting a larger car (1323 kg); and

Mechanism (3): a 270° far-side crash between two medium sized cars (1050 kg target car and 1060 kg bullet car).

Car into car crashes were modelled as they are more typical of crashes generally. The simulations were modelled using a customised standard side-impact model of a small European car with a compatible, mobile barrier taken from the MADYMO Applications database [45]. The bullet vehicle used in the simulation was a mobile crash barrier/trolley (as specified by the European ECE Regulation No. 95) with front vehicle characteristics where it impacted into the stationary target vehicle. Bullet vehicle speed was set to twice the delta-V recorded in the case data.

For each case simulated a vehicle of the same make and model as that in the database was measured. Internal surfaces, where the occupant could have contact and injury may have been caused, were coded into the MADYMO model.

The modification of each vehicle modelled involved the addition of a 3 plane knee bolster, toepan and footwell plane, steering column and brake, accelerator and clutch (for manual vehicle only) pedals, centre console (case 3 only), floor and door geometry such as rigid pockets, speakers and armrests. These were used as contact sources from which contact forces with the dummies were obtained in the simulations. The steering column was assumed to be stiff (as there was no deformation from knee strike). Tape measures and long and short rulers as well as a protractor were used to measure the dimensions and angles of the vehicle parts modelled. Contact interactions were added between the barrier and target vehicle and between the dummy and vehicle interior after potential injury sources were assessed. A front-left

side panel for contact with the barrier was added as in the basic model this was not present and was required for barrier contact.

The driver side door was modelled as four planes to represent the lower and upper, forward and rearward parts of the door. The armrest was modelled as an ellipsoid. The velocities of the bullet vehicle for each case, in the x (longitudinal) and y (lateral) directions, were calculated and incorporated in the model.

The dummy used in two of the simulation crash models (90° and 270°) was the EuroSID (left hand side) provided by the Netherlands Organisation for Applied Scientific Research (TNO) [46] in the MADYMO-3D dummy database. The dummy for the 30° impact (Mechanism (1)) was a Hybrid III 5th %ile female. The seat was modelled from ellipsoids. The belt was a series of springs attached to the dummy hips, floor, base of the B-Pillar and positioned around the dummy's pelvis. The positions of the dummies were different for the males, i.e. further from the dash in the middle seat position 0.39 m behind the vehicle's centre of gravity (COG). Females were more forward at around 0.14 to 0.19 m behind the COG.

The basic model was set up with the impacting vehicle and near-side driver dummy as shown in Figures 5, 6 and 7. Figure 5 shows the configuration for the 30° near-side oblique crash (Mechanism (1)). Figure 6 shows the configuration for the near-side 90° crash demonstrating Mechanism (2). Figure 7 shows the configuration for the far-side 270° crash demonstrating Mechanism (3). The driver dummy was moved to the opposite side of the vehicle for the far-side crash and the measured interior vehicle parts modelled in the target car were mirrored.

MADYMO was coded to list results such as door displacement and velocity, and forces on the parts of the LE resulting from the crash. The actual mass ratios of the vehicle crashes were used in the simulations.

Only injuries to the lower leg and knee were analysed as no ankle or foot injuries were reported in these cases. There are, however, numerous studies on the ankle already performed by other researchers ([4], [5], [8], [22]).

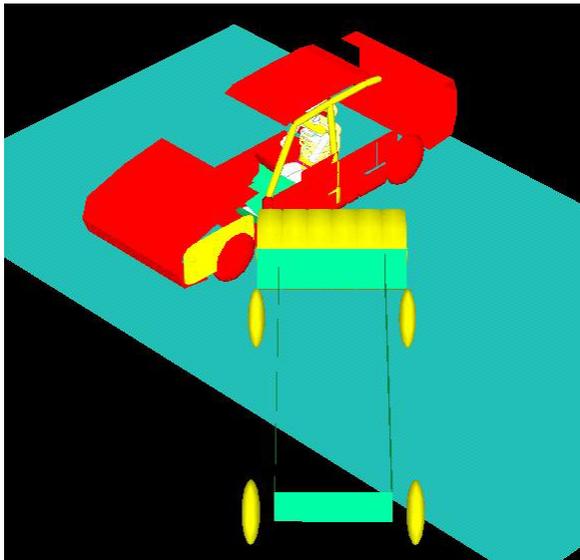


Figure 5: Mechanism (1) 30° near-side oblique crash.

