LOWER EXTREMITY INJURIES AND ASSOCIATED INJURY CRITERIA

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ABSTRACT

An analysis of the National Automotive Sampling System/ Crashworthiness Data System (NASS/CDS) for the years 1993-1999 was conducted to determine the risk of injury to different body regions in frontal crashes. Lower extremities were the leading injured body region. The risk of lower limb injuries was significant in all crash modes. A detailed examination of these lower extremity injuries was then conducted using the AIS-90 injury codes. The long term consequence of lower extremity injuries was estimated using the Functional Capacity Index (FCI) associated with each AIS-90 injury code. The effect of a particular injury on society was reported in terms of total Functional Life-years Lost to Injury (LLI) which is defined as the product of FCI and the injured person's life expectancy.

Using existing biomechanical data on lower extremity injuries, injury criteria and associated injury risk curves were synthesized for different regions of the lower extremity, namely 1) knee-thigh-hip complex fractures, 2) knee ligaments tears, 3) tibial plateau/condyle fractures, 4) tibia/ fibula shaft fractures, 5) calcaneus, ankle, and midfoot fractures, 6) malleolar, ligament, and ankle injuries. The threshold for a 25% probability of injury for the 50th percentile male were then scaled to obtain the corresponding threshold for other adult sizes.

INTRODUCTION

Lower limb injuries resulting from vehicle crashes are the second most common site of AIS 2+ injuries (Thomas, 1995) and have been reported to be a frequent cause of permanent disability and impairment (Burgess et al., 1995). Consequently, it is important to be able to detect and quantify the risk of these injuries from vehicle impact tests.

Stucki et al. (1998) examined the NASS database for the years 1988-96 for the distribution of lower extremity injuries among front seat occupants in air bag equipped vehicles involved in frontal crashes. Stucki noted that the risk of AIS 2+ lower limb injuries was almost two times greater than the risk of head/face, thorax, or arm injuries. Stucki conducted an examination of the proportion of leg injuries in different crash modes and found foot and ankle fractures to be the most prominent injured lower limb region. However, common ankle injuries such as malleolar fractures were coded as tibia and fibula injuries in his analysis. The analysis also did not examine the long term consequences of these injuries. Therefore, a new analysis of the NASS data files was initiated to better understand lower extremity injuries in real world crashes and the long term consequences associated with these injuries.

Following the analysis of real world crash data, injury criteria and injury risk curves for lower limb injuries were developed using published biomechanical test data. The first part of this paper presents the analysis of real world crash data and the second part presents the development of relevant lower extremity injury criteria and injury limits for various adult sizes.

REAL WORLD CRASH DATA

Methods

The NASS/CDS data files for the years 1993-1999 were examined to determine the risk of injury to different body regions for outboard front seat occupants in air bag equipped vehicles involved in frontal crashes. Only those front outboard passengers were considered in the analysis who were in vehicles with passenger side air bags. Crashes involving rollovers and ejections were excluded in the analysis. All data presented in the paper are weighted according to NASS recommendations.

Frontal crashes were defined as those with the principal direction of force (DOF1) between 11 and 1 o'clock or DOF1 between 10 or 2 o'clock with general area of damage (GAD) being front or side with damage forward of A-pillar. The frontal impact population was then separated into specific crash modes to identify differences in injury risk between the crash modes. Frontal crashes were separated by damage distribution (left or right offset or distributed) and by object contacted (another vehicle or a fixed object). For frontal damage (GAD1-F), overlap was defined by the crash "D" variable when known, otherwise, the primary specific horizontal location (SLH1) was used to separate into distributed, left offset, and right offset impacts. Left and right offset crashes included collinear and oblique impacts.

The injuries, coded according to the Abbreviated Injury Scale (AIS, 1990), were divided into seven body regions 1) head/face, 2) neck, 3) chest 4) abdomen, 5) spine, 6) upper limb, 7) lower limb. The data was analyzed using only the maximum AIS level injury to each body region. If there were two or more maximum injuries to a body region with the same AIS level, only one was used. The risk of AIS 2+ injury was computed using Equation 1.

$$\text{risk of AIS} \geq 2 \text{ injury to a body region in a crash mode} = (\text{no. occupants with at least one AIS} \geq 2 \text{ injury to body region in specified crash mode}) / \text{no. of occupants in specified crash mode} \quad (1)$$

The analysis was conducted for front outboard occupants who were belted, unbelted, and all occupants regardless of belt use. The risk of injury to different body regions for different restraint conditions and crash modes was examined.

After estimating the risk of AIS 2+ lower extremity injuries relative to the risk of injury to other body regions, a detailed examination of the distribution of lower extremity injuries for different restraint conditions and crash modes was made. The AIS codes were utilized to group the lower limb injuries into 1) hip, 2) femur, 3) knee, 4) tibial plateau, 5) leg shaft, 6) ankle (including malleoli), and 7) foot for the detailed analysis. This analysis examined only the maximum AIS level lower extremity injury for each occupant. If an occupant had more than one maximum lower extremity injury with the same AIS level, then the injury with the highest LLI (defined later in this section) was used for that occupant. Injury codes of the lower extremity regarding skin, blood vessels, or the nerves were not considered in this analysis.

The ranking levels of the Abbreviated Injury Scale have been found to be associated with risk to life and not necessarily to impairment, disability, or loss in functional capacity that result from the injury. Almost all lower extremity injuries are classified at a minor (AIS=1) or moderate (AIS=2) severity level. These injuries appear to have little or no influence on mortality but are associated with impairment and loss in functional capacity due to the injury. Therefore, in order to address the long term consequences of lower extremity injuries, the Functional Capacity Index (Luchter, 1995) was utilized. The Functional Capacity Index (FCI) is an estimate of the long term effects of injury, based on the functional state of an injured individual one year post injury. FCI values vary from 0 for no loss to 1.0 for complete loss of function. In order to describe the long term effect of an injury on the population, the Functional Life-years Lost to Injury (LLI) was used. The LLI for an injury is defined as the product of its FCI and the life expectancy of the injured person, which captures the age and gender makeup of the injured population. The units of LLI are years.

Results of Analysis

Among front outboard occupants in air bag equipped vehicles in frontal crashes, 25 percent were in full frontal crashes while 37 percent were in left offset and 38 percent were in right offset crashes (Figure 1).

