Estimating the loads in femurs of occupants in actual motor vehicle crashes using frontal crash test data

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ABSTRACT

In a sample of direct frontal collisions which were investigated, the only major injury suffered by the occupant was a femur fracture. In order to attempt to explain these injuries, suffered by partly or completely restrained occupants at an average speed change of 25 mph (40.2 kph), the force acting on the occupant's femur was estimated and compared to predictors for femur fractures based on cadaver testing. In order to estimate the load on the occupant's femur in this type of collision, a relationship was developed between vehicle speed change, crush distance, occupant weight, and measured femur load based on the New Car Assessment Program (NCAP) frontal crash tests for the same vehicles. This estimate of femur loading considered also the type and extent of restraint system used. All the occupants (7 males, average age 26.7 years, 13 females, average age 36 years) sustained at least a transverse midshaft fracture of the femur with comminution, which is characteristic of axial compressive impact, causing bending and impaction of the femur. However, the estimated maximum average axial load was 8187N (sd = 4343N), and the average probability for fracture was only 19%. In 13 crashes the fracture probability was less than 10%. Compared to the established axial compressive threshold of 8900N, the occupants were above this load level in only 5 crashes. A missing component in the estimate of the axial load, was most likely that resulting from contraction of the strong muscles about the femur. Maximal quadriceps and hamstrings muscle contraction can generate axial compressive loads along the femur between 1800 N and 5360N, and muscle contraction would be expected in braking and bracing for an impact. Adding this internal load on the femur to the estimated external load, increased the femur loads beyond threshold, explaining the fracture in all but one of the cases. Since dummy crash tests cannot simulate muscle contraction loading, they may underestimate the total loads acting on the femur during impact and may explain why we observed these femur fractures at relatively low impact speeds.

INTRODUCTION

Fractures about the femur due to motor vehicle impacts can result in extensive medical care, and if they have an intra-articular component, may result in permanent disability (1,2). Two general approaches have been taken to studying the mechanisms of femur fractures in frontal collisions. Risk factor analyses have shown that occupant compartment intrusions act as direct mechanisms for contact injuries of the femur (3,4), that females are at higher risk (5), and that seatbelts and airbags are not particularly effective in reducing femur injury risk (5). An extensive study by Karlson, et al, (6) showed that a frontal crash direction, being female, having a head-on vehicle to vehicle as opposed to a single-vehicle to-fixed-object collision, being in a smaller sized vehicle, and not using seatbelts were risk factors for serious femur fractures. However the specific mechanisms of the injuries, including contact points of the occupant's femur were not determined in that study.

Extensive biomechanical studies of cadaveric femur fracture mechanisms and forces in frontal impacts have been performed. A summary of the findings are given in Table 1 (7-14) and shown in the Injury Risk Function Curve, Figure 1, derived from those studies, relating femur axial compressive load to the probability of fracture (15). The studies showed, from dynamic measurements, that the approximate range of axial compressive fracture load for cadaveric femurs was 7500 N- 15000 N, with an accepted threshold load of 8900N (17). The probability of fracture risk at these force levels was, from Figure 1, about 6% at 7500 N and 90% at 15,000 N.

In an ongoing study of motor vehicle crashes, part of the Crash Injury Research and Engineering Network (CIREN) sponsored by the National Highway Traffic Safety Administration (NHTSA) and General Motors, we have noticed that a significant proportion of relatively low deceleration frontal crashes resulted in isolated fracture of the occupant's femur. The mechanism in each case, based on appearance of the fracture (a transverse fracture line indicating failure by bending combined with comminution indicating compression), was axial compressive loading by impact with the dashboard. The goal of the study was to compare the best estimate of the external force acting in the femur during impact in these crashes with two published criteria defining femur fracture tolerance, since by first estimates the accelerations were low and the resulting femur loads below those which would produce this fracture. If the femur loads were below tolerances, the explanation for the fracture might lie in the additional load generated by internal muscle contractions, not normally simulated in dummy or cadaveric crash testing.

METHODS

Hypothesis

The hypothesis to be tested in this study was that for front seated, partly or totally restrained occupants in a sample of frontal crashes, who sustained an isolated femur fracture, the external force generated in the crash which acted on the occupant's femur reached at least the threshold for fracture.