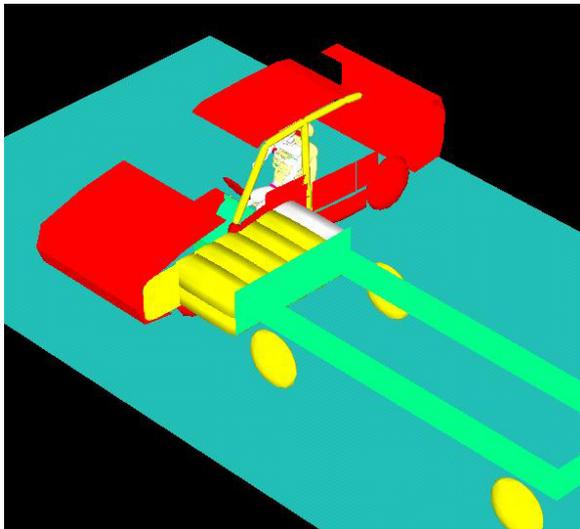


Figure 6: Mechanism (2) 90° near-side perpendicular crash.

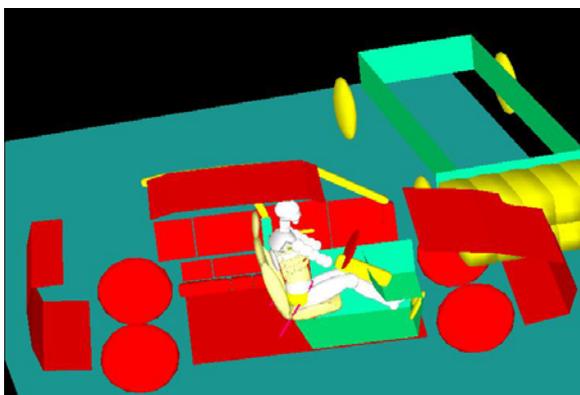


Figure 7: Mechanism (3) 270° far-side crash.

Mechanism (1) Near-Side 30° Oblique Crash

In this crash, the injured occupant was the driver. The LE injuries sustained included: ruptured and distracted right knee joint and right fibula fracture (injured leg on near-side to crash/impact object). The crash mass ratio (target vehicle mass/bullet vehicle mass) was <1.0 and ΔV was 46 km/h (Figure 5). A frontal dummy (5th %ile female Hybrid III taken from the MADYMO database [46]) was used because the major inertia component was predominantly in the frontal direction. The occupant was a female, 62 years of age and belted, whose height and weight was not known. The vehicles involved were a small 1982 automatic hatchback sedan impacted by a 1974 medium sized vehicle.

Mechanism (2) Near-Side 90° Crash

In this crash, the injured occupant was a near-side driver. The LE injuries sustained included a fractured right fibula (injured limb on near-side to crash). The mass ratio was >1.0 and ΔV was 32 km/h (Figure 6). The impact was at 90°, near-side and perpendicular. The occupant was a male, 67 years of age and belted. His height was 168 cm (close to an average male: 175 cm [47]) and weight 55 kg. The vehicles involved were a 1986 medium automatic car impacted by a 1993 large sized vehicle. The dummy used in this particular simulation was a 50th %ile male EuroSID.

Mechanism (3) Far-Side 270° Crash

In this crash, the injured occupant was a driver on the far-side. The LE injuries sustained included a fractured right tibial plateau (Figure 2) (the injured leg was on the opposite side to the impact). The mass ratio was 1.0 and ΔV was 23 km/h, (Figure 7). The impact was at 270°, perpendicular, in the forward part of the vehicle on the far-side. The driver was female, 58 years of age and belted. Her height was 163 cm and weight 70 kg. The vehicles involved were a 1981 automatic medium car impacted by a 1986 medium car.

The dummy used in this particular simulation was a 50th %ile male EuroSID. There is no female side-impact dummy available nor a smaller side-impact male. The dummy's right foot was positioned on the brake and the left foot in a relaxed position to the left of the brake. The distances between the occupant and modelled vehicle parts were determined using a person who was the same height and weight as the injured occupant and seating her in the car while taking measurements.

RESULTS

The relative intrusions simulated were compared with the intrusions noted in the real-world crash data. The dummy contact sources and contact loads which were compared to tolerances specified by other researchers are presented in Table 1 (Appendix). The contacts for the upper leg and foot were also provided even though the upper leg was not examined in this study and there were no ankle/foot fractures or dislocations reported in the cases examined.

Mechanism (1) Near-Side 30° Oblique Crash

Maximum intrusion of the front door was 31 cm in the computer simulation model, correlating with the intrusion recorded in the actual crash data as 30 cm. The injuries recorded in the database for this case included a disrupted right knee joint and fractured fibula. It should be noted that the dummy model did not have a fibula, only a tibia, which approximates the lower leg bones.

There was side-intrusion at the door and front side panel, as noted from the 5th %ile Hybrid III's contact with the pelvis plate.

The results show there was contact of the leg plate with the knee and upper part of the lower leg (upper tibia). The fibular fracture was probably due to the contact with the door as well, as identified by lower leg contact with the leg plate (Table 1).