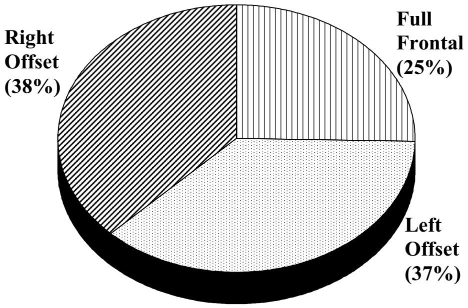

Figure 1. **Percentage of front outboard occupants involved in different frontal crash modes.**

Among front outboard occupants in air bag equipped vehicles involved in frontal crashes, 88% were restrained by seat belts while 12% were not. The risk of AIS 2+ injuries to different body regions for all front outboard occupants and only belted front outboard occupants in air bag equipped vehicles involved in frontal crashes are presented in Figures 2 and 3, respectively. Figures 2 and 3 suggest that the risk of AIS 2+ lower extremity injuries in all frontal crashes is higher than for any other body regions. The risk of AIS 2+ lower limb injuries is significant in all crash modes. The trends for all front outboard occupants regardless of belt use and those for only belted front outboard occupants are similar in all crash modes due to the high percentage of belt use in this data set.

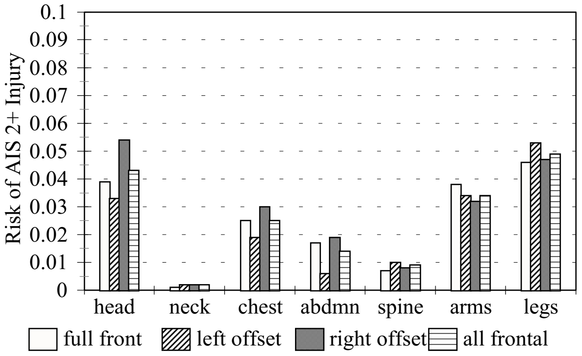

Figure 2. **Risk of AIS 2+ injuries to front outboard occupants in frontal crashes (vehicles with air bags).**

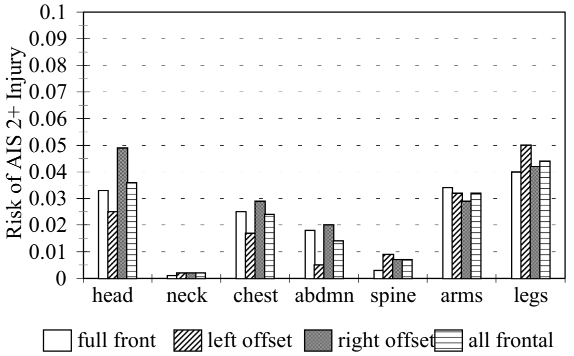

Figure 3. Risk of AIS 2+ injuries to belted front seat occupants in frontal crashes (vehicles with air bags).

Table 1. **Average number of AIS 2+ injuries and associated LLI occurring annually to front outboard occupants in air bag equipped vehicles (current proportion in fleet) involved in frontal crashes**

	No. of AIS 2+ injuries	Associated LLI
hip	2153	18691.2
femur	1657	8230.3
knee	5928	5917.0
tib.plat	1257	6320.1
tib. shft	794	6243.7
foot/ank	5880	31325.7
total	17669	76728.0

The average number of AIS 2+ lower extremity injuries occurring annually to front outboard occupants in air bag equipped vehicles (using current proportion of air bag equipped vehicles in the fleet) involved in frontal crashes and the associated Life-years Lost to Injury is presented in Table 1. The injuries involving skin, blood vessels, and nerves are not included in this analysis. An average total of 17669 lower extremity injuries occur annually to front outboard occupants in air bag equipped vehicles (1993-1999 Nass data files) which are associated with 76728 life-years lost to injury.

The proportion of all AIS 2+ lower extremity injuries for front outboard occupants in air bag equipped vehicles involved in frontal crashes is presented in Figure 4. The long term consequences of these injuries in terms of Functional Life-years Lost to Injury is presented in Figure 5. Foot and ankle injuries are the dominant injuries accounting for 33% of AIS 2+ lower limb injuries and 41% of associated LLI. Note that knee injuries account for more than 34% of AIS 2+ lower limb injuries in frontal crashes but only account for 8% of LLI. This is because most of the AIS 2+ knee injuries are knee sprains which do not have long term consequences.

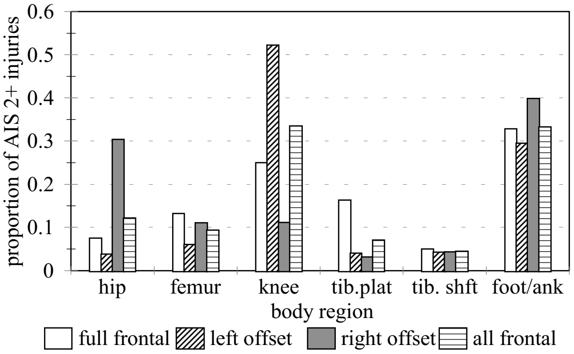

Figure 4. **Proportion of AIS 2+ lower limb injuries to front outboard occupants in air bag equipped vehicles involved in frontal crashes.**

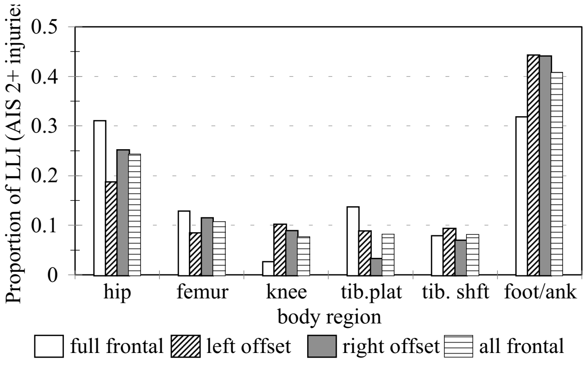

Figure 5. **Proportion of functional Life-years Lost to AIS 2+ lower limb injuries to front outboard occupants in air bag equipped vehicles involved in frontal crashes.**

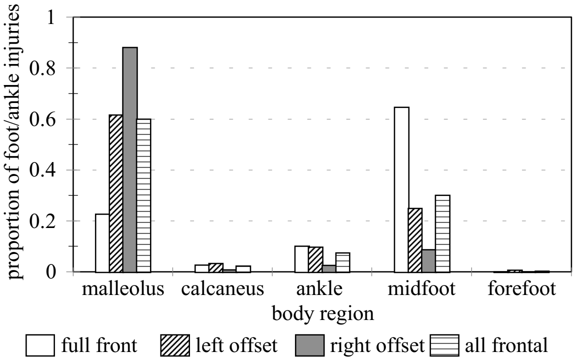

Figure 6. Proportion of AIS 2+ foot and ankle injuries to front outboard occupants in air bag equipped vehicles involved in frontal crashes.