General Approach

The motor vehicle crash information included in this study was collected from CIREN (Crash Injury Research and Engineering Network, National Highway Transportation Safety Administration) Centers. Crashes in the CIREN database are sampled based on the fulfillment of several criteria. Among these are that the occupant must have been restrained and that an injury of AIS 3 or greater must have occurred. Each case was reviewed by a multidisciplinary team consisting of a crash investigator, a bioengineer, a research nurse, and the treating physicians. Each center employs a crash investigator who has been certified in vehicle crash reconstruction and data collection through the training program given by the Transportation Safety Institute's National Automotive Sampling System (NASS). Each crash scene and vehicle investigation conducted by CIREN centers follow the data collection format established by NASS. Once the crash information was analyzed, and the injuries and hospital course documentation were obtained, the crash was reviewed by the multidisciplinary team to establish a probable mechanism. Of the cases reviewed, a subset of 20, involving a femur fracture as the predominant injury, were selected for this study.

Case Selection Criteria

The crashes selected all involved frontal or nearly frontal collisions (+20 deg to –10 deg). These included vehicles which were impacted by other vehicles but also included about 1/3 that impacted trees, poles, barriers, or other stationary objects. The major resulting injury was limited to an isolated femur fracture, usually involving the midshaft but in some cases, including additional injuries about the knee or hip.

Crash Investigation

Each crash site had scaled documentation of the roadway, traffic controls, road surface type, conditions, and road grade at both pre- and post- impact locations. Physical evidence such as tire skid marks were located and referenced to establish the heading angle and post impact trajectory of the colliding vehicles. A scaled drawing with impact and final rest positions was completed to assist in calculation of the speed and force at impact. Exterior inspections of the vehicle were performed, which included detailed measurements of the direct and induced damage. For this study, all crash damage involved the front of the vehicle. With a contour gauge, a damage crush profile was collected from the front bumper and a specific Classification Deformation Code (CDC), which includes the principal direction of force

(PDOF) was assigned. These measurements were entered into crash analysis software (Win SMASH, U.S. Dept of Transportation) to calculate the change in velocity (Delta V) of the vehicle during impact and the energy dissipated during the crash event.

An inspection of the interior of the vehicle from which the injured person had been removed was performed to determine points of contact and restraint system use. This inspection also included assessing the integrity of the passenger compartment, status of glazing, and intruding components. The exact locations and all evidence of contact by the occupant who had sustained the femur fracture with the interior surfaces was documented. The lower extremity contact evidence consisted of dents in the padding, fabric transfers, and minor cracking of instrument panels or knee bolsters. The dash panel was however not disassembled to identify deformation to the knee bolster. An examination of the restraint system was performed, including lap and shoulder belts and the air bag, if available, to confirm use by the injured occupant.

Estimation of femur load on impact

We used data from the New car Assessment Program (NCAP) testing in 35 mph frontal collisions with 2 front seat fully restrained instrumented anthropometric dummies. A set of data was produced for the specific vehicles of our collision sample, including change of velocity of the vehicle at impact, crush deformation of the vehicle, average deceleration during impact, and load on the femurs, lap belt, and shoulder belt, all measured parameters in these tests. The data set used is shown in Table 2. The relationships for total femur load (both femurs) as function of vehicle average deceleration is given below:

The average deceleration of the vehicle is:

$$\mathbf{a = 3.93 * \{(?V)^2 / S\}} \qquad \mathbf{(1)}$$

where,

3.93 = unit conversion factor

a = average deceleration of vehicle (g)

? V = change in velocity of the vehicle (kph)

S = average frontal crush distance (mm)

The total force acting in a single femur, from Table 1 data, for the following conditions are:

Both femur contact, lap and shoulder belt restrained occupant,

C = (Ffll + Ffrl +Fflr+Ffrr)/4 = 194 (standard deviation 30)

F = 194 * (Wo/Wd)* a **(2a)**

Single femur contact, lap and shoulder belt restrained occupant,

C = (Ffll + Ffrl +Fflr+Ffrr)/2 = 388 (st dev = 59)

F = 388 * (Wo/Wd) * a **(2b)**

Single femur contact, lap belt restrained occupant,

C = (Ffll + Ffrl +Fflr+Ffrr)/2 + (2Fcl + 2Fcr) = 661 (st dev = 129)

F = <u>661</u> * (Wo/Wd) * a **(2c)**

Single femur contact, shoulder belt restrained occupant,

C = (Ffll + Ffrl +Fflr+Ffrr)/2 + (2Fsl + 2Fsr) = 541 (st dev = 129)

F = <u>541</u> * (Wo/Wd) * a **(2d)**

Single femur contact, airbag only restrained occupant,

C = (Ffll + Ffrl +Fflr+Ffrr)/2 + (2Fsl + 2Fsr) = 541 (st dev = 81)

