PHYSICAL SIMULATION OF HUMAN LEG-BUMPER IMPACTS

by

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Abstract.

A method was developed for experimental studies of leg injuries in simulated car-pedestrian collisions. Human legs, amputated at the femur, were used. The legs were loaded with a mass corresponding to the actual body weight and were hit at either of two different speeds, 17 or 24 km/h by a bumper fitted to a test cart. A narrow rigid and a wider semi-rigid standard bumper were used together with a simulated bonnet. The bumpers were mounted at 25 cm or 45 cm above ground level. A smooth and compliant impact surface was also tested to investigate its injury reducing potential. Skeletal and soft tissue injuries produced by this technique are described and the significance of impact speed, bumper hight and the mechanical properties of the frontal car structures are discussed.

Scope.

A prospective investigation of real car-pedestrian accidents in the Gothenburg area is combined with an experimental biomechanical study in an attempt to correlate the type and severity of leg injuries to the shape and mechanical properties of the vehicle front structures and to different impact speeds.

Background.

The aggressiveness of the vehicle front design is a documented safety problem to pedestrians hit by motor cars. Fisher and Hall (1972) and McLean (1972) were among the first to discuss car front shape and pedestrian injury. Kramer et al. (1973) investigated fracture mechanism of lower legs under impact load, Schneider and Beier (1974) compared dummy experiments and accidents. Appel et al. (1975) discussed the influence of speed and vehicle parameters in accidents. Ashton et al.(1976) made a comprehensive review of the knowledge, Bacon and Wilson (1976) discussed bumper characteristics and Krieger et al. (1976) reported full scale experiments. Kramer (1977) discussed equivalent injury severity in experimental research, Weiss et al. (1977) reported experimental automobile-pedestrian injury, Padgaonkar et al. (1977) presented a mathematical model and Twigg et al. (1977) and Ashton et al. (1977) discussed car design for pedestrian protection. Kuhnel and Rau (1978) discussed dummy fidelity and Lucchini and Weissner (1978) the influence of bumper adjustment on the kinematics of an impacted pedestrian. Data from real accidents as well as from experimental testing using mechanical or mathematical simulations of the car and the human body have thus been used to evaluate an optimal car exterior. The bumper and bonnet edge have been shown to be important injury producing structures.

A low mounting of the bumper and a short bumper lead distance have been recommended to minimize the injuries to the lower leg and knee. On the other hand a low leading edge of the car front seems to result in a higher impact velocity of the head against the bonnet. A smooth and compliant front profile may reduce the injuries on the lower body segments and also the overall injury severity (Ashton and Mackay 1979). Tests have been made on production vehicles to show the benefit of increased impact surface compliance on the human injuries in car-pedestrian collisions (Pritz 1979). Related to earlier tests on human specimens, a standard test procedure has been proposed for leg injury evaluation. An impactor system and a simulated leg have been suggested for this (Eppinger and Pritz 1979). There is, however, no well defined method available to correlate the results from current experiments to real accident data.

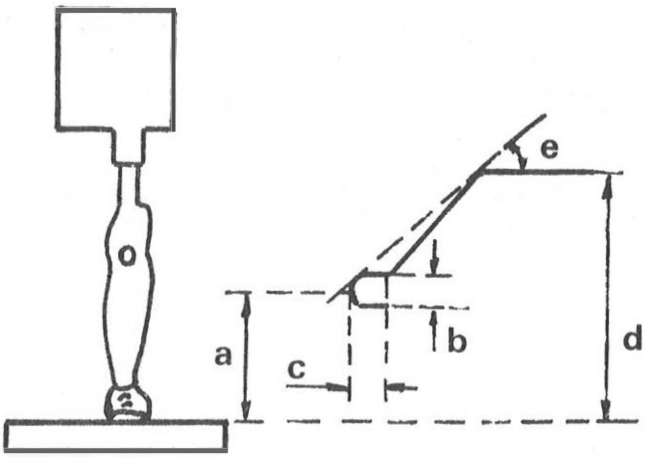
Material and methods.

Thirtysix human leg specimens amputated at mid-femur were used. They originated from individuals 15-92 years of age and were not affected by skeletal abnormalities (table I). The specimens were unembalmed but were stored in a freezer and thawed before the test.

Table I. Age and sex distribution in the material.