Among all below the knee AIS 2+ injuries, 74% are foot and ankle injuries while 26% are injuries to the tibia/fibula shaft and plateau. The distribution of AIS 2+ foot and ankle injuries for different crash modes is presented in Figure 6. Malleolar fractures account for 60% of all foot and ankle injuries in frontal crashes while ankle and calcaneus fractures account for only 10% of these injuries. Midfoot injuries are the dominant foot and ankle injuries in full frontal crashes (65%).

Discussion

The current study reports a significantly higher proportion of knee and midfoot injuries than that reported by Manning et al. (1998) in a retrospective analysis of the UK CCIS accident database. The differences in the proportion of lower extremity injuries in the two studies could be attributed to differences in sampling techniques, sample size, and injury coding scales used in the two studies. Unlike NASS which uses the AIS scale to code and rank injuries, Manning et al. used the injury scale developed by the American Orthopaedic Foot and Ankle Society (AOFAS). Further, the sample size of the Manning study is smaller (114 occupants) than that of the current study (2200 occupants - unweighted).

The Functional Capacity Index used in the current study appears not to reflect the true impairment and long term consequence of some foot and ankle injuries. For example, Manning et al. (1998) and Ore and States et al. (1993) associated calcaneal, pilon, and talar fractures with greater impairment, disability, and long term consequence than femur shaft fractures. However, the FCI for femur shaft fractures are higher than the more disabling ankle injuries. Therefore, the Life years Lost to Injury reported in the current study underestimate the long term consequences of foot and ankle injuries.

The current analysis of the NASS data files indicates lower extremities are the most frequent AIS 2+ injured body region for front outboard occupants in air bag equipped vehicles. Though most lower limb injuries are not life threatening, they are associated with a high level of functional loss, impairment, and societal cost. Therefore, efforts in injury prevention to the lower limbs have potential for high benefits.

LOWER EXTREMITY INJURY CRITERIA

This section presents the injury criteria associated with various lower extremity injuries.

Injury Criteria for the Knee-Thigh-Hip Complex

Injury to the knee-thigh-hip complex account for approximately 55% of AIS 2+ lower extremity injuries and 42% of the corresponding Life-years Lost to Injury (LLI) for front outboard occupants in air bag equipped vehicles. The injury threshold limit for the knee-thigh-hip complex prescribed in FMVSS 208 and used in NCAP is 10 kN of axial femur force for the 50th percentile male. Morgan et al. (1990) analyzed knee impact cadaver test data from various research efforts using maximum likelihood methods and suggested that 10 kN of applied force at the knee corresponds to a 35% probability of AIS 2+ injury.

Some researchers have proposed alternate injury criteria for knee-thigh-hip fractures/dislocations which take into consideration not only the peak load, but also the loading duration (Mertz, 1993 and Viano, 1997). Mertz (1993) proposed an axial femur force injury threshold level of 9070 N for the 50th percentile male which corresponds to the peak force in his time-dependent criterion.

The test data (126 single impact tests using whole cadaveric subjects) reported by Morgan et al. (1990) was reanalysed using logistic regression for AIS 2+ and 3+ knee-thigh-hip injuries. Among the 126 cadaveric subjects in this data, only 4 subjects sustained a hip fracture. The dominant injuries in this data set were patellar and femur fractures. The data used in the analysis is presented in Appendix A, Table A-I. The results of the analysis suggested that femur axial force alone was a reasonably good predictor of knee-thigh-hip injuries (p=0.0001). The probability of knee-thigh-hip injuries as a function of applied femur force is presented in Figure 7 and Equation 2. According to this analysis, a femur axial force of 9040 N and 11150 N are associated with a 25% and 50% probability of AIS 2+ knee-thigh-hip injuries respectively.

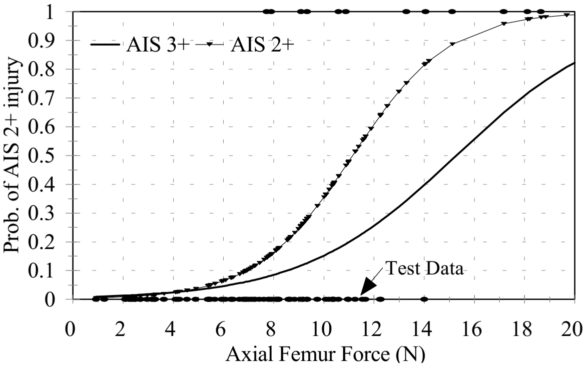

Figure 7. **Probability of AIS 2+ and 3+ knee-thigh-hip injuries.**

$$p(AIS\ \ 2+) = \frac{1}{1+e^{5.7949-0.5196F}} \qquad (2)$$

$$p(AIS\ \ 3+) = \frac{1}{1+e^{4.9795-0.326F}}$$

$F =$ femur axial force

Injury Criteria for Knee Ligament Injuries

Knee ligament injuries account for less than 1% of AIS 2+ lower extremity injuries and the corresponding LLI in frontal crashes for air bag equipped vehicles. When the flexed knee and tibia are impacted, the proximal tibia translates posteriorly relative to the distal femur resulting in stretching of the posterior cruciate ligament. Excessive relative translation between the femur and tibia may result in damage to the posterior cruciate ligament. Viano (1978) conducted dynamic tolerance tests on isolated cadaveric knee joints and observed that partial ligament tears occurred at 14.4 mm relative translation between the femur and the tibia and complete failure of the ligament occurred at 22.6 mm relative translation. Based on this data, Mertz (1990) recommended an injury threshold level of 15 mm for relative translation between the femur and tibia at the knee joint for a 50th percentile male to minimize rupture of the posterior cruciate ligament. Due to lack of sufficient biomechanical data, injury risk curves to address knee ligament injuries could not be constructed.