F = <u>541</u> * (Wo/Wd) * a **(2e)**

Single femur contact, unbelted occupant,

C = (Ffll + Ffrl +Fflr+Ffrr)/2 + (2Fsl + 2Fsr) + (2Fcl + 2Fcr) = 620 (st dev = 206)

$$F = \underline{620} * (Wo/Wd) * a \qquad (2f)$$

where,

F = axial force in femur (N)

a = average vehicle deceleration (g)

(Wo/Wd) = ratio of weight of occupant in collision/ weight of dummy in test

Numerical value = derived factor from measured deceleration and femur loads in NCAP tests, data from Table 1

Ffll, Ffrl, Fflr, Ffrr = measured femur loads, left femur, left dummy, right femur, left dummy, left femur, right dummy, right femur, right dummy

2Fcl,2Fcr = measured chest load, 2 x shoulder belt load, left dummy, right dummy

2Fsl, 2Fsr = measured chest load, 2 x shoulder belt load, left dummy, right dummy

Probability of axial loading exceeding fracture level

In order to assess the potential for axial impact forces to have reached levels consistent with femur fracture, we employed two criteria.

The probability of femur fracture, based on Figure 1, (15) is:

$$p = (-1E-10)F^3 + (5E-06)F^2 - 0.0413(F) + 98.133, \quad (r^2 = 0.9946, \text{range } p = 1\% - 95\%) \qquad (3)$$

where p = probability of fracture

Based on the criteria given in the literature, for impact durations greater than 20 msec, the threshold force for fracture is (17):

$$F > 8900 \text{ N} \qquad (4)$$

RESULTS

A total of 20 crashes were studied, shown in Table 3. In the sample of occupants who sustained an isolated femur fracture, there were 13 females with an average age of 36 years, weight of 177 lbs (80.5 kg), and height of 64.8 in (1.65 m). There were 7 males, with an average age of 26.7 years, weight of 179 lbs (81.5 kg), and height of 69.5 in (1.77 m). In the sample, Table 4, the occupants used the following restraint types; 6 were restrained with shoulder and lap belts and an air bag, 2 used shoulder and lap belts, 2 used shoulder belts and an airbag, 5 used a shoulder belt only, 1 used a lap belt only, and 3 used an airbag only. None was completely unrestrained. Those using a shoulder belt with an airbag or a shoulder belt only were in vehicles with automatic shoulder belt devices, in which the lap belt had to be attached manually. All sustained at least a midshaft femur fracture, with 5 having additional supracondylar or femoral neck involvement. Contact points of the injured femur of the occupant with some part of the instrument panel, as shown in Table 5.

The principal direction of force ranged from +20 deg to -10 deg, with 11 crashes having an estimated direction of 0 deg (directly frontal). The average delta V of the collisions was 25.3 mph (40.7 kph), (sd = 8.5 mph (13.7 kph)), with an average deceleration of 13.7g (sd = 6.4 g), Table 3. The average vehicle curb weight of the cars involved was 2648 lbs (1203 kg) (sd = 419 lbs (190 kg)), Table 4. The estimated load on the occupant's femur during the impact, based on equations (1) and (2) are given in Table 5, along with the calculated probability of fracture from equation (3). The observed points of contact of the occupant's lower limb and the resulting fracture type are also given in Table 5. The mean best estimate of the femur load was 8187 N (sd = 4343 N) for the 19 cases for which complete data were available, with a mean probability of 19% that the femur load was in the range for fracture, based on equation 3 and Figure 1. Of the sample, 13 had a probability of fracture less than 10%. Based on the criteria that an axial compressive force greater than 8900N is required for fracture, only 5 met this criterion.

Eighteen of the 20 occupants were drivers and of these, 13 fractured their right femur, Table 5. The remaining two occupants were seated in the right front passenger's seat and both fractured their left femurs. The specific contact component only intruded in 5 of the cases and in 2 , the intrusion was minimal. In 3 cases the toe pan intruded, acting on the lower leg, but for the majority, the intrusion did not appear to play a role in the axial loading on the femur. The contacts to the knee bolster systems and the lower instrument panels consisted of only scuffs, small cracks or dents, with minimal observable deformation, although elastic rebound of the padding could have occurred. The narrow area of contact for the driver's right knee, between the steering column and the center of the dashboard, was the location of contact for 8 drivers who fractured their right femurs. Some drivers' right knees contacted at or near the steering column and others became cornered into the vertical center part of the dashboard. Some knee contacts were with other rigid components such as the ignition cylinder and the lock/latch of the glove box. Overall, for half of the femurs injured, the knees appeared to strike the stiffer areas or became cornered within the center of the dashboard, with the area of contact not appearing to yield to the force of impact.