The values of force obtained from the first model output resulting from the dummy contact with the vehicle in the crash were as follows: left hip contacting the upper door (pelvis plate) at (2.0 kN), the upper part of the lower leg (1.3 kN) and the middle part of the lower leg (0.36 kN) contacting the lower door (leg plate) and the left knee contacting the leg plate (2.2 kN).

Large compressive forces were not observed but fracture from bending was likely due to the side forces being above the tolerance values for a female fibula. The measured loads are likely to cause bending in the lower leg. The calculated values are all higher than the tolerances described by Levine [24] for females for the fibula (bending failure loads: **0.21 to 0.39 kN**; compression loads: **0.2 to 0.83 kN**) and thus fracture is likely to occur. A value of **0.36 kN** found in this study for the middle part of the lower leg corresponds to Levine's [24] failure load for the fibula injury and falls within the range specified for a female.

The side force from door intrusion could have caused the knee to open up and the ligaments to be

disrupted with subsequent knee joint failure. The upper tibia force value of **1.3 kN** calculated using MADYMO is higher than the loads found by others to cause ligament failure (anterior cruciate (ACL) failure: **0.6 kN** and collateral ligaments failure: between **0.15 kN** and **0.3 kN**). These findings verify the recorded knee injury.

The ligaments in the knee can be ruptured by differential movement between the tibia and femur. This crash simulation did not yield any contact between the knee bolsters and the knees, although in a crash of this type this kind of interaction could be likely, due to the forward component of force in such a configuration.

In an oblique angled crash such as this one, it is possible that the frontal component of inertia and intrusion could cause the knee to be entrapped by the knee bolster/dash and with toepan intrusion, causing axial loading of the lower leg especially when fixed at either the dash and/or toepan. The side component of force can cause bending in the lower leg.

The interaction of the foot with the clutch (Table 1) is probably due to inertia causing the foot to hit the pedal. The hip contact with the upper door (pelvis plate) was not examined further as this study only concerns the knee and below parts of the LE.

Mechanism (2) 90° Near-Side Crash

Maximum intrusion of the front door reached 50 cm for this model. In the recorded crash data the door intrusion was reported as being 40 cm.

In this case the EuroSID (left hand side) dummy was used. Results were compatible with the recorded real-world crash injury data. The LE injury sustained by the male driver in this crash was a fibular fracture (type of fracture not specified). The injury recorded in the real-world data was identified as being caused by "*interaction with the floor and crushing between the footwell and pedal*".

There was significant door intrusion. From the contacts with the LE in this crash simulation, there was a small force applied to the upper leg by the armrest, and forces from contact with the side of the vehicle, represented by the pelvis plate at the location of the knee and upper leg and leg plate at the location of the lower leg.

Dischinger et al. [11] also identified this mechanism in their study of side-impacts: "the door and armrest impacted the LE of the driver with loading from lateral to medial from the inside panel of the door".

The results of the second computer simulation show contact of the left upper leg with upper part of the door (pelvis plate 1) (**2.1 kN**), left knee with the upper door (pelvis plate 1) (**11.9 kN**) and lower leg with the leg plate (**6.6 kN**). The loads in the lower leg (fibula) are greater than the tolerances as found by Levine [24] for the male fibula (bending failure loads: **0.35 to 0.54 kN**; compression loads: **0.24 to 0.88 kN**).

Mechanism (3) 270° Far-Side Crash

There was no intrusion in this case. The LE injury sustained by the far-side, female driver occupant in this crash was a right tibial plateau (knee) fracture. The injury contact sources as reported in the original crash data were “*Lower leg contact with the steering column and lower dash*”.

There was also a small inertial force causing the right foot to contact the brake pedal.

The dummy, which is restrained in the seat by the belt at the abdomen, exhibited flailing of its lower extremities towards the crashed side of the vehicle with the right LE impacting the steering column. No shoulder sash was added in the model as this would not affect the LE [40].

The contact force between the upper tibia and steering column was perpendicular to the long axis of the tibia, thus shear loading took place. Bone is weaker in shear than compression (Carter cited in [28]). The force of contact between the steering column and knee in the simulation was **4.6 kN**. This force is greater or within the range of upper tibia fracture loads found by other researchers ([20], [29], Kramer et al. and Viano et al. cited in [29]).

Analysis of the outputs of this model showed that the peak force (4.6 kN) on the knee occurred at about 40 ms into the crash, from contacting the steering column. The peak acceleration also occurred at 40 ms into the crash. However, this was not investigated any further. Kajzer et al. [20] and Strother et al. [42] reported all injuries occurred during the first 30 ms of the crash.