Injury Criteria for Tibial Plateau and Condyle Fractures

Tibial plateau fractures account for approximately 7% of AIS 2+ lower extremity injuries and 8% of the corresponding LLI for front seat occupants in frontal crashes with air bag equipped vehicles. Hirsch and Sullivan (1965) conducted quasi-static axial compression tests on cadaveric tibiofemoral joints at various flexion angles. They documented an average failure load of 8 kN for specimens tested at flexion angles between 0° and 20°. Based on these tests, Mertz (1993) recommended a proximal tibia axial force limit of 8 kN to address tibial plateau and condyle fractures for the 50th percentile male. Recently, Bangelmaier et al. (1999) dynamically tested 12 matched pairs of isolated tibiofemoral joints. One aspect of each pair was repeatedly impacted until gross fracture was observed and the contralateral limb was subjected to a single impact. Fractures of the femoral notch, femoral condyles, tibial plateau, and a combination of these injuries were reported. Bangelmaier found the average peak failure load in the repeat impact tests to be 8 kN.

The impact tests conducted by Bangelmaier were further analyzed using logistic regression to develop injury risk curves for tibial plateau and condyle fractures. In some of the sequentially impacted joints, the force resulting in gross fracture was lower than that in the previous impact to the joint. This suggests that the impacted joint may have developed microcracks in the previous impact effectively reducing the force needed to cause fracture. Therefore, while using the repeat impact data, the second to last impact was considered as the impact causing injury and the impact where gross fracture was observed was discarded. The resulting data is shown in Appendix A, Table A-II. The data consists of 12 joints subjected to repeated impacts and six joints subjected to a single impact. The group of six impacts conducted at constant energy were not included in the analysis since Fuji pressure films were placed in the joint prior to impact, which may have compromised the joint. Results of logistic regression showed a linear combination of tibia axial force and mass of the subject to be a good predictor ($p=0.005$) of tibial plateau injuries (Equation 3). Applying a mass of 75 kg for the 50th percentile adult male in Equation 3, the risk of tibial plateau and condyle injury was derived and is presented in Figure 8.

$$p(AIS\ \ 2+) = \frac{1}{1+e^{(0.5204-0.8189F+0.0686mass)}} \qquad (3)$$

$F =$ upper tibia axial force

According to this risk curve, 5.6 kN and 7 kN of proximal tibia axial force corresponds to a 25% and 50% probability of AIS 2+ tibial condyle and plateau fractures, respectively.

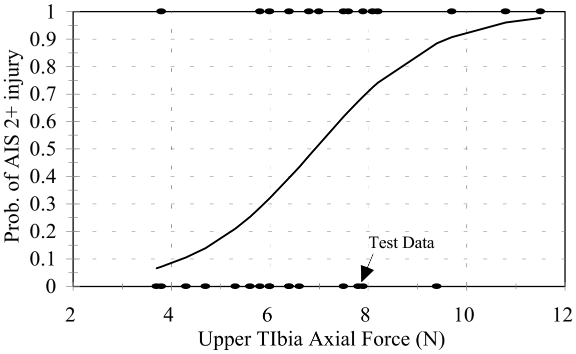

Figure 8. **Risk of AIS 2+ tibial plateau or condyle injury as a function of upper tibia axial force.**

Injury Criteria for Tibia and Fibula Shaft Fractures

Tibial and fibular shaft fractures account for 5% of AIS≥2 lower extremity injuries and 8% of Life-years Lost due to lower extremity injuries for front outboard occupants involved in frontal crashes. An existing injury criteria proposal for leg shaft fractures is the Tibia Index (Mertz, 1993). The Tibia Index is an injury tolerance criterion for combined bending and axial compressive loads on the tibia. The Tibia Index (TI) is given by Equation 4.

$$TI = \frac{F}{F_c} + \frac{M}{M_c} < 1 \qquad (4)$$

where: F is the measured compressive axial force (kN) in the superior-inferior direction. M is the measured bending moment in newton meters (Nm) in the leg. The bending moment M was originally defined in the medial-lateral direction but later redefined as the resultant moment of the medial-lateral and the anterior-posterior moments. The Tibia Index is computed using the corresponding force and moment measurements at the upper and lower tibia. M_C and $F_{C,}$ the critical values of bending moment and axial compressive force in the tibia, were recommended by Mertz (1993) to be equal to 225 Nm and 35.9 kN for the 50th percentile male. A modified TI threshold of 1.3 as a compliance margin associated with the Hybrid III dummy leg is currently in use by the EEVC in Euro NCAP.

Schreiber (1997) conducted quasi-static and dynamic 3-point bending tests on intact cadaveric leg specimens and noted that the critical force limit, F_C proposed by Mertz appeared too high, while the critical moment, Mc, of the Tibia Index appeared low. The average quasi-static failure moment among 10 cadaveric specimens was 240 Nm. Nyquist et al. (1985) conducted dynamic 3-point bending tests on 21 unembalmed intact human legs loaded in the anteroposterior and lateromedial directions. Nyquist noted that the bending strength was independent of loading direction with midshaft tibial fractures occurring at an average bending moment of 320 Nm for adult male subjects.

Messerer (Nyquist, 1986) conducted quasi-static axial compression of isolated whole bones from embalmed specimens and observed fracture to occur at an average axial force in the tibia of 10.4 kN. Taking into consideration that the fibula shares 10-15% of the axial compressive load in the leg and that embalmed specimens have lower fracture tolerance (Melvin, 1975) than unembalmed specimens, the axial compressive failure force of the human leg was estimated to be 12 kN. Through simulation, using a 3-D finite element model of the lower limb, Schuster, et al. (2000) predicted an axial compressive force of 12 kN for tibial shaft fractures in a 50th percentile male. Using these existing experimental results, an axial force critical value (F_c) equal to 12 kN and a moment critical value (M_c) equal to 240 Nm for the 50th percentile male is recommended as part of leg injury assessment. Equation 4 with the new critical values for F_c and M_c is referred to as the Revised Tibia Index (RTI).

The injury risk curve for leg shaft fractures using the Revised Tibia Index (RTI) was developed using the 3-point bending test data from Schreiber (1997) and Nyquist (1985) and is listed in Appendix A, Table A-III. Since all the specimens were taken to failure, a survival analysis was conducted using the computed Tibia Index as the explanatory variable. The probability of leg fracture (AIS 2+) is presented in Equation 5 and Figure 9. According to the risk curve, RTI values of 0.91 and 1.16 correspond to 25% and 50% probability of AIS 2+ leg shaft injuries. A RTI value of 1 corresponds to 33% probability of injury.