DISCUSSION

In this study, femur, lap belt, and shoulder belt forces measured during standardized frontal collisions performed as part of the New Car Assessment Program were used to develop relationships between vehicle closing velocity, crush distance, and the probable axial compressive load from direct femur contact with the dashboard, for different conditions of occupant restraint. These relationships were used in assessing the estimated probability of femur fracture by axial compressive loading in a series of frontal crashes in which the major injury to the occupant was an isolated femur fracture. We found the mean probability for femur fracture by axial loading in these crashes to be 19%. Thirteen of 19 the group had a probability under 10%, based on the femur load-fracture risk curve published by NHTSA, and 14 of 19 were below the 8900N threshold. Although the estimated probability was low, all fractures appeared to be transverse with comminution, which would be expected to result from axial impact. Therefore, despite the low external forces, direct axial contact was the probable mechanism for these injuries.

Since the great majority did not meet the criterion for sufficient external axial load magnitude, and yet the femur fractures were characteristic of those due to axial compressive impact, other axial forces must have been present. Muscle loading, which must occur in living humans, was not accounted for in estimating the compressive loads acting on the occupants' femurs in this study. In a frontal crash when the driver forcefully presses on the brake and braces for the impact, the leg muscles (quadriceps and hamstrings) are tensed. Estimates based on muscle crossectional area and muscle power demonstrate that these muscles can generate significant compressive loads. Quasistatic measurements of maximum voluntary flexor and extensor muscle torques (20-22), show that a mean extensor muscle torque around the knee for 26 year old males (the average age of the male subjects in our study) is 273 Nm. With an approximate moment arm of 5 cm, this results in a compressive force of 5383N acting along the axis of the femur. For 36 year old females (the average age in our study for the female subjects), the extensor force is about 3356N. The knee flexors produce about 3002N for males and 1801N for females. It is impossible to determine specifically the extent of muscle contraction that the occupants of the vehicles in the crashes that we studied actually exerted, but it is entirely reasonable to assume that forceful braking and anticipatory bracing for the impact will produce considerable contraction of the knee flexor and extensor muscles. This appears to be the most reasonable explanation for the discrepancy between the mechanism of the femur fracture, axial loading, and the relatively low loads predicted. Review of the papers describing femur ultimate loads (7-11) do not appear to have considered dynamic muscle loading as a potential contributor to the overall load that the femur could be subjected to in a crash. For comparison, the predicted loads, without and with the contributions of muscles (taken as the force generated by the knee flexors and an equal load from the extensors at maximum contraction), are shown in Figure 2.

This observation, if correct, has significant implications for the design of dashboards and knee bolsters. If internal muscle loads add considerably to the external loads experienced by the occupant's femur in the crash, then

the dashboard or knee bolster, if designed for an external load criterion of 8900N, and tested using dummy femurs, may be to stiff to prevent femur injury in crashes involving human occupants.

The assumptions upon which this study is based require discussion. The values provided for the femur forces experienced by occupants in the collisions we studied represent our best estimates, working from the quantitative data of the NCAP test results and considering the weight of the occupant, average deceleration in the frontal collisions, the contact points of the occupant with the interior of the vehicle, and the variable use of occupant restraints. The crash is a dynamic event with loads in the shoulder and lap belts and femur contact loads reaching peak values at slightly different times during the crash. In this case, we made the simplifying assumption that all restraint and femur loads reached their peak values together and that the forces acting on the occupant were all essentially horizontal, preventing forward movement, and therefore acting in the same direction. Inspection of individual time histories from NCAP tests showed that peak loads occurred close together in time, so this assumption is probably reasonable. A second assumption concerns the femur fracture probability curve of Figure 1. The femur fractures in bending, which occurs because the load acting at the knee and the reaction, at the hip, are offset from each other. Therefore the neck length of an individual's femur is likely to be important in determining the actual bending moment applied during contact of the knee against the dashboard. Also, the midshaft diameter and moment of inertia require consideration in determining the actual failure stresses of an individual femur .

A very important question relates to how well the hybrid III dummy represents the human femur in terms of its ability to predict femur loading during impact. The Hybrid III dummy femur load measurement is used as a criterion for determining the potential for femur fracture during NCAP 35 mph frontal collisions. Donnelly and Davis (19) used load cells implanted into cadaveric femora and compared both maximumforce and force impulse. They found that the hybrid III dummy measured force was much higher at the same impact velocity, than that measured in the cadaver femur. For example, at a typical impact velocity of 30 ft/sec), the hybrid III dummy femur measured a force of 12115 lbs compared with 4213 lbs for the femur, or a difference of 288%. However, Morgan, et al (14) stated that the hybrid III response was close to that of the cadaver femora and that it correctly predicted injury and no injury conditions.