DISCUSSION

The results compared favourably with the real-world crash data injuries recorded despite the approximate nature of the models. The loads calculated by MADYMO on the LE exceeded the tolerance values set by other researchers for the specific injuries noted in each case and lower for those parts of the LE that were not injured. Hence trends are discernible.

The two near-side (30° and 90°) crashes simulated in this study indicated possible fibular fractures. Similarly these simulations indicated that the tibia compression tolerance was not exceeded. For Mechanism (2) the tibia bending tolerance was exceeded by a small amount. It should be noted that tolerance fracture values documented by Levine and others were found from tests on isolated bones. Failure load values for an intact leg with soft tissues attached would be slightly greater. Lower leg fractures including fractures of the fibula are relatively common in these types of crashes. However, there are few studies, which investigate lower leg fractures, especially relating to the fibula. Pattimore et al. [33] in a frontal- and side-impact study found that 39% of skeletal leg injuries from impacts involved the fibula and 61%, the tibia. The results from this study indicate a more even distribution, being 56% tibia and 44% fibula fractures. More cases are required to determine the propensity of either bone to fracture in Mechanism (1) or (2) crash types.

Door contact with the LE is a common cause of injury in side-impact crashes [12], [17], [23], [36]. In this study, impact with the door (represented by pelvis and leg plates) occurred in the 30° and 90° simulated crash cases. Pattimore et al. [33] also found the most frequent source of injuries in near-side impacts was the front door. They additionally found vehicle intrusion was an important factor associated with the LE fractures. The footwell was also a major contributor for lower leg injuries. Their findings are in agreement with the findings from the MADYMO simulations in this study.

Collection and examination of more cases is also required to ascertain if major footwell intrusion and entrapment caused by interaction with knee bolsters is occurring. In this study, entrapment was not modelled but it does occur, though it is more common in frontal impacts.

In regards to the far-side Mechanism (3) simulation, knee impact with the steering column exceeded the tolerance values. This confirms Stolinski et al.’s [40] report that the steering column is a contact source of injury in far-side impacts. Crandall and Martin [7] also reported the steering column to be a source of injury for drivers, increasing the driver’s injury risk.

Brooks [6] stated from a study by Saab’s Female Reference Group in Australia that when looking at vehicle comfort and general functionality, “*women and men operate vehicles differently...Most women sit with their legs closer together than men, who normally sit with their legs apart. This means that the space under the steering column, where they place their knees, can easily become cramped*”.

Women also sit closer to the dash and column. There were no cases with men contacting the steering column recorded in the data analysed. The female (163 cm tall) in the simulated case who was shorter than an average male would have had her knees closer to the dash and lower part of the steering column and thus more likely to have a knee injury.

The contact sources estimated from post-crash inspection are based on signs of contact. Some of the reported contacts in the real-world data may not correlate exactly with those found using MADYMO though the trends are certainly evident here.

COUNTERMEASURES

Analysis of the CVF, classification of the observed LE injuries into the three mechanisms and the MADYMO analysis have allowed new injury countermeasures to be considered to mitigate LE injuries in side-impacts. However, as in the case of identifying the injury mechanisms, these strategies are only preliminary suggestions and require more research to validate their possible effectiveness. The strategies are as follows:

Seatbelts

In the case of frontal and in some far-side impacts, belts prevent upper body injuries when combined with airbag use. However, belts have little effect in preventing LE injuries in near-side impacts [7]. Most of the effect they have on the LE is above the knee. Their main role is frontal restraint and preventing ejection [17], [40]. Belts can reduce pelvis/thigh injuries including femoral fractures in frontal-impacts but not knee, lower leg and ankle/foot injuries [7], [31]. In far-side crashes, a lap belt would only help prevent sliding across the cabin.

A greater number of cases is required to determine the effect of belts on LE fractures and/or dislocations in side-impacts, but considering the above, it is likely that there will be little difference between LE injuries of belted and unbelted occupants. In near-side and severe far-side crashes it is more likely that intrusion will cause injury before a belt would have any effect.

Strengthening the Toepan, Door and Lower A-Pillar Region

Fundamental Mechanism (1): Initial consideration of this case suggests that strengthening the toepan to reduce its intrusion, could reduce over 50% of LE injuries caused by entrapment from the deforming footwell. However, toepan

strengthening may increase other (head, neck, and chest) injuries caused by increasing the vehicle crush stiffness. Thus the effect of such changes to the vehicle structure needs to be further investigated to determine if overall harm is reduced.

Changing the shape and properties of the bolsters would be beneficial, so that the knee misses the bolster in a crash (bolster sloping away from the leg). If the knee does contact it, the bolster should be sufficiently and appropriately padded so that knee contact forces are reduced, mitigating fractures and dislocations.

Fundamental Mechanism (2): Strengthening the door and A- and B-pillars in combination with padding can reduce the transfer of high energy impulse forces to the knee and lower leg. However, this again increases vehicle stiffness possibly increasing Harm in other body regions.

