AN INFLATABLE CARPET TO REDUCE THE LOADING OF THE LOWER EXTREMITIES - EVALUATION BY A NEW SLED TEST METHOD WITH TOEPAN INTRUSION

Yngve Håland
Erik Hjerpe
Autoliv Research
Sweden
Per Lövsund
Dept. of Injury Prevention
Chalmers University of Technology
Sweden
Paper Number 98-S1-P-18

ABSTRACT

For occupants protected by seat belts, air bags, or both, the most frequently injured body region in frontal crashes is the lower extremities. These injuries are usually not life threatening, but they are often associated with long term impairment. The injury mechanisms are not yet fully understood. However, high local accelerations in the footwell area and the location of the feet probably play an important role in the causation of the injuries. A reduction of the footwell intrusion by structural reinforcements of the car body may therefore not be sufficient to reduce injuries. Other counter-measures are also needed.

This paper describes a new dynamic sled test method with an instrumented Hybrid III dummy in a car body, in which the toepan intrusion is simulated mechanically. The acceleration-time history of the toepan and its displacement can be varied. Toepan accelerations/intrusions as in severe frontal off-set collisions have been simulated. Two foot positions, against the toepan or at a certain distance (as if the foot was on a pedal), were evaluated.

The effect of an inflatable device, called the Inflatable Carpet (InCa), under the floor carpet in the footwell area is evaluated by this method. The Inflatable Carpet lifts the feet away a certain distance from the floor/toepan, before they are subjected to acceleration and intrusion by the toepan.

The study has shown that the acceleration of the toepan, the position of the feet relative to the toepan, and the use of the Inflatable Carpet, all significantly influenced the load on the foot and the lower leg. The use of the Inflatable Carpet reduced the foot acceleration by up to 65 % and the tibia force by up to 50 %. The tibia index was reduced by 30 to 60 %. The Inflatable Carpet therefore seems to be able to significantly reduce the risk of receiving an injury to the foot/ankle and lower leg in collisions, where violent foot-well intrusion occurs.

INTRODUCTION

The lower extremities are among the most frequently injured body regions in car collisions regardless of restraint (Crandall and Martin, 1997a). About 70 % of these injuries are sustained in frontal collisions (Pattimore et al., 1991; Parenteau et al., 1995; Crandall and Martin, 1997a). Pattimore et al. (1991) found, using U.K. crash data (U.K. Cooperative Crash Injury Study), that 37 % of injured car occupants had sustained injuries to the lower extremities. The seat belt use was high, at about 85 %. Crandall and Martin (1997a) found, using U.S. crash data (NASS-CDS), that in frontal collisions almost 40 % of the AIS 2+ injuries to front seat occupants, restrained by airbags and belts, were to the lower extremities. 60 % of these injuries were below the knee; 20 % to the lower leg and 40 % to the foot/ankle.

Ankle injuries account for the majority of AIS 2+ injuries in Volvo's data base (Forsell et al., 1996). Malleolus fractures in the distal ends of tibia and fibula and "pilon" fractures of the talus were typical. Crandall et al. (1995) found that ankle and calcaneus (heel bone) fractures are the most frequent injuries, evident at all levels of footwell intrusion.

Although the injuries to lower extremities are rarely life threatening, they can lead to long term disability and impairment (Pattimore et al., 1991; Frampton et al., 1995). Parenteau (1996) found in a Swedish study that 48 % of AIS 2+ foot/ankle injuries were estimated to have residual impairment. A German study by Zeidler et al. (1989) found that the rate of permanent impairment for heel fractures was as high as 72 %, and for open tibia/fibula fractures 43 %.

About 50 % of AIS 2+ lower extremity injuries sustained in frontal crashes occur in collisions with Δv ranging from 25-50 km/h. Only 20 % occur in extremely high severity crashes, where Δv exceeds 70 km/h (Crandall and Martin, 1997a). However, the risk of injury to the lower extremities increase, when either Δv or the magnitude of intrusion increases (Thomas et al., 1995; Fildes et al., 1995; Crandall and Martin, 1997a). Substantial intrusion of the footwell is not a necessary condition. 71 % of all and 61 % of AIS 2+ below-knee injuries sustained by front seat occupants in head-on crashes occurred with less than 30 mm of footwell intrusion according to a study by Crandall et al. (1995). This suggests that for these injuries there may be more sensitive crash factors other than the level of intrusion, e.g. the rate or the acceleration of intrusion.