Age (years)	Male	Female
11-20	2	1
21-50	4	3
51-70	8	3
71-100	7	8
Σ	21	15

The test equipment developed used a simulated car front to impact the specimens. The leg was loaded at impact by a concentrated mass approximately corresponding to the actual body weight and with its center of gravity as close as possible to that of the entire body. The specimen was balanced, with the knee extended. It was standing in a shoe on a high friction support platform. The test cart was carrying a simulated bonnet structure and a production car bumper. It was possible to change the impact velocity, the bumper level above the support platform, the bumper lead distance, the bumper lead angle and the bonnet height, figure 1.



a = bumper level
b = bumper width
c = bumper lead distance
d = bonnet edge height
e = bumper lead angle

Figure 1. The experimental set up.

The equipment was instrumented with horizontal and vertical force transducers in the bumper mounting brackets, the bonnet support and the frame of the support platform. Accelerometers were strapped to the specimens at the ankle and at the impact level on the side opposite to that impacted by the bumper. One accelerometer was also strapped to the concentrated body mass at the approximate level of its center of gravity. During impact signals from these transducers were recorded and stored on magnetic tape. The impact sequence was also covered by high-speed cinematography. After each test the leg was radiographed and dissected by the ortopedic surgeon, who is also the principal investigator of the real car-pedestrian accidents. Some pieces of bone were then taken from the leg for subsequent determination of the bone mineral content and the physical properties of the bone.

The leg was hit from the anteromedial (-) or the anterolateral (+) side. The impact angle is defined in figure 2.

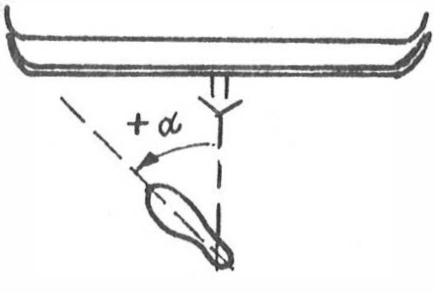


Figure 2. The impact angle (right leg).

In some experiments (nos. 17,23 and 35) an exaggarated knee hyperextension was prevented by using a thin wooden stick attached to the specimen. In three tests (nos. 2,21 and 39) a reduced body mass was used and in one case (no. 18) the leg was tilted about 5^0 from its equilibrium position in the impact direction. During the test series the connexion of the body mass to the femur was altered. In some experiments (nos. 5,12,13,21) the originally used rigid junction caused femoral fractures probably due to stress concentration at the attachment point. A rearrangement was made by the introduction of a universal joint, simulating the hip, which permitted a controlled angulation of the leg relative to the body mass during the impact (experiments nos. 15-20; 22-36).

A 10 cm wide semi-rigid standard bumper (SAAB99) was used in experiments nos. 1-16 and a 3 cm wide rigid standard bumper (SAAB 96) was used in experiments nos. 17-31 and 34,35. The bumper lead distance was 15 cm. The bumper lead angle was 60 degrees. The bonnet height was 50 cm above the bumper level. A 5 cm layer of plastic foam covered the front shield. In three experiments one similar layer also covered the rigid bumper and two such layers on the front shield reduced the bumper lead to zero in experiments (nos. 32,33 and 36). The static deformation characteristics of these front structures were tested with a 60 mm diameter iron tube which was held vertically and pressed against the impact area, table II.

Table II. Bumper deformation values.

Bumper No	Type	Impact width cm	Deformation mm	Force kN
I	Semi-rigid SAAB 99	10	25	1.0
II	Rigid SAAB 96	3	0	> 1.0
III	Rigid SAAB 96 + 5 cm plastic foam layer	25	45	.25

The test cart was accelerated to a constant speed before the collision. Its mass was approximately 300 kg. A low (16-17 km/h) or a moderate (23-24 km/h) impact velocity and a low (25 cm) or a high (45 cm) bumper level above the ground were chosen. The heel of the shoe used on the foot was 3.5 cm high. The friction coefficient of the support platform was approximately 1.

Results.

Injuries occurred in 31 experiments, see table III. In two experiments with legs from people,15 and 16 years of age (nos. 2 and 18),epiphyseal fractures of the knee were obtained. Some other typical injuries were seen for example: undisplaced malleolar fracture or ankle ligament rupture produced by a violent tilting of the ankle joint when the leg was hit by the bumper at the lower level and at the lower velocity, comminuted tibia and/or fibula fracture at impact level when the leg was hit at the lower level and at the higher velocity ligament rupture of the knee joint opposite the impact side when the leg

Table III. Experimental test data.