Strengthening the door and A- and B-Pillars would have a detrimental effect for Mechanism (3) as decelerations would increase, thus increasing inertial effects. It is clear that strengthening alone could prove detrimental.

Reducing Intrusion and Providing Padding and/or Airbags

A combination of reducing intrusion with addition of padding is required in side-impacts to reduce injuries. Reinforcing side structures such as the doors and footwell as suggested by Palaniappan et al. [32] combined with strategically placed padding could be a useful countermeasure to test. Originally the regulations for side-impact were to reduce side intrusion to a maximum of 3 to 4 inches (7.62 to 10.16 cm) in the US in pole and car-car impacts. Doors were stiffened and front ends of vehicles softened, but increasing the door stiffness actually increased test dummy injury parameters [42]. However, when increasing stiffness, other energy-absorbing vehicle parts must be enhanced to provide soft ride-down within a firm protective shell.

Fundamental Mechanism (2): Lower door airbags may reduce knee and lower leg injuries from high-energy, side-impact loads, where the LE may be in direct contact with the portion of the vehicle that has been directly struck by the bullet vehicle or when it hits an object (such as a pole). Because in a side-impact the occupant is effectively punched by the encroaching vehicle interior, padding or an airbag can provide wider contact areas and an “earlier and prolonged contact period for the occupant, and hence provide a greater distance to dissipate the kinetic energy” [23].

Fundamental Mechanism (3): Airbags and padding on the steering column, centre console and dash may reduce contact forces preventing injury caused by knee impact with these structures. Floor airbags could help foot slip-off-pedal injuries by making the floor flush with the pedal level.

Padding in the door will reduce the relative velocity between the occupant and vehicle but not the effects of intrusion. Padding will allow injury criteria based on acceleration to result in a better outcome but criteria based on intrusion may provide greater gains in reducing LE injuries. Combination of these two strategies would be useful in reducing injuries.

The occupant's location relative to the door also determines the contact velocity of the door when it strikes the occupant and hence injury outcome. Delaying the occupant contact with the encroaching door can decrease the energy transferred from the punch to the occupant. If contact begins while the door is already decelerating, less energy is transferred to the occupant [23]. Vehicle size and seat position in the vehicle design could have an effect on how close the occupant's LE is to the door.

RECOMMENDATIONS

Future data collections should have more detailed fracture descriptions of the LE including their exact locations and types. This would help in the determination of LE injury mechanisms as the types of fractures can reflect the types of loading conditions on the bone. In particular, more detailed recording of information regarding ankle and foot injuries would be useful.

According to Thomas and Frampton [44] "past research has shown that speeds at which serious injury occurred were above those used for regulation crash testing, as seen by the delta-Vs of the real-world crashes where injuries were sustained". Current side-impact regulation crash-test configurations are limited to around 50-60 km/h. A greater range of crash configurations should be tested, and at higher speeds than current regulations, if more injuries are to be prevented and Harm on the road from side-impacts reduced. However, "at (very) high speeds side-impact protection may disappear" [44]. (The vehicle design may not be able to cope with very high-speed impacts).

Improved dummy legs with greater measurement potential for injury tolerances would help improve the understanding of LE injury mechanisms in side-impact crash tests.

Measurement of the timing of intrusions and accelerations and forces on the LE during the crash event would also provide data useful for validating simulations.

For further verification of injury mechanisms, a greater number of side-impact crashes in which a LE fracture or dislocation is sustained is required.

The effects of age and gender should also be considered when designing side-impact injury prevention systems for the LE. It is clear from the data that females and older occupants have lower LE injury tolerances in side-impact crashes.

CONCLUSIONS

- LE injuries are significant and should be addressed in regards to their mitigation.
- The three fundamental LE mechanisms identified in [2] were successfully simulated and validated using a multi-body model.
- Simulations of the three fundamental mechanisms identified showed that injury tolerance levels were exceeded (Table 1), hence, providing plausible validation of how the injuries occurred.
- A number of possible LE countermeasures were identified from the simulations of the three mechanisms that included strengthening the footwell region, providing padding and airbags to reduce side-punch forces, and/or redesigning interior surfaces away from direct contact with LE (contact with door, raising steering column, etc). More research work needs to be carried out to assess which of these measures would be the most cost effective particularly in relation to total Harm.

ACKNOWLEDGMENTS

We would like to acknowledge:

- Brian Fildes, Monash University Accident Research Centre for the data.
- Laurie Sparke, Holden's Automotive Ltd for funding.
- Christopher Spitzer, TNO and Advea Pty Ltd for MADYMO assistance.