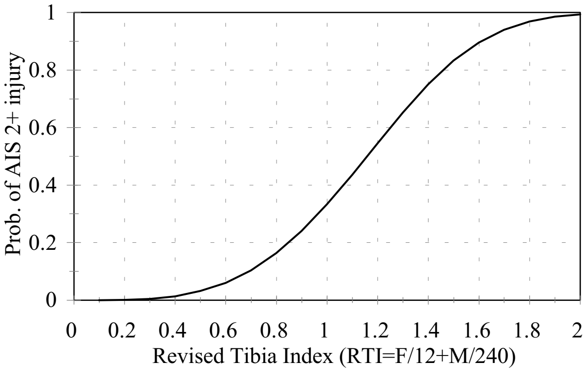

Figure 9. **Probability of AIS 2+ leg shaft fracture versus RTI (F/12+M/240).**

$$p(AIS\ \ 2+) = 1 - \exp(-e^{\frac{\ln(RTI)-0.2728}{0.2468}}) \quad (5)$$

$$where\ \mathrm{R}TI = \frac{M}{240} + \frac{F}{12}$$

Injury Criteria for Calcaneus, Talus, Ankle and Midfoot Fractures

Calcaneal, talar, midfoot, and various ankle fracture have been attributed to the mechanism of axial loading through the plantar surface of the foot in the vehicle crash environment (Manning, et al., 1998). These injuries are especially severe and debilitating and account for 13% of AIS$\geq$2 lower extremity injuries and 15% of life years lost to injury for front outboard occupants involved in frontal crashes.

Recent epidemiological studies and laboratory experiments using postmortem human subjects have provided a better understanding of injury mechanisms and injury criteria for the foot and ankle. Lower limb axial impact tests (Klopp, 1997) demonstrated that even malleolar fractures can occur from pure axial loading of the leg.. The study also indicated that while the Tibia Index is not a good predictor of foot and ankle injuries, the peak applied axial force was a good predictor.

Begeman (1997) conducted impact tests where unembalmed cadaveric legs were subjected to uniaxial plantar surface loads along the axis of the tibia. Pilon and calcaneal fractures were observed and the average failure tibial axial force was 7590 N.

Yoganandan (1996) applied dynamic axial loads to the plantar surface of the foot using a pendulum device. Fractures to the calcaneus and distal tibia were observed. These tests were combined with the axial impact tests conducted by Begeman (1997) and Roberts (1993). The results of the analysis using the combined data set suggested a 50% probability of injury for an axial force in the tibia of 6.7 kN.

Kitagawa (1998) conducted impact tests using human cadaveric leg specimens to investigate the combined effect of muscle preloading and external force. A constant tendon force was applied to the calcaneus while an external impact force was applied to the forefoot. Calcaneal and pilon fractures were observed in the specimens. The average failure load in the tibia was 8115 N for calcaneal fractures and 7293 N for pilon fractures.

A logistic regression analysis was conducted on the combined data set published by Yoganandan et al. (1996) which is listed in Appendix A, Table A-IV. The analysis indicated that lower tibia axial force was a reasonably good predictor of injury (p-value =0.0001) The resulting risk of AIS 2+ injury versus lower tibia axial force is presented in Figure 10 and Equation 6. Lower tibia axial force of 5.2 kN and 6.8 kN correspond to 25% and 50% probability of AIS 2+ calcaneal/talar/ankle and midfoot fractures, respectively.

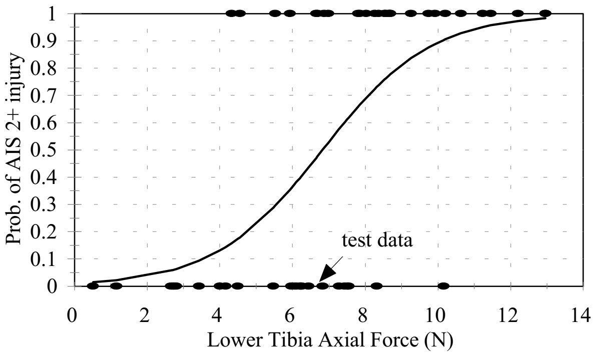

Figure 10. **Probability of AIS 2+ calcaneus, talus, ankle, and midfoot fractures as a function of axial lower tibia axial force.**

$$p(AIS\ \ 2+) = \frac{1}{1+e^{4.572-0.670F}} \qquad (6)$$

$$where\ \mathrm{F} = \text{lower tibia axial force}$$

Injury Criteria for malleolar fractures and ankle ligament injuries

Malleolar/talar fractures and ligamentous ankle injuries are common ankle injuries which account for 60% of foot and ankle injuries to front outboard occupants in air bag equipped vehicles involved in frontal crashes. These injuries may result from rotation of the foot alone or in combination with dynamic axial compressive forces. In the presence of significant toepan intrusion such as in offset crashes, the possibility of extreme rotation of the foot is high (Figure 6) and so injury criteria to prevent these common ankle injuries is required.

Portier, et al. (1997) conducted pendulum and sled tests using whole human cadaveric subjects to characterize dynamic dorsiflexion response and tolerance. In all the tests, the forces and moments within the ankle joint were computed from the measured forces, moments, and acceleration at the distal tibia. The results derived from the sled and pendulum tests were similar. The injuries sustained by the subjects were mainly malleolar fractures and ligamentous tears. The average ankle joint moment at time of injury was 60 Nm for the 12 cadaveric subjects used in the sled and pendulum tests. Further analysis of the test data, reported by Portier (1997) and presented in Appendix A, Table A-V, was conducted using logistic regression. Due to the small sample size, the model using the computed ankle joint moment is a significant predictor of injury only at the 90% confidence interval with p=0.093. The probability of injury as a function of ankle joint moment is presented in Figure 11 and Equation 7. An ankle joint moment of 50 Nm and 60 Nm due to dorsiflexion correspond to 25% and 50% probability of AIS 2+ ankle and malleolar injuries, respectively.