Kuppa and Sieveka (1995) found in a series of full-scale tests that the axial loads measured just above the ankles in the dummies were highly correlated with the peak acceleration of the floor/toepan or the brake pedal. However, these axial loads did not correlate well with the amount of floor/toepan or brake pedal intrusion. This suggests that the axial loads through the feet of the dummy are caused by the dynamic motion of the surface on which the feet rest. The tests showed that high acceleration-short duration floor/toepan pulses led to low levels of intrusion but resulted in high axial loads through the dummy feet. Conversely, the data from the tests showed that low acceleration-long duration floor/toepan pulses led to high levels of intrusion but resulted in low axial loads through the dummy feet.

About half of all drivers, who sustain lower extremity injuries, are braking at the time of collision. Several studies have shown that the increased risk of below-knee injuries for drivers is primarily the result of interaction with pedal controls (Morgan et al., 1991; Pattimore et al., 1991). When the foot is on a pedal and the heel is off the toepan, a velocity differential develops between the foot and toepan that makes the foot vulnerable to impact injury (Crandall and Martin, 1997a). Crandall et al. (1995) also found in a series of crash tests that there was a tendency for greater loads in the right leg compared to the left. The right foot of the dummy was placed on the accelerator pedal, while the left foot rested on the toepan. Forsell et al. (1996) found by mathematical simulations that the foot to toepan impact speed affected the tibia force. An increased distance between the foot and toepan led to a higher foot impact speed.

The question is then raised. Can an energy absorbing padding material placed over the floor/toepan reduce the high forces being transmitted to the occupant's feet, when there is a violent footwell intrusion? Kuppa and Sieveka (1995), and Forsell et al. (1996) found by mathematical simulations, and the latter also by tests, that padding was efficient in reducing the axial load in the dummy's lower leg. A thickness of about 30 mm reduced the tibia force by about one third.

This study focuses on an alternative to padding in the footwell area, an inflatable device called the Inflatable Carpet to protect the feet/ankles and the lower legs of the front seat occupants. The thickness of the Inflatable Carpet is about 70 mm, when it is inflated in a frontal collision. Normally the (uninflated) thickness is less than 10 mm.

The aim of the present study was to investigate the effect of the acceleration of the toepan on the loading of the foot and lower leg for two foot positions, against the toepan or at a certain distance (as if the foot was on a pedal), by means of a new sled test method. Furthermore, the study aimed to investigate the effect of the Inflatable Carpet.

METHOD

A sled test method was developed, where a translational toepan intrusion could be simulated mechanically. The acceleration of the toepan as well as the amount of intrusion could be varied. A translational toepan intrusion was chosen based on results of mathematical simulations of a 56 km/h, 50 % off-set crash with a Ford Taurus against a rigid barrier (Pipkorn, 1998). In these simulations, the toepan intrusion was found to be mainly translational. This type of toepan simulation has also been performed by others (Bass et al., 1997). The tests were made with two different foot positions, against the toepan or at a certain distance, with and without the Inflatable Carpet. The acceleration of the dummy's right foot and the axial force of the right lower leg were measured for all test configurations. The crash pulse of the car body on the sled was achieved by a steel bar bending brake system and the desired acceleration pulse of the toepan was achieved by crushing of a honey comb block mounted in front of the brake.

Vehicle rig

A body in white (BIW) of a large-size car was placed on the crash sled of Autoliv Research (Figure 1). The tests were performed for the driver's side. A Hybrid III dummy with instrumented lower leg (45° ankle joint with soft stops) was placed in a reinforced standard car seat. The steering wheel attachment was also reinforced so as not to deform in the tests. The knee bolster had the dimension of the original car but was made of steel covered with a 25 mm thick padding (Ethafoam 400) which was replaced, when there was a permanent crush. The outside of the knee bolster was covered with a 1 mm polyethylene sheet. A 3-point static seat belt with high webbing elongation (18 % at 10 kN) was used. The belt was replaced before each test and pre-tensioned to about 100 N. These measures were taken in order to achieve the best level of repeatability for the tests as possible.

Toepan intrusion simulation

The toepan, a piece of the fire wall, and the greater part of the floorpan were cut out of the BIW. A new structure with the same geometry was made of stiff steel plates. This new toe- and floorpan floor was mounted on a separate small sled. The toe- and floorpan sled was equipped with ball bearings running in horizontal guiding rails, which were mounted to the crash sled with the BIW (Figure 1). A honey comb block (Hexcel CRIII-3/8-ACG-.003N) was placed in front of the brake system. By choosing size and position of the honey comb block, the timing and amplitude of the intrusion pulse could be varied. The maximum intrusion of the toepan was controlled by a stop, which could be moved within the BIW and fitted with a thin piece of stiff polyurethane padding.