REFERENCES

- [1] American Association for Automotive Medicine (AAAM), 'The Abbreviated Injury Scale-1985 revision', Arlington Heights, IL, 1985.
- [2] Arndt, N., R. Grzebieta, B. Fildes, and L. Sparke, 'Lower Extremity Injuries in Side-Impact Vehicle Crashes', Proceedings of the International Crashworthiness Conference 2002, Melbourne, Australia, SAE, p. 1-15.
- [3] Arnoux, P. J., C. Cavallero, P. Chabrand, and C. Brunet, 'Knee ligament failure under dynamic loadings', International Journal of Crashworthiness, 2002 7(3) 255-268.
- [4] Beaugonin, M., E. Haug, and D. Cesari, 'A numerical model of the human ankle/foot under impact loading in inversion and eversion.', Proceedings of the 40th Stapp Car Crash Conference, New Mexico, SAE, 1996 p. 239-249.
- [5] Begeman, P., P. Balakrishnan, R. Levine, and A. King, 'Dynamic human ankle response to inversion and eversion', 37th Stapp car crash conference, San Antonio, Texas, SAE, 1993 p. 83 - 93.
- [6] Brooks, G., Women Feel the Heat, in Autoengineer, 2002. p. 31.
- [7] Crandall, J. R. and P. G. Martin, 'Lower limb injuries sustained in crashes and corresponding biomechanical research', International Symposium on Real World Crash Injury Research, UK, 1997 p. 3.5.1-3.5.16.
- [8] Crandall, J. R., L. Portier, P. Petit, G. W. Hall, C. R. Bass, G. S. Klopp, S. Hurwitz, W. D. Pilkey, X. Trosseille, C. Tarrriere, and J. P. Lassau, 'Biomechanical response and physical properties of the leg, foot and ankle', 40th Stapp Car Crash Conference, Albuquerque, New Mexico, SAE, 1996 p. 173 - 192.
- [9] Daffner, R. H., Z. L. Deeb, and A. R. Lupetin, 'Patterns of high-speed impact injuries in motor vehicle occupants', The Journal of Trauma, 1988 28(4) 498-501.
- [10] Digges, K. and D. Dalmotas, 'Injuries to Restrained Occupants in Far-Side Crashes', 17th International Conference on the Enhanced Safety of Vehicles, Amsterdam, 2001 p. 1-6.
- [11] Dischinger, P. C., C. B. Schmidhauser, A. R. Burgess, S. M. Ho, B. M. Cushing, T. D. O'Quinn, P. J. Juliano, and F. D. Bents, 'Lower extremity trauma in vehicular front seat occupants: patients admitted to a level 1 trauma centre', SAE international congress and exposition. In depth accident investigation: trauma team findings in late model vehicle collisions, SAE Paper No. 940710, ISBN 1-56091-494-7, Detroit, Michigan, SAE, 1994 p. 11-18.
- [12] Fildes, B., L. Sparke, and K. Seyer, 'Improved Side Impact Protection (ISIP) in Australia: Overview of a Collaborative Approach', 17th International Conference on the Enhanced Safety of Vehicles, Amsterdam, 2001.
- [13] Fildes, B. N., K. Digges, D. Carr, D. Dyte, and P. Vulcan, 'Side impact regulation benefits', Monash University Accident Research Centre, Melbourne, 1995.
- [14] Funk, J. R., J. R. Crandall, L. J. Tournet, C. B. MacMahon, and C. Bass, 'The Effect of Active Muscle Tension on the Axial Injury Tolerance of the Human Foot/Ankle Complex', 17th International Conference on the Enhanced Safety of Vehicles, Amsterdam, 2001 p. 1-15.
- [15] Gibson, T., B. Fildes, H. Deery, L. Sparke, E. Benetatos, M. Fitzharris, J. McLean, and P. Vulcan, 'Improved Side Impact Protection: A Review of Injury Patterns, Injury Tolerance and Dummy Measurement Capabilities', Monash University Accident Research Centre Report 147, Melbourne, 2001.
- [16] Gopal, M. and A. Vital, 'Performance Evaluation of Door and Seat Side Impact Airbags For Passenger Van and Sport utility Vehicles', Airbag Technology SAE Special Publications, Paper No. 980912, 1998 February 153-157.
- [17] Haland, Y., P. Lovsund, and A. Nygren, 'Life-threatening and disabling injuries in car-to-car side impacts-implications for development of protective systems', Accident Analysis and Prevention, 1993 Apr;25(2) 199-205.
- [18] Hayashi, S., H.-Y. Choi, R. S. Levine, K. H. Yang, and A. I. King, 'Experimental and analytical study of knee fracture mechanisms in a frontal knee impact', Proc. 40th Stapp Car Crash Conference, Paper No. 962425, ISBN 0585-086X, New Mexico, 1996 p. 161-171.
- [19] Hoglund, N., D. C. Viano, and P. Lovsund, 'Mathematical modelling of lower leg responses in offset crashes', ICRASH2002, Melbourne, Australia, SAE, 2001 p. 1 - 22.
- [20] Kajzer, J., C. Cavallero, S. Ghanouchi, J. Bonnoit, and A. Ghorbel, 'Response of the knee joint in lateral impact: Effect of shearing loads',

1990 international IRCOBI Conference on the Biomechanics of Impacts, Bron, Lyon, France, 1990 p. 293 - 304.