Exp. No.	Age and sex	Body weight (kg)	Bumper type and level (cm)	Impact angle α (o)	Velocity (km/h)	Acceleration		Bumper force (kN)	Ground friction force (kN)	Injury	AIS
						impact level (g)	ankle level (g)				
1	62 m	70	I 25	+ 80	16	115	75	1.9	.4	Undisplaced bimalleolar fracture	2
2	15 m	(80) 4/	I 45	+ 25	16	75	60	3.3	.8	Femoral epiphyseal fracture	3
3	56 m	75	I 45	+ 85	17	160	40	2.5	.4	Rupture of the medial ligament of the knee	3
4	60 m	60	I 45	+ 85	17	160	15	3.1	.6	Partial rupture of the medial ligament of the knee	2
5	40 m	80	I 45	+ 85	17	190	30	3.7	.8	Femoral fr.at the mass connexion	-
6	57 m	70	I 45	+ 30	17	200	60	2.7	< .1	Knee ligament sprain	2
7	15 f	50	I 25	+ 85	16	120	80	.9	.3	Rupt.of the anterior part of the deltoid ligament	2
8	50 m	80	I 25	+ 80	17	70	90	1.1	.5	Rupt.of the anterior part of the deltoid ligament	2
9	72 f	50	I 25	+ 85	24	190	110	.9	.2	Fr.of tibia and fibula at impact lev.	3
10	78 m	50	I 25	+ 85	23	160	160	1.4	.5	Undisplaced bimalleolar fract.	2
11	81 f	45	I 25	+ 80	17	90	110	.6	.2	Fr.of the medial malleolus + fr. of fibula at impact level	2
12	58 m	75	I 45	+ 85	23	170	40	3.6	.3	Femoral fr.at the mass connexion	-
13	79 m	75	I 45	+ 80	24	160	50	3.3	< .1	Femoral fr.at the mass connexion + rupt.of the medial ligament of the knee	(2)
14	61 m	75	I 25	- 75	24	170	140	1.7	.7	Rupt.of the anterior talofibul.ligam.	3
15	42 m	80	I 45	- 75	24	110	110	1.7	< .1	Rupt.of the lateral ligament of the knee	3
16	75 m	55	I 45	- 80	23	160	95	1.3	< .1	Undisplaced patellar fr. + rupt.of the posterior cruciate ligament	3
17	- f	(55) 4/	II 45	- 80	23	> 80	60	1.3	.2	Compression fr.of the medial tibial condyle	3
18	16 m	(65) 4/	II 45	+ 75	23	120	130	1.5	< .1	Undisplaced tibial epiphyseal fracture 1/	2
19	- m	(75) 4/	II 25	+ 80	23	190	160	1.1	< .1	No injury	0
20	- f	(55) 4/	II 25	+ 80	24	150	180	1.0	.2	Fr.of the medial malleolus + fr.of fibula at impact level	2
21	78 f	(12) 4/	II 45	+ 75	24	145	30	.8	< .1	Fr.of femur at the mass connexion + small fr.of the lateral tibial plateau 2/	(2)
22	56 m	70	II 45	- 80	24	175	150	1.8	.2	Knee ligament sprain	2
23	72 f	55	II 45	+ 75	23	175	55	.8	.1	Comminuted fr.of the femoral condyle	3
24	53 f	(60) 4/	II 45	+ 75	23	175	105	.8	< .1	Avulsion fr.of the medial ligament of the knee 3/	3
25	91 f	60	II 45	- 75	23	210	90	1.9	.2	Fr.of the tibial plateau + fr. of the fibular head	3
26	72 f	60	II 45	- 75	24	> 110	55	1.1	.4	Rupture of the lateral ligament of the knee 3/	3
27	65 f	(60) 4/	II 45	- 75	23	> 155	75	1.7	.2	Rupture of the lateral ligament of the knee 3/	3
28	69 f	45	II 45	+ 80	17	155	75	.7	< .1	Part.rupt.of the medial ligam.of the knee + rupt.of the talofibular ligament 3/	3
29	33 f	55	II 25	- 75	23	175	> 150	1.0	.3	Fr.of tibia at impact level + fr. of fibula at the ankle	3
30	76 m	55	II 25	- 80	17	110	150	.8	.7	No primary injury 3/	0
31	70 m	70	II 25	+ 75	24	160	160	1.2	.3	Fr.of tibia and fibula at imp. lev. 3/	3
32	92 m	75	III 20-45	+ 75	23	70	95	.7	.4	Undisplaced fr.of the medial malleolus 3/	2
33	72 m	80	III 20-45	+ 80	23	70	140	.7	.5	Undisplaced fr.of the medial malleol.	2
34	71 m	75	II 25	+ 80	24	175	160	1.3	.3	No injury	0
35	82 f	(55) 4/	II 25	- 75	24	170	160	.9	.3	Fr.of tibia and fibula at imp. lev.	3
36	82 f	(55) 4/	III 20-45	- 75	24	90	160	.7	.2	Undisplaced bimalleolar fr. + fr.of the fibular head	2

1/ The leg was tilted 5^0 in the direction of impact.