A number of studies, including those referred to in Table 1, have been used to develop failure criteria for the human femur to impact loading. Viano (17) proposed an allowable force of F = 23.14 – 0.71T (where F = peak impact force in Newtons, and T = time duration of impact load (msec), T < 20 msec) and F = 8900 N for T > 20 msec, which is the case for impacts into padded dashboards. Leung, et al (18) showed that ultimate load on the femur during impact is directly related to compact bone crossectional area and midsection, with bone area related directly to the weight of the subject, and to density. Based on their tests they proposed the same criterion as Viano (17)for impact durations greater than 20 msec, F = 8900N. They also showed that femur midshaft crossectional area varied by a factor of 2 in their sample as did femur failure load.

It appears that three factors led to axial impact fractures of the victims femora in the cases studied. First was single knee contact, second at least in most of the group, lack of complete restraint use, and third the stiffness of the area of contact around the knee bolster. The knee bolster is a device which is considered part of the passive restraint system in frontal loading since it distributes some of the overall impact load away from the torso and to the femora. It is sloped back and downward to avoid loading the tibia to prevent loading across the knee joint.

The reason that the occupants in our study group contacted only a single femur in not clear, although some important factors might have played a role. One possible factor might have been that the driver in an actual crash may have one foot braced against the brake pedal. This along with a slight off-center contact load may result in significantly more contact of one femur with the dashboard. While we did not disassemble the dashboard/knee bolster to look for hidden damage and signs of contact, there were signs of contact on the surfaces of the dashboards themselves as well as medical evidence of the location of contact.

In conclusion, if the estimates of the external force acting on the femur during the crash that we studied are representative, then femur fracture by axial compression should not have occurred during most of these crashes. That all the occupants sustained femur fractures by axial compression/bending indicates that some load component in the estimate was missing. This missing component is most likely that produced by the large muscles around the leg, which under maximum contraction can contribute a significant axial compressive load. If knee bolsters and dashboards are designed based on tests purely from dummy knee and femur force measurements, this significant muscle loading will be overlooked and the resulting components may be too stiff to prevent femur fractures in some crashes.

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SAE **Paper**	Author	specimen type (age range)	no tested (m/f)	direction	velocity (ft/sec)	peak force mean (sd) (N)	type of fx produced/ comments
751159	Melvin JW	unembalmed (45-90)	22(16/6)	axial	21-43	15045 (18343)	none, distal 1/3, supracondylar
876042	Roberts DP	unembalmed (55-71)	18(18/0)	axial	13.2-39.3	15588 (5927)	knee or supra condylar
841661	Cheng R	unembalmed (21-63)	11(9/2)	axial		7925 (1482)	had femur load cell
831629	Leung YC	unembalmed (34-73	11(10/1)	axial	2.8-10.5 m/s	7552 (2537)	knee or supra condylar
770925	Viano DC	unembalmed				7565	FMVSS 208
751160	Powell WR	embalmed	15 (10/5)	axial/obl	6.7-9.2 m/sec		patella, supracondylar femoral shaft fx
730984	King JJ					10013-7565	higher at 1-2 msec pulse
1990 IRCOBI	Morgan RM					4997-15998	Represents 5% to 95% probability

TABLE 1 Summary of data available in the literature related to axial compressive fracture loads of human cadaveric femora (N = Newtons)