[21] Kajzer, J., G. Schroeder, H. Ishikawa, Y. Matsui, and U. Bosch, 'Shearing and bending effects at the knee joint at high speed lateral loading', 41st Stapp Car Crash Conference, Lake Buena Vista, Florida, SAE, 1997 p. 151-165.

[22] Kallieris, D., H. Riedl, and R. Mattern, 'Response and Vulnerability of the Ankle Joint in Simulated Footwell Intrusion Experiments- A Study With Cadavers.', 17th International Conference on the Enhanced Safety of Vehicles, Paper No. 105, from CDROM: <http://www.med.uni.heidelberg.de/rechtmed/publ2001.htm>, Amsterdam, 2001.

[23] Lau, I. V., J. P. Capp, and J. A. Obermeyer, 'Comparison of frontal and side impact. Crash dynamics, countermeasures and subsystem tests', Proceedings of the 35th Stapp Car Crash Conference, SAE, P-251, San Diego, 1991 p. 109-124.

[24] Levine, R., Injury to the extremities, in Accidental Injury. Biomechanics and Prevention, Nahum, A., M. and J. W. Melvin, Editors, Springer-Verlag, 1993 p. 460-491.

[25] Manning, P., A. Wallace, C. Owen, A. Roberts, C. Oakleigh, and R. Lowne, 'Dynamic Response and Injury Mechanism in the Human Foot and Ankle and an Analysis of Dummy Biofidelity', 16th International Technical Conference on the Enhanced Safety of Vehicles. Proceedings, Vol. 3, Ontario, Canada, 1998 p. 1960-1999.

[26] Morgan, R. M., R. H. Eppinger, and B. C. Hennessey, 'Ankle joint injury mechanism for adults in frontal automotive impact', 35th Stapp Car Crash Conference, P-251, ISBN 1-56091-190-5, San Diego, SAE, 1991 p. 189-198.

[27] Nagel, D. A., D. S. Burton, and J. Manning, 'The dashboard knee injury.', Clinical Orthopaedics and Related Research., 1977 126(July-Aug) 203-208.

[28] Nordin, M. and V. H. Frankel, 'Basic Biomechanics of the Musculoskeletal System', Second ed, Yelle, L., Philadelphia, PA, Lea and Febiger, 1980.

[29] Nyquist, G. W., 'Injury tolerance characteristics of the adult human lower extremities under static and dynamic loading', Symposium on

Biomechanics and Medical Aspects of Lower Limb Injuries, San Diego, CA, SAE, 1986 p. 79-90.

[30] Nyquist, G. W., R. Cheng, A. R. El-Bohy, and A. I. King, 'Tibia bending: strength and response', SAE Transactions, 1985 6.240-6.253.

[31] Otte, D., H. von-Rheibaben, and H. Zwipp, 'Biomechanics of injuries to the foot and ankle joint of car drivers and improvements for an optimal car floor development', 36th Stapp Car Crash Conference Proceedings, Seattle, Washington, 1992 p. 43-58.

[32] Palaniappan, P. J., V. Maripudi, P. Wipasuramont, A. S. Tanavde, and K. Gudipaty, 'Numerical Simulation of Side Impact Sled Tests with Chambered Side Airbag', Crashworthiness, Occupant Protection and Biomechanics in Transportation Systems, 1997 255 - 273.

[33] Pattimore, D., E. Ward, P. Thomas, and M. Bradford, 'The nature and cause of lower limb injuries in car crashes', 35th Stapp Car Crash Conference Proceedings, Paper No. 912901, San Diego, California, Society of Automotive Engineers, 1991 p. 177-198.

[34] Sakura, M., 'An analysis of injury mechanisms for ankle/foot region in frontal offset collisions.', Proceedings of the 40th stapp car crash conference., New Mexico., 1996 p. 251-267.

[35] Silver, F. H., 'Biomaterials, Medical Devices and Tissue Engineering. An integrated approach', London, Chapman and Hall, 1994.

[36] Sparke, L., Holden uses unique research to improve side impact protection.,, July 28, 2000, www.autoweb.com.au.

[37] Stolinski, R., 'Vehicle safety - a new look at side impact protection', Motoring Directions, 1998 4(4) 4 - 7.