The crash pulse of the BIW was intended to correspond to a 56 km/h off-set rigid barrier test. The tests were performed with two different toepan accelerations. A high amplitude acceleration pulse of the toepan with small residual (translational) intrusion (140g/80mm), and a low amplitude acceleration pulse with large residual intrusion, (70g/160mm) were used. It was decided to begin the toepan intrusion at about 32 ms for both pulses (Figure 2). Two different foot positions were tested.

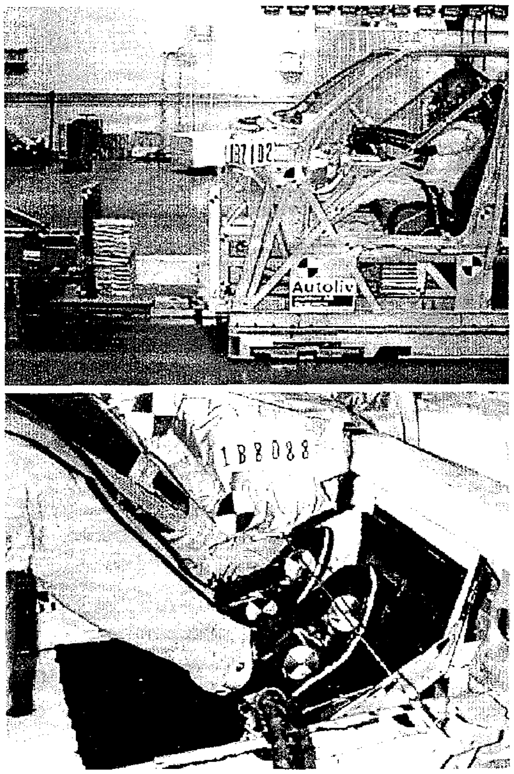


Figure 1. The vehicle rig with toepan intrusion simulation. (The knee- to knee bolster clearance is about 85 mm).

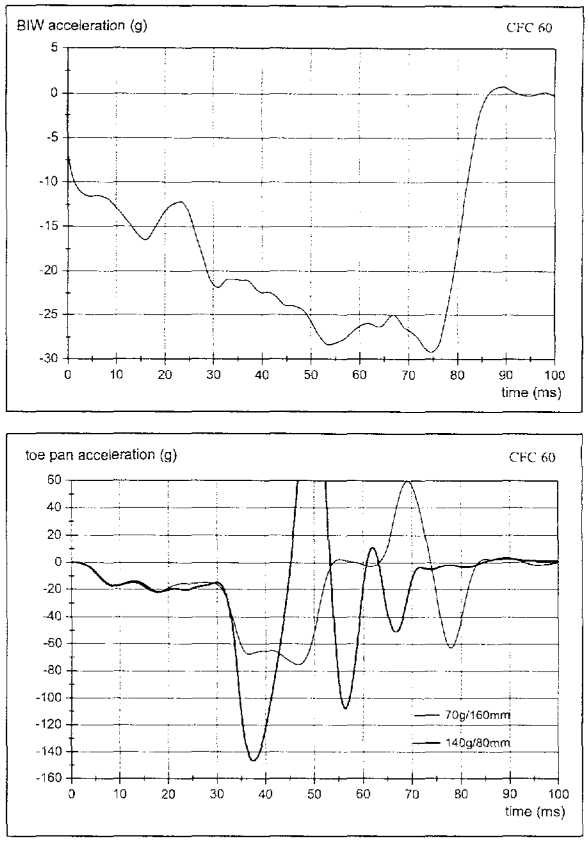


Figure 2. The acceleration pulse of the BIW and the two toepan acceleration pulses. BIW Δv = 56 km/h.
Note. The feet loose contact with the toepan, when the acceleration changes sign. The second acceleration peak is not inducing any foot or lower leg loads.