$$p(AIS\ \ 2+) = \frac{1}{1+e^{6.535-0.1085M)}} \qquad (7)$$

where M is the ankle joint moment due to dorsiflexion

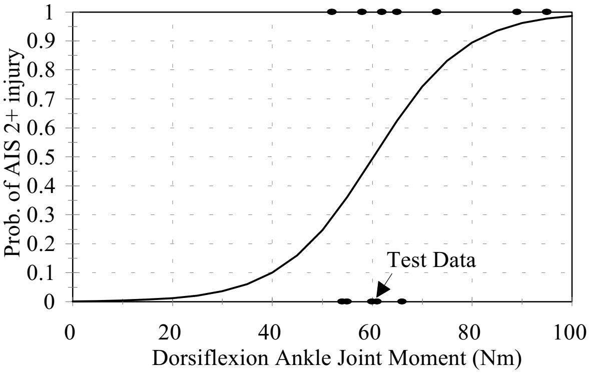

Figure 11. **Probability of AIS 2+ malleolar and ligamentous injuries as a function of ankle joint moment due to dorsiflexion.**

Quasi-static inversion/eversion tests using fresh amputated human legs were conducted by Paranteau et al. (1995) and Petit et al. (1996). Paranteau and Petit (1998) reanalyzed their test data and reported a static subtalar joint failure moment of 34.1±14.5 Nm in inversion and 48.1±12.2 Nm in eversion. The foot rotation angle at failure was 34.3±7.5 degrees in inversion and 32.4±7.3 in eversion. The injuries resulting from these tests were malleolar fractures and ligamentous rupture. Age and gender were found not to influence injury outcome in this data set. Sokol Jaffredo et al. (2000) conducted dynamic pure inversion/eversion tests on human cadaver legs using a unique test rig. The tests were conducted at subinjury level and it was noted that most of the inversion/eversion occurred at the midtarsal joint.

The results from the Paranteau and Petit (1998) reanalysis was used in developing injury limits for inversion/eversion. Since the average subtalar joint failure moment in inversion and eversion are similar and within the one standard deviation limits of each other, the average subtalar failure moment in inversion and eversion were considered to be the same and equal to 40 Nm with a standard deviation of 10 Nm. Since the moment at failure for each test Paranteau et al. (1995) was unavailable to conduct a regression analysis, a preliminary risk of injury curve in inversion/ eversion was constructed as a cumulative normal distribution with mean of 40 Nm and standard deviation of 10 Nm (Figure 12). Using this risk curve, 33 Nm and 40 Nm of inversion/ eversion moment at the subtalar joint corresponds to 25% and 50% probability of AIS 2+ malleolar and ligamentous injuries, respectively.

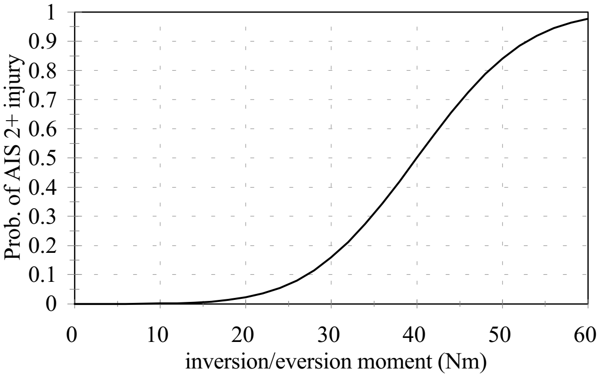

Figure 12. **Probability of AIS 2+ malleolar and ligamentous injuries as a function of subtalar joint moment due to inversion/eversion.**

SCALING OF IARV TO DIFFERENT SIZE ADULT OCCUPANTS

The injury risk curves developed for various lower extremity injuries were taken to represent that for a 50th percentile adult male. The injury measures at 25% risk of AIS 2+ injury for a 50th percentile adult male that were derived from the injury risk curves, were then scaled to represent the corresponding injury measures for the 5th percentile adult female and the 95th percentile adult male. The scaling techniques proposed by Eppinger et al. (1984) and Melvin (1995) were used for this purpose. In these scaling methods, the failure stress was assumed to be the same for different size adults. The ratio of the characteristic length of the cross-section of the femur, leg, and ankle were derived from anthropometric data published by Schneider et al. (1983) and presented in Appendix B, Table B-I. These scale factors are similar but not the same as those obtained by Mertz et al. (1989). This section presents the scaling technique used for different injury criteria. The injury measures at 25% risk of AIS 2+ injury for the 50th percentile male, the corresponding scaled injury measures for the 5th percentile female and the 95th percentile male, the associated scaling factors, and the percentage of injuries and Life-years Lost to injury addressed by each injury criteria are presented in Table 2.

Scaling of Axial Femur Failure Force

If σ_f is the failure stress in the femur then the failure force F is given by the relation $F=\sigma_f A$, where A is the cross-sectional area of the femur. If $\lambda_{x\text{-femur}}$ is the ratio of the cross-sectional characteristic length of the femur for different sizes, then the ratio of failure force λ_F is given by the relation $\lambda_F=\lambda_{\sigma f} \cdot \lambda_{x\text{-femur}}^2$. Since the failure stress for different size adults is assumed to be the same, $\lambda_{\sigma f}=1$, the ratio of failure threshold of axial femur force is $\lambda_F=\lambda_{x\text{-femur}}^2$. The values of $\lambda_{x\text{-femur}}$ for the 5th percentile female and 95th percentile male adults are 0.85 and 1.08, respectively (Appendix B). The scaling factors along with the scaled injury threshold levels for the 5th percentile adult female and the 95th percentile adult male are presented in Table 2.

Scaling of Femur-Tibia Relative Translation at Failure

The relative translation between the femur and tibia when the knee is impacted, is resisted by the cruciate ligaments. The length of the cruciate ligament (l) is primarily in the longitudinal direction oriented in its normal position. The strain (ε) is defined as the ratio of the stretch (dl) to the original length (l) of the ligament. It is assumed that the failure of the cruciate ligament occurs at the same strain level (ε_f) for different size adults. Then the failure threshold ratio of relative displacement (λ_{dl}) is given by the relation $\lambda_{dl} = \lambda_l$, where λ_l is the ratio of the average characteristic length in the longitudinal direction for the femur and tibia obtained from Schneider et al., 1983 (Appendix B). For the 5th percentile adult female, $\lambda_x=0.85$ and for the 95th percentile adult male $\lambda_x=1.09$.