[38] Stolinski, R. and R. Grzebieta, 'Priorities to reduce vehicle side impact trauma: which countermeasures matter most?', Proceedings of the 15th Enhanced Safety of Vehicles Conference, Melbourne, 1996 p. 1-14.

[39] Stolinski, R., R. Grzebieta, and B. Fildes, 'Vehicle Side Impact Trauma: A Focus on Head Injury', Civil Engineering, Monash University Report, Clayton

[40] Stolinski, R., R. Grzebieta, and B. Fildes, 'Side Impact Protection - occupants in the far-side seat', International Journal of Crashworthiness, 1998 3(2) 93-121.

- [41] Stolinski, R., R. Grzebieta, and B. Fildes, 'Vehicle far-side impact crashes', 16th International Technical Conference on the Enhanced Safety of Vehicles, Windsor, Canada, 1998 p. 1819-1826.
- [42] Strother, C. E., G. C. Smith, M. B. James, and C. Y. Warner, 'Injury and intrusion in side impacts and rollovers', SAE Transactions, 1984 93(3) 3.1 - 3.24.
- [43] Thomas, P. and M. Bradford, 'A logistic regression analysis of lower limb injury risk in frontal collisions.', 39th Annual Proceedings of the Association for the Advancement of Automotive Medicine, Chicago, 1995 p. 287-309.
- [44] Thomas, P. and R. Frampton, 'Injury patterns in side collisions - a new look with reference to current test methods and injury criteria', 43rd Stapp Car Crash Conference, San Diego, California, SAE, 1999 p. 1-12.
- [45] TNO, 'MADYMO Applications Manual Version 5.4', 1999.
- [46] TNO, 'MADYMO Databases Manual Version 5.4', 1999.
- [47] Williams and Lissner, 'Biomechanics of Human Motion', Third ed, LeVeau, B. F., Sydney, W. B. Saunders Company, 1992.
- [48] Yoganandan, N., F. A. Pintar, S. Kumaresan, and M. Boynton, 'Axial impact biomechanics of the human foot - ankle complex', Journal of biomechanical engineering, 1997 119(November) 433 - 437.

APPENDIX

Table 1. Dummy Contact Interactions, Associated Contact Forces* and Tolerances

Contact Source	Dummy Body Part	Associated Contact Force (kN)	Tolerances (kN)
MECHANISM (1) Near-Side 30° Oblique Crash, Female Occupant (Knee Joint Disruption and Fibula Fracture)			
Upper door (Pelvis Plate 1)	Left hip	2.0	5.6 female pelvis lateral impact tolerance [Cesari et al. cited in [15]. Not examined in this study.
Lower door (Leg plate)	Left knee	2.2	0.15–0.3 collateral ligaments [3] 0.6 ACL [35]
Lower door (Leg plate)	Left (upper) lower leg	1.3	0.21–0.39 female fibula in bending 0.2–0.83 female fibula in compression
Lower door (Leg plate)	Left (middle) lower leg	0.36	1.86–2.65 female tibia in bending 4.89–10.37 female tibia in compression [24]
Clutch	Left sole of shoe	0.44	2.0 [34], 3.3–5.5 [Begeman and Aekbote cited in [48]]. No ankle/foot injury reported.
MECHANISM (2) Near-Side 90° Crash, Male Occupant (Fibula Fracture)			
Armrest	Left upper leg (femur)	0.35	3.1 femur in side-impact [Kress cited in [15], 2.58 (female femur bending) [24]]. Upper leg not examined.
Upper door (Pelvis Plate 1)	Left upper leg (femur)	2.1	
Upper door (Pelvis Plate 1)	Left knee	11.9	> 15.0 [Melvin et al. cited in [18]]. No knee injury reported.
Lower door (Leg plate)	Left lower leg	6.6	0.35–0.54 male fibula in bending 0.24–0.88 male fibula in compression 2.3–4.9 male tibia in bending 7.05–16.39 male tibia in compression [24]
MECHANISM (3) Far-Side 270° Crash, Female Occupant (Tibial Plateau Fracture)			
Steering column	Right upper leg (femur)	0.25	3.1 femur in side-impact [Kress cited in [15]], 2.26–3.33 female femur in bending [24]
Steering column	Right knee	4.6	1.0–4.3 upper tibia (Kramer in [29])
Steering column	Right lower leg	0.06	1.86–2.65 female tibia in bending 4.89–10.37 female tibia in compression 0.2–0.83 female fibula in bending 4.89–10.37 female fibula in compression [24] No lower leg injury reported
Brake pedal	Right foot	0.34	2.0 [34], 3.3–5.5 [Begeman and Aekbote cited in [48]]. No ankle/foot injury reported.

* The Associated Contact Forces of the LE segments in Bold exceeded their tolerances.