2/ A reduced "body mass" (12 kg) was used.

3/ A "late" femoral fracture occurred at the mass connexion.

4/ The number in brackets denotes the actual load used.

was hit at the higher level and at the lower or the higher speed, fracture of the tibial or femoral condyle when the leg was hit by the bumper at the higher level and at the higher velocity. No knee injuries occurred when the leg was hit at the lower level.

In seven experiments femoral fractures were produced late in the impact sequence viz. when the body mass was hit by the bonnet edge. In six of these a primary injury had already been produced by the bumper. By the introduction of a deformable aluminium disc to control the angulation of the leg relative to the body mass it seems to be possible to sufficiently reduce the stress concentration at the femur attachment.

A hypothesis was presented stating that the use of one concentrated body mass instead of the more distributed mass of a human body would lead to a delayed translational movement of the simulated pelvic region and thus change the kinematics of the leg in relation to real accidents. In order to test this hypothesis films from cadaver tests made at Wayne State University were examined. In these it was not possible to detect any translation of the pelvic region before it was hit by the bonnet edge of the car. In test number 21 and in one additional test (no. 39, which is not included in table III) an attempt was made to test the hypothesis experimentally. The body mass was therefore reduced to 12 kg in these experiments and the time after impact when this reduced mass begun its translational movement was compared with that of the original mass in tests at equal impact speed. For both the original and the reduced mass the translational movement begun within a 5 ms time interval 30 ms after the first contact between the bumper and the lower leg. No significant difference could be noted between the two different masses used.

The type of injury was not clearly related to age or sex. The bone strength and mineral content have not yet been determined. In tests nos. 32,33 and 36 a smooth, compliant front modification was used. In these experiments lower bumper forces were recorded, .7 kN in all three tests as compared to a mean value of 1.2 kN (.9-1.7 kN) in the corresponding nine experiments (nos. 9,10,14,19,20,29,31,34 and 35) with the two production bumpers. Even when the body weights are taken into account this difference remains. No obvious correlations were noted between the bumper forces, ground friction forces, the accelerations of the foot and leg recorded and the injury ratings in the other experiments, nor did the impact angle seem to matter.

The injury ratings at the two velocities used and at the two bumper mounting levels differed significantly in a χ^2-test on the 95% level (tables IV and V).

Table IV. AIS vs. velocity

AIS	Velocity (km/h) 17	24	Total
≤ 2	7	6	13
= 3	3	13	16
Σ	10	19	29

$\chi^2 = 3.91$

Table V. AIS vs. bumper level.

AIS	Bumper level (cm) 25	45	Total
≤ 2	9	4	13
= 3	5	11	16
Σ	14	15	29

$\chi^2 = 4.14$

Table VI indicates the AIS ratings for the different velocities, bumper levels and bumper types. Tests nos. 5,12,13 and 21 were excluded in thesecalculations because of the fractures which occurred at the body mass connexion.

Table VI. Mean AIS related to velocity, bumper type, bumper level and number of tests.

Velocity	Bumper type	Mean AIS (number of tests)		Mean AIS	(number of tests)
		Bumper level			
km/h		25 cm	45 cm		
17	I	2.0 (4)	2.5 (4)	2.1	(10)
	II	0 (1)	3 (1)		
	I; II	1.6 (5)	2.6 (5)		
24	I	2.7 (3)	3.0 (2)	2.5	(19)
	II	1.8 (6)	2.8 (8)		
	I; II	2.1 (9)	2.8 (10)		
17; 24	I; II	1.9 (14)	2.7 (15)	2.3	(29)
24	III	"Level" 20-45 cm		2.0	(3)

A velocity increment from 17 to 24 km/h raised the mean AIS level from 2.1 to 2.5. The higher bumper level caused an increase in the mean AIS from 1.9 to 2.7 mainly due to the knee injuries which occurred in every test with a high bumper mounting level. A higher AIS rate seemed to appear for bumper type I as compared to bumper type II. However, the test performances were varied and the number of tests are yet too small to justify this conclusion. Bumper type III caused similar injuries in all three tests: undisplaced malleolar fractures and in one case also a partial ligament injury of the knee. All these injuries were given the AIS rating of 2. The difference in AIS rating for bumpers of type III as compared to bumpers of types I and II are not statistically significant.