Vehicle type	Year of vehicle in study	Year of vehicle in crash test	Closing speed (kph)	Damage To front of vehicle (mm)	Avg acc'n (X) (g)	LAP AND SHOULDER BELTED OCCUPANT **DOUBLE** FEMUR CONTACT LOAD (N)	LAP AND SHOULDER BELTED OCCUPANT **SINGLE** FEMUR CONTACT LOAD (N)	**LAP** BELTED OCCUPANT **SINGLE** FEMUR CONTACT LOAD (N)	**SH'LDER** BELTED OCCUPANT **SINGLE** FEMUR CONTACT LOAD (N)	**AIRBAG ONLY** OCCUPANT **SINGLE** FEMUR CONTACT LOAD (N)	**UNBELT** OCCUPANT **SINGLE** FEMUR CONTACT LOAD (N)
HYUNDAI ACCENT	1995	1995	56	433	28.5	4278	8557	14549	14023	14023	15737
HONDA CIVIC	1994	1994	56.5	577	21.7	3179	6359	15981	15060	15060	21503
TOYOTA CELICA	1990	1990	55.8	502	24.4	4199	8398	16056	12851	12851	16310
TOYOTA COROLLA	1992	1993	56.3	489	25.5	4682	9364	16444	12043	12043	14442
TOYOTA COROLLA	1992	1993	56.3	489	25.5	4682	9364	16444	12043	12043	14442
GEO PRIZM	1991	1990	56.5	502.9	24.9	4218	8436	16961	12467	12467	16774
MERCURY SABLE	1991	1988	56.5	474	26.5	5597	11194	17684	15818	15818	16711
FORD ESCORT	1995	1995	56.4	502.7	24.9	5270	10541	19512	15497	15497	19198
CHEVY BLAZER	1996	1997	56.3	556	22.4	3658	7315	15416	13165	13165	17609
TOYOTA COROLLA	1990	1991	56.3	491.1	25.4	5675	11350	23137	13580	13580	19693
VW JETTA	1996	1994	56.2	536	23.2	5734	11469	18786	14629	14629	16212
FORD TAURUS	1991	1991	56.3	502.9	24.8	5039	10077	16827	14032	14032	15743
ACURA INTEGRA	1996	1995	56.3	455.2	27.4	5214	10428	18317	14993	14993	17669
MERCURY TRACER	1994	1989	56.5	493.6	25.4	4498	8997	18213	13125	13125	17843
FORD ESCORT	1993	1994	56.3	412.5	30.2	5235	10470	16707	13058	13058	14059
VW JETTA	1991	1988	46.8	391.2	22.0	5037	10075	10075	10075	10075	5037
NISSAN MAXIMA	1995	1995	46.5	292.7	29.0	5729	11458	11458	11458	11458	5729
TOYOTA CAMRY	1990	1992	47.6	550.3	16.2	3959	7918	7918	7918	7918	3959
FORD	1988	1987	56.7	590.6	21.4	3759	7518	14535	12524	12524	15782

MUSTANG											
VOLVO	1990	1988	56	574.9	21.4	4774	9548	17813	14728	14728	18219
740 GLE											

Table 2 Data from New Car Assessment Program (NCAP) tests used to develop relationship between vehicle change in velocity, crush distance, and total load on both femurs of occupant in frontal collision.

Case no	M/F	Age	Weight (lbs)	Height (in)	Vehicle Class	Vehicle Weight (lbs)	Vehicle type
1	F	21	155	66	01	2101	95 Hyundai Accent
2	F	21	128	69	02	2313	94 Honda Civic
3	M	26	160	68	01	2696	90 Toyota Celica
4	F	58	155	64	01	2253	92 Toyota Corolla
5	F	24	125	66	01	2253	92 Toyota Corolla
6	F	33	260	66	01	2435	91 Geo Prism
7	F	80	150	64	03	3131	91 Mercury Sable
8	M	38	262	70	01	2404	95 Ford Escort
9	M	26	165	?	14	3993	96 Chevy Blazer
10	F	15	90	56	01	2330	90 Toyota Corolla
11	M	26	180	67	01	2647	96 VW Jetta
12	M	30	200	73	03	3276	91 Ford Taurus
13	F	39	179	70	02	2628	96 Acura Integra
14	F	22	200	63	01	2393	94 Mercury Tracer
15	M	20	150	70	01	2371	93 Ford Escort
16	F	27	264	66	01	2275	91 VW Jetta
17	F	48	178	61	03	3001	95 Nissan Maxima
18	F	25	146	65.5	02	2690	90 Toyota Camry
19	M	21	138	69	02	2818	88 Ford Mustang
20	F	55	245	66	03	2854	90 Volvo 740

TABLE 3 Demographics of the occupants involved in the crashes studied in which the occupant sustained an isolated fracture of the femur. (Class, 01 = subcompact, 02 = compact, 03 = intermediate, 14 = compact utility)

Case No	Restraint Use	Delta V (mph)	PDOF (deg)	Max crush (in)	Average decel (g)
1	shoulder, lap belt, airbag	34	0	24.4	19.0
2	airbag	37	5	22.4	24.4
3	shoulder, lap belt, airbag	24	0	17.7	13.0
4	shoulder belt only	22	0	19.3	10.0
5	lab belt only	22	0	19.3	10.0
6	shoulder, lap belts	43	0	43.7	16.9
7	shoulder, lap belts,airbag	12	0	8.7	6.6
8	shoulder belt, air bag	27.8	0	38.8	8.0
9	shoulder, lap belts,airbag	10	-10	n/a	n/a
10	shoulder belt only	20	-10	10	16.0
11	airbag only	21.1	0	16.1	11.1
12	shoulder, lap belts,airbag	32	0	30.7	13.3
13	airbag	36	10	17.7	29.3
14	shoulder belt, air bag	24	20	24.4	9.4
15	shoulder belt only	29	-10	28.3	11.9
16	shoulder belt only	12	-10	11.75	4.9
17	airbag	22	0	13	14.9
18	shoulder belt only	19.4	10	16.5	9.1
19	lap and shoulder belt	30	0	15	24
20	lap, shoulder belts, airbag	28.9	-10	37.75	8.8

TABLE 4 Vehicle crash data from the 20 crashes studied in which the occupant sustained a femur fracture (PDOF = principal direction of force, (0 deg = 12 o'clock, direct frontal, -10 deg = 11 o'clock from left, 10 deg = 1 o'clock, from right).