Scaling of Proximal and Lower Tibia Axial Failure Forces

The failure axial force F in the tibia is given by the relation $F=\sigma_f A$, where σ_f is the failure stress of the tibia and A is its cross-sectional area. Since σ_f is assumed to be the same for all adult sizes, the ratio of axial failure force is given by the relation $\lambda_F=\lambda_{x\text{-tibia}}^2$, where $\lambda_{x\text{-tibia}}$ is the ratio of the average characteristic length of the cross-sectional area of the tibia. The values of $\lambda_{x\text{-tibia}}$ for the 5th percentile female and 95th percentile male adults were obtained from Schneider et al. (1983) and are 0.85 and 1.09, respectively.

Scaling of Tibia and Ankle Failure Moments

The failure stress in the tibia due to an applied moment is $\sigma_f = M / S$ where M is the failure moment and S is the section modulus. The ratio of section moduli for different size dummies is $\lambda_S = \lambda_{x\text{-tibia}}^3$ for tibia moments and $\lambda_S = \lambda_{x\text{-ankle}}^3$ for ankle moments. Assuming failure stress in bone is the same for different size adults, the ratio of the failure tibia moments is $\lambda_{M\_tibia} = \lambda_{x\text{-tibia}}^3$ and the failure ankle moments is $\lambda_{M\_ankle} = \lambda_{x\text{-ankle}}^3$. The value of $\lambda_{x\text{-tibia}}$ and $\lambda_{x\text{-ankle}}$ for the 5th percentile female and 95th percentile male adults were obtained from Schneider et al. (1983) and are 0.85 and 1.09, respectively.

CONCLUSIONS

The analysis of real world crash data showed that the lower extremities are the most frequent AIS 2+ injured body region for front outboard occupants in air bag equipped vehicles. The total number of AIS 2+ lower extremity injuries occurring annually in the USA to front outboard occupants in air bag equipped vehicles involved in frontal crashes is 17669. Among these lower extremity injuries, 33% are to the foot and ankle which account for 41% of the life years lost to injury. Though foot and ankle injuries are not life threatening, both the combination of the absolute number of annual injuries and their associated high level of disability, impairment, and functional loss makes injury prevention efforts in this area have the potential for high benefits.

Therefore, new injury criteria were presented to address foot and ankle injuries. Also, existing injury criteria were reexamined and altered to better represent recent biomechanical data.

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Table 2. Summary of Lower Extremity Injuries in Real World Crashes, Proposed Injury Criteria, and Injury Limits for 25% Probability of AIS 2+ Lower Extremity Injury for the 50th Percentile Adult Male, 5th Percentile Adult Female, and 95th Percentile Adult Male

Body Region	Percent AIS 2+ injury	Percent LLI	Injury Criteria	50th pcntile male 25% prob. of injury limit	5th percentile adult female		95th percentile adult male	
					scale factor	injury limit	scale factor	injury limit
Hip	12.2%	24.3%	axial femur force	9040 N	$\lambda_F=\lambda_{x\text{-femur}}^2=0.85^2$ $=0.72$	6510 N	$\lambda_F=\lambda_{x\text{-femur}}^2$ $=1.08^2$ $=1.17$	10580 N
Femur	9.4%	10.7%						
knee	33.1%	6.9%						
Knee ligament	0.5%	0.8%	Tibia/fibula relative translation	15 mm	$\lambda_l=$ $(0.85+0.85)/2$ $=0.85$	13 mm	$\lambda_l=$ $(1.08+1.09)/2$ $=1.09$	16.5 mm
Tibia Plateau	7.1%	8.2%	Proximal tibia axial force	5.6 kN	$\lambda_F=\lambda_{x\text{-tibia}}^2=0.85^2$ $=0.72$	4.0 kN	$\lambda_F=\lambda_{x\text{-tibia}}^2=1.09^2$ $=1.2$	6.7 kN
Tibia/fibula shaft	4.5%	8.1%	Revised Tibia Index $F/F_c+M/M_c<0.9$	$F_c=12$ kN $M_c=240$ Nm	$\lambda_F=\lambda_{x\text{-tibia}}^2=0.72$ $\lambda_M=\lambda_{x\text{-tibia}}^3=0.61$	$F_c=8.64$ kN $M_c=146$ Nm	$\lambda_F=\lambda_{x\text{-tibia}}^2=1.2$ $\lambda_M=\lambda_{x\text{-tibia}}^3=1.3$	$F_c=14.4$ kN $M_c=312$ Nm
ankle+calcaneus	3.3%	3.7%	Distal tibia axial force	5.2 kN	$\lambda_F=\lambda_{x\text{-tibia}}^2=0.72$	3.75 kN	$\lambda_F=\lambda_{x\text{-tibia}}^2=1.2$	6.25 kN
midfoot	10.0%	10.8%						
ankle malleolus	19.9%	26.5%	dorsiflexion moment	50 Nm	$\lambda_M=\lambda_{x\text{-ankle}}^3=0.85^3$ $=0.61$	31 Nm	$\lambda_M=\lambda_{x\text{-ankle}}^3=1.3$	65 Nm
			Xversion moment	33 Nm	$\lambda_M=\lambda_{x\text{-ankle}}^3=0.61$	20 Nm	$\lambda_M=\lambda_{x\text{-ankle}}^3=1.3$	43 Nm

The real world crash data was obtained from NASS data files for the years 1993-1999 for front seat outboard occupants in air bag equipped vehicles involved in a frontal crash. Injuries to the skin, blood vessels, and nerves were not included in the analysis. The scale factors were derived (Appendix B) from anthropomorphic data published by Schneider et al. (1983).

APPENDIX A

This appendix presents the biomechanical test data used to develop injury criteria.