Discussion.

In this first report from a continuing test series the experimental conditions were varied to obtain different injuries. The age range was large and the loads as well as the impact angles differed. The influence of the high friction surface of the support platform is not yet clear. In most cases the friction forces recorded were low and this may be explained by the reduced normal load on the platform which occurred when the leg was forced to bend during the impact.

A high injury incidence was obtained (86%). Ligament injuries occurred in fourteen experiments, eight of which were given an AIS rating of 3. The extended knee position is probably an unfavourable one, but was used to ensure the full loading of the leg. In normal walking the knee is flexed during the major part of the walking cycle and this may to some extent influence the risk of knee injuries. The leg is also not fully loaded during a considerable part of the walking cycle and the leg may therefore be pushed away somewhat easier by a striking car. On the other hand the injuries obtained should be considered to be minimum injuries for these conditions since the leg was catched in a protective net after the collision to prevent secondary dislocations. The injuries caused by the bonnet edge were not investigated in this study. For this to be done a modified body-mass connexion is probably needed. Open fractures and serious injuries (AIS $>$ 3) were not seen. A higher velocity would probably be needed to obtain such injuries. The cutaneous injuries were all of a minor degree. The muscular and subcutaneous injuries were not examined here, although those soft tissue injuries are important in real accidents since they will probably extend the healing time of any adjacent fracture.

Compared to the earlier investigations of this type by Kramer et al. (1973), Krieger et al. (1976) and Weiss et al. (1977) the results in this study are somewhat different. Kramer et al. (1973) investigated the injuries caused by a direct blow on cadavers with no static load on the legs. The results described were only tibial fractures at the impact level. The critical speed limit for these fractures (v_{50}) was about 24 km/h. In our investigation nine experiments (nos. 9,10,14,19,20,29,31,34 and 35) were performed at this velocity with a 25 cm bumper level. In five tests (nos. 9,20,29,31 and 35) lower leg fractures occurred at the impact level. In three cases, however, (nos 10,14 and 20) malleolar fractures or ankle ligament injuries occurred probably due to the ground reaction force. The maximum impact force in our investigation was 3.7 kN compared to the "critical force" of 4.3 kN according to Kramer et al. (1973).

Krieger et al. (1976) made five experiments with cadavers hit by a car. The results mainly consists of accelerometer data and the injuries were not described in detail.

Weiss et al. (1977) made fifteen experiments with cadavers hit by a car. A comparison was made between the injuries caused by a rigid impactor at a standard (50 cm) or a low (35 cm) height and a soft impactor at varying heights. The velocity range (17-45 km/h) was greater than in our experiments and the number of experiments in each group was small. They do not describe any ligament injuries or malleolar fractures. However, the conclusion that a low bumper level will be favourable for the leg impact is in good agreement with ours.

In this presentation the abbreviated injury scale is used. The comprehensive injury scale is more differentiated but in our opinion still not enough detailed. A more distinct injury scale would probably be more suitable for studies of the influence of the bumper and front design on the leg injuries in a model like this.

The model described is capable of simulating some of the leg injury mechanisms acting in real accidents. A mathematical or non biological model can be used to simulate other details. This experimental model may for this reason be the correlating link between real accidents and other theoretical and mechanical models. Such a link is urgently needed for further studies in this field.

Conclusions.

The test procedure and the experimental equipment described can rather well simulate the biomechanics and disclose the injury mechanisms of the bumper-leg impact seen in real car-pedestrian accidents.

Serious ($AIS > 3$) injuries are not seen at velocities below 25 km/h. However, severe ($AIS = 3$) injuries already occur at 17 km/h.

A 45 cm bumper level caused knee injuries. A 25 cm bumper level did not. The AIS rating of the injuries caused by the 45 cm bumper level was significantly higher than those caused by the 25 cm level.

The compliance of the impacting surface is probably important. An impact zone ranging from 20 to 45 cm with a smooth and soft surface is supposed to mitigate the leg injuries in car-pedestrian collisions.

Acknowledgements.

This work has been accomplished under a contract entered with the Commission of the European Communities.

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