Femur Force factor	Avg Acc'n (g)	Weight (lbs)	estimate dfemur load (N)	Prob (%)	>8900 N Yes/no	Lower leg Contact points	Intrus	Contact Evidence	Femur fracture type
388	19	155	6722	8	n	Knee bolster /steer col	None	Scuffed	trans, midshaft
737	24.4	128	13540	80	y	Knee bolster /steer col	2"	Cracked,scuffd	trans, midshaft
388	13	160	4747	3	n	Knee bolster /ign cyl	None	Deformed	trans, midshaft
737	10	155	6720	8	n	Inst panel /center dash	None	Scuffed	trans, midshaft
1019	10	125	7493	9	n	Glove box at latch	None	Cracked	trans, midshaft
388	16.9	260	10029	27	y	Inst panel/center dash	None	Scuffed	midshaft, troch
388	6.6	150	2260	0	n	Knee bolster /steer col	None	Small dent	medial cond
737	8	262	9087	17	y	Knee bolster	4"	Scuffed	supracond dist
388	n/a	165				Knee bolster	6"	Scuffed,deform	trans, midshaft
737	16	90	6243	3	n	Inst panel/center dash	None	Scuffed	trans, midshaft
737	11.1	180	8662	14	n	Knee bolster	None	Deformed	trans, midshaft
388	13.3	200	6071	3	n	Knee bolster/steer col	2"	Scuffed	midshaft, neck
737	29.3	179	22737	100	y	Knee bolster	None	Scuffed	trans, midshaft
737	9.4	200	8150	9	n	Knee bolster/center dash	None	None	comminuted mid
737	11.9	150	7739	8	n	Inst panel/steer col	5.5"	Deformed	comminuted mid
737	4.9	264	5608	1	n	Inst panel	None	Small dent	comminuted
737	14.9	178	11498	50	y	Knee bolster/steer col	None	Scuffed	femoral neck
737	9.1	146	5760	2	n	Inst panel	None	Dent	trans, midshaft
388	24	138	7559	7	n	Inst panel	None	Small dent	comm shaft
388	8.8	245	4921	1	n	Knee bolster	None	Scuffed, dent	comminuted

TABLE 5 Estimated load at fracture, contact points and injury sustained (Restraints, S = shoulder belt, L = lap belt, A = airbag, Seats, D = drivers, RF = front passenger's)