Table A-I. Applied knee force (KNEEFZ) and maximum AIS level injury (MAIS) to the knee-thigh-femur complex (Morgan, et al. 1990)

KneeFz (kN)	MAIS	KneeFz (kN)	MAIS	KneeFz (kN)	MAIS	KneeFz (kN)	MAIS
7.94	0	10.08	3	11.6	3	8.6	0
8.68	0	9.27	3	11.88	3	1.26	0
5.45	0	10.09	0	0.93	0	2.97	0
4.25	0	12.25	0	2.13	0	6.09	0
10.22	0	8.21	0	2.51	0	2.41	0
10.4	0	10.33	0	2.7	0	7.15	0
12.28	0	14.02	0	3.25	0	3.3	0
11.67	0	11.26	0	2.69	0	6	0
11	0	9.33	0	3.22	0	6.91	0
10.37	0	7.02	3	2.37	0	8.09	0
9.18	0	18.66	2	7.24	0	7.28	0
8.18	0	18.13	2	4.11	0	2.28	0
7.08	0	14.06	2	8.63	0	3.16	0
6.86	0	13.29	2	2.09	0	7.45	0
8.85	0	8.55	3	6.66	0	5.68	0
7.63	0	7.73	2	4.91	0	8.12	0
6.94	0	9.4	3	4.56	0	5.39	0
9.08	0	7.91	2	6.79	0	5.5	0
8.23	0	21.06	2	4.18	0	7.8	0
9.35	0	19.68	3	6.39	0	5.42	0
9.16	0	11.39	3	2.26	0	3.64	0
6.31	0	15.13	2	12.99	3	2.49	0
9.75	0	17.18	2	21.7	3	12.53	3
10.97	0	10.89	2	18.21	3	10.6	2
10.42	0	9.34	2	21.73	3	7.73	3
5.94	0	8.99	3	20.75	3	9.1	2
10.6	0	10.01	3	18.84	3	11.26	3
7.86	0	14.19	3	6.35	0	11.56	0

Table A-II. Tibia axial force (TibFz), mass of subject, and injury outcome (0=no injury, 1=injury) to the tibiofemoral joint, Bangelmaier (1999)

TibFz (kN)	Mass (kg)	injury	TibFz (kN)	Mass (kg)	injury
3.7	59.1	0	6.4	53.2	0
6	59.1	1	7.5	53.2	1
3.8	59.1	1	7	53.2	1
5.3	81.8	0	7.5	68.2	0
6.4	81.8	1	7.9	68.2	1
5.8	81.8	0	7.9	100.9	0
6	102.7	0	11.5	100.9	1
8.1	102.7	1	6	69.5	0
4.3	102.7	0	7.6	69.5	1
4.7	65.9	0	7.8	.	0
5.8	65.9	1	8.2	.	1
3.8	65.9	0	5.6	61.4	0
9.4	90.9	0	6.8	61.4	1
10.8	90.9	1	6.4	86.4	0
6.6	90.9	0	9.7	86.4	1

Table A-III. Revised Tibia Index (F/12+M/240) at failure in the 3-point bending tests conducted by Nyquist (1985) and Schreiber (1997).

Tibia Index at failure		
Nyquist, 1985		Schreiber,1997
0.73	1.10	0.60
1.36	1.68	0.69
1.65	1.20	1.10
1.26	1.35	1.06
1.89	1.77	1.05
1.20	1.31	0.99
0.76	1.80	1.07
0.93	1.06	1.07
0.99	1.14	1.25
1.30	1.03	1.19
1.45		

Table A-IV. Combined test data of axial leg impacts Yoganandan et al. (1996). TibFz = tibia axial force in kN, injury outcome to the foot and ankle (injury=0 : no injury; injury=1: injury)

TibFz	Injury	TibFz	Injury	TibFz	Injury	TibFz	Injury
2.669	0	6.654	1	7.854	1	8.69	1
10.159	0	5.529	1	8.377	1	6.11	0
2.718	0	2.802	0	8.694	1	6.99	1
11.454	1	9.265	1	3.43	0	6.44	0
11.236	1	7.815	1	5.48	0	6.88	1
4.493	0	6.685	1	4	0	7.44	0
9.75	1	5.934	1	6.05	0	8.65	1
6.227	0	9.928	1	5.97	0	6.203	0
8.269	1	8.541	1	6.84	0	7.51	0
10.204	1	12.206	1	6.26	0	0.508	0
2.749	0	10.64	1	7.55	0	1.162	0
4.154	0	8.562	1	8.03	1	4.559	1
7.281	0	12.964	1	8.315	0	4.328	1

Table A-V: Ankle joint moment at time of injury and injury outcome in dynamic dorsiflexion tests (Portier, 1997)

ankle moment	injury
58	1
62	1
89	1
95	1
52	1
66	0
55	0
61	0
65	1
73	1
60	0
54	0

Appendix B

This appendix presents the principal measurements for estimating scale factors for the thigh, leg, and foot/ankle for the 5th percentile adult female and the 95th percentile adult male.

Table B-I. Principal measures and corresponding scale factors for the 50th percentile male, 5th percentile adult female and the 95th percentile adult male (from Schneider et al., 1983).

Measurement	50th % male	5th % female	ratio (5th/50th)	95th % male	ratio (95th/50th)
Thigh Measurements					
Upper leg Mass (kg)	9.00	5.91	0.66	11.34	1.26
Thigh Length (cm)	44.70	38.10	0.85	46.60	1.04
Mid Thigh Circumference (cm)	50.40	42.70	0.85	55.90	1.11
Mid Thigh Breadth (cm)	15.50	12.50	0.81	16.90	1.09
average ratio			0.85		1.08
Leg Measurements					
Leg Mass (kg)	3.90	2.36	0.61	5.06	1.30
Tibia Length (cm)	40.20	34.60	0.86	45.20	1.12
Calf Breadth (cm)	11.00	9.40	0.85	12.10	1.10
Calf Depth (cm)	11.80	9.60	0.81	12.80	1.08
Calf Circumference (cm)	37.30	31.50	0.84	40.60	1.09
average ratio			0.85		1.09
Foot/Ankle Measurements					
Foot Mass (kg)	1.06	0.64	0.60	1.55	1.46
Foot Length (cm)	26.40	22.10	0.84	28.20	1.07
Ankle Breadth at Condyles (cm)	7.30	6.30	0.86	7.70	1.05
Ankle Depth at Condyles (cm)	9.40	8.10	0.86	10.20	1.09
Ankle Circum. at Condyles (cm)	26.10	22.00	0.84	28.70	1.10
average ratio			0.85		1.08

According to the scaling techniques by Eppinger (1984) and Melvin (1995), the characteristic length scale factor (λ_L) can also be obtained as $\lambda_L = (\text{mass\_model} / \text{mass\_standard})^{1/3}$. Therefore, the mass ratios shown in the above Table approximately represent the cube of the length ratios ($\lambda_L)^3$.