Inflatable Carpet (InCa)

The Inflatable Carpet is of the same design as the Inflatable Curtain (Öhlund et al., 1998), about 70 mm thick when inflated and covering and area of about 450 x 350 mm (Figure 3). A hybrid gas generator (Autoflator H2010) was used and inflated the Inflatable Carpet to a pressure of about 150 kPa within 20 ms from triggering. A 3 mm sheet of acetal plastic and the regular carpet were placed on top of the Inflatable Carpet. On the reverse side of the toepan section of the acetal sheet, three horizontal load distributing stripes of aluminium, 50 mm wide and 3 mm thick, were attached. The acetal sheet, the aluminium stripes and the regular carpet were glued together. In the tests without the Inflatable Carpet this package was placed directly on the floor- and toepan.

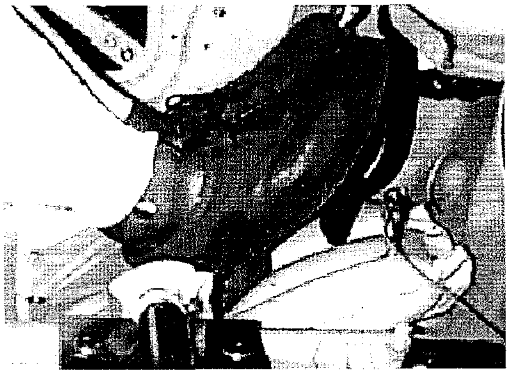


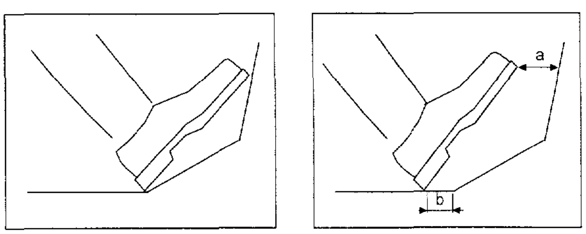
Figure 3. The Inflatable Carpet (InCa). The picture shows the Inflatable Carpet only, without plastic sheet and regular carpet.

Instrumentation

The accelerations of the BIW and the toe- and floorpan sled were measured with accelerometers (Entran EGCS-D1CM-100 and Endevco 7231C-750). The position of the intruding toepan was measured with a string potentiometer (Celesco PT101-25-311-S11D). A standard Hybrid III 50th percentile dummy was used. The right and left upper legs of the dummy were equipped with femur load sensors (Load Indicator). The right leg was equipped with an enhanced lower tibia and with an accelerometer in the foot (Endevco 7264B-2000). The foot accelerometer was placed on the steel plate directly in front of the ankle joint. The internal pressure of the Inflatable Carpet was measured with a pressure transducer (Endevco 8510C-100 M37). On board and over view high speed video cameras were used (Kodak Ektapro RO).

Foot positions

The tests were performed with two different foot positions (Figure 4 and Table 1). In the first position, the feet were in contact with the toepan and in the second at a small distance away from the toepan. These two positions were chosen so the effect of a clearance to the toepan (simulating a foot on an accelerator or a brake pedal) could be studied.



"Contact" position "Clearance" position

Figure 4. The two foot positions; each tested with and without the Inflatable Carpet.

Table 1.
Measures according to Fig. 4 for the two foot positions

Configuration	a (mm)	b (mm)
contact	0	0
clearance	100	50

Test matrix

The tests were run with the two foot positions according to figure 4, and with the two different toepan pulses, 70 g and 140 g according to figure 2. For each test condition, tests with and without the Inflatable Carpet were run (Table 2).

Table 2.
Test matrix

Foot position	Toepan pulse (g)	Residual intrusion (mm)	Inflatable Carpet (Y/N)
Contact	140	80	N
Contact	140	80	Y
Contact	70	160	N
Contact	70	160	Y
Clearance	140	80	N
Clearance	140	80	Y
Clearance	70	160	N
Clearance	70	160	Y

Each test configuration was normally run only once. However, the configuration with the foot position "contact", intrusion of 160 mm and without the Inflatable Carpet was run four times to study the repeatability. (These found variations were then considered to be the same for all evaluated configurations, when testing the statistical significance).

Injury assessment reference values (IARVs)

- The injury assessment reference value of the foot acceleration is proposed to be 150 g (Zeidler et al., 1996). (As there is no prescriptions for placement of the accelerometer, filter class or duration of the maximum acceleration, this value can only be used as a guideline).
- The tibia force should not exceed 8 kN (EU, 1996).
- The tibia index should not exceed 1.3 at the proximal or distal end of the tibia (EU, 1996).