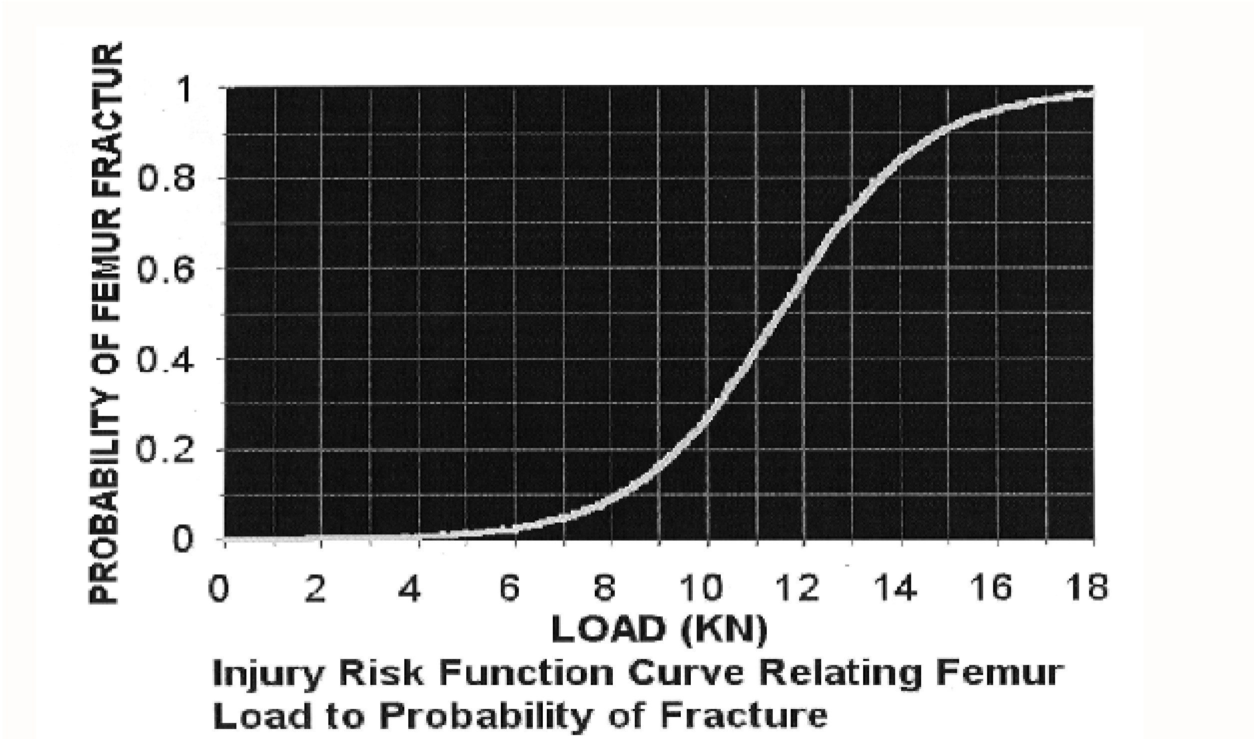

Figure 1 Reproduction of the femur fracture injury risk curve published by the National Highway Traffic Safety Administration

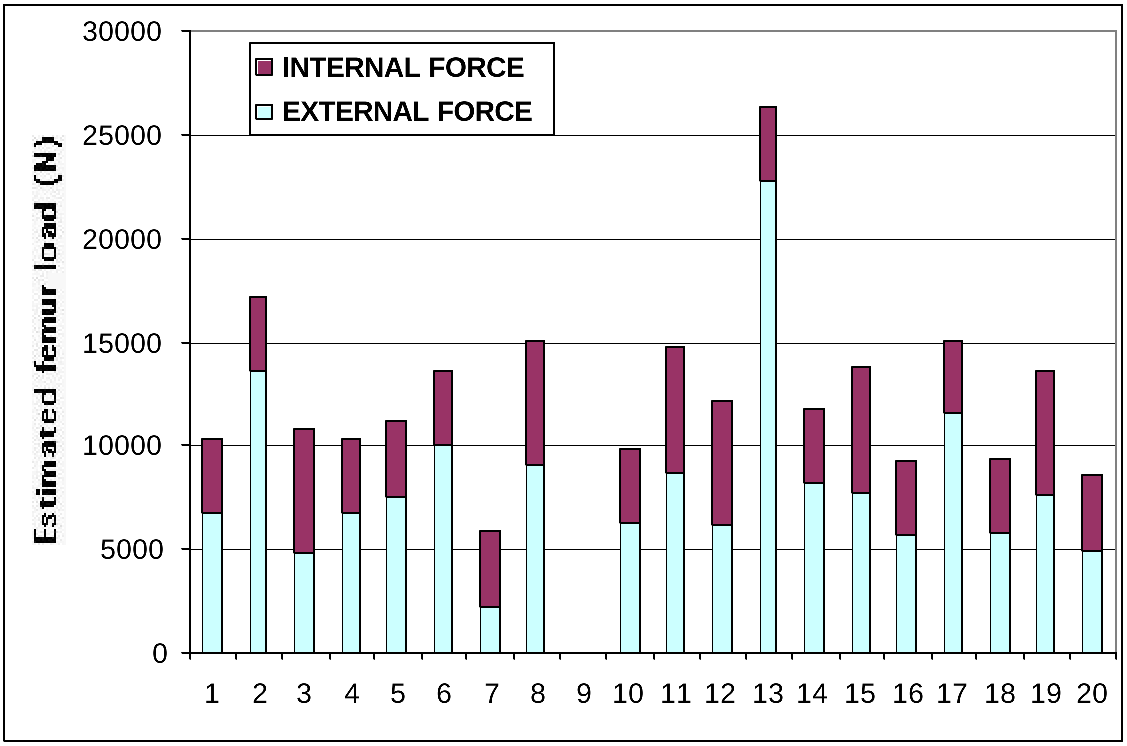

Figure 2 Comparison of the estimated loads acting on the femur due to external forces of contact with the dashboard during the crash, and combined with possible maximum contraction forces (considering males and females) due to muscle tensing around the knee resulting from braking and /or bracing for the impact (femur fracture threshold, 8900N, indicated by dashed line)