RESULTS

The foot acceleration, tibia force and the upper tibia index were all significantly reduced in the tests with the Inflatable Carpet (Figure 5 and Table 3) compared to the tests without. The lower tibia index was reduced in the "clearance" position but was unaffected or even slightly increased in the "contact" position. The results clearly show that the toepan pulse with 140 g acceleration and 80 mm of residual intrusion results in higher foot and lower leg loads than the 70 g toepan pulse with a larger (160 mm) intrusion. The foot acceleration for the higher pulse was doubled, and the tibia force increased 35 to 93 % (without the Inflatable Carpet).

It is also obvious when comparing the results of the tests with the feet in "contact" with those in "clearance" positions, that the pre-crash position of the feet is a very important factor. The foot acceleration was reduced by 33 to 66 % and the tibia force by 22 to 49 %, when the results from tests with the Inflatable Carpet were compared with the tests without the Inflatable Carpet. The upper tibia index was reduced by 30 to 62 %.

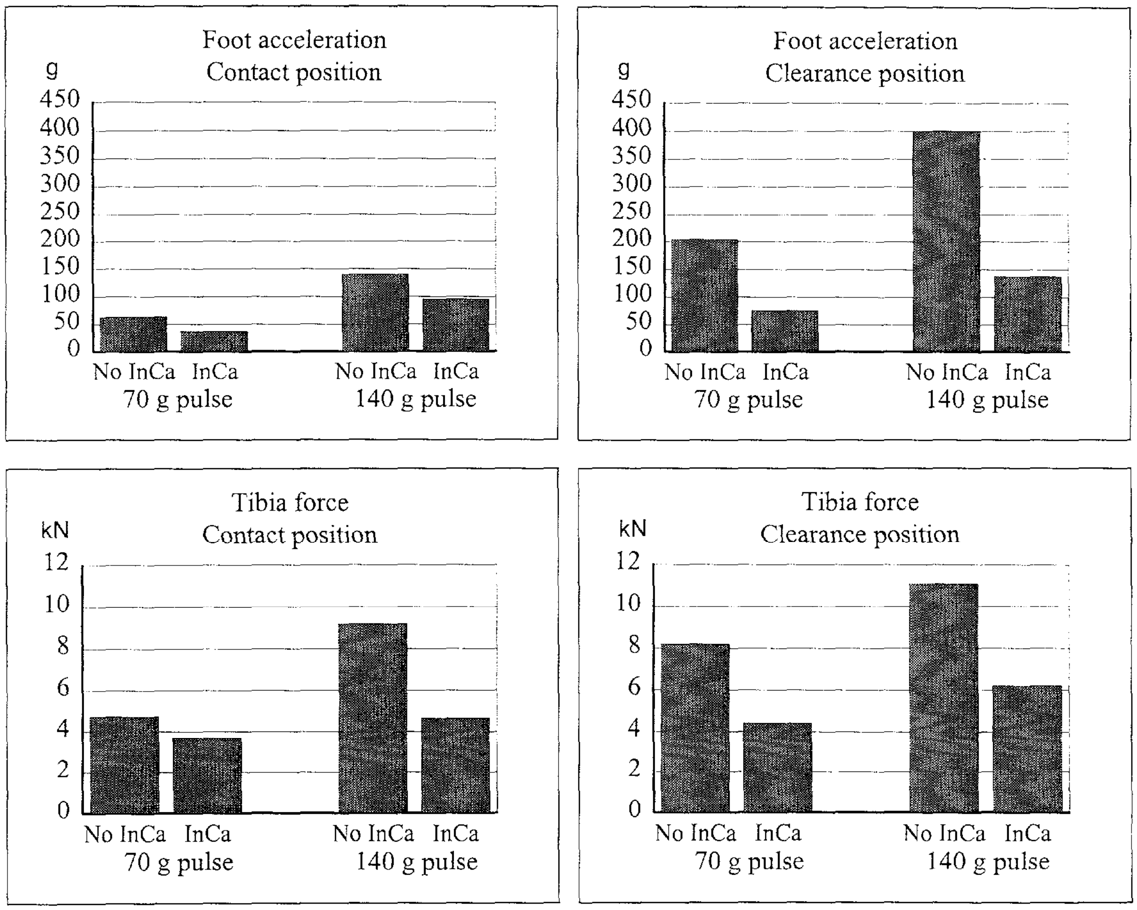


Figure 5. The peak values of the foot acceleration, tibia force and tibia index (lower and upper tibia) for all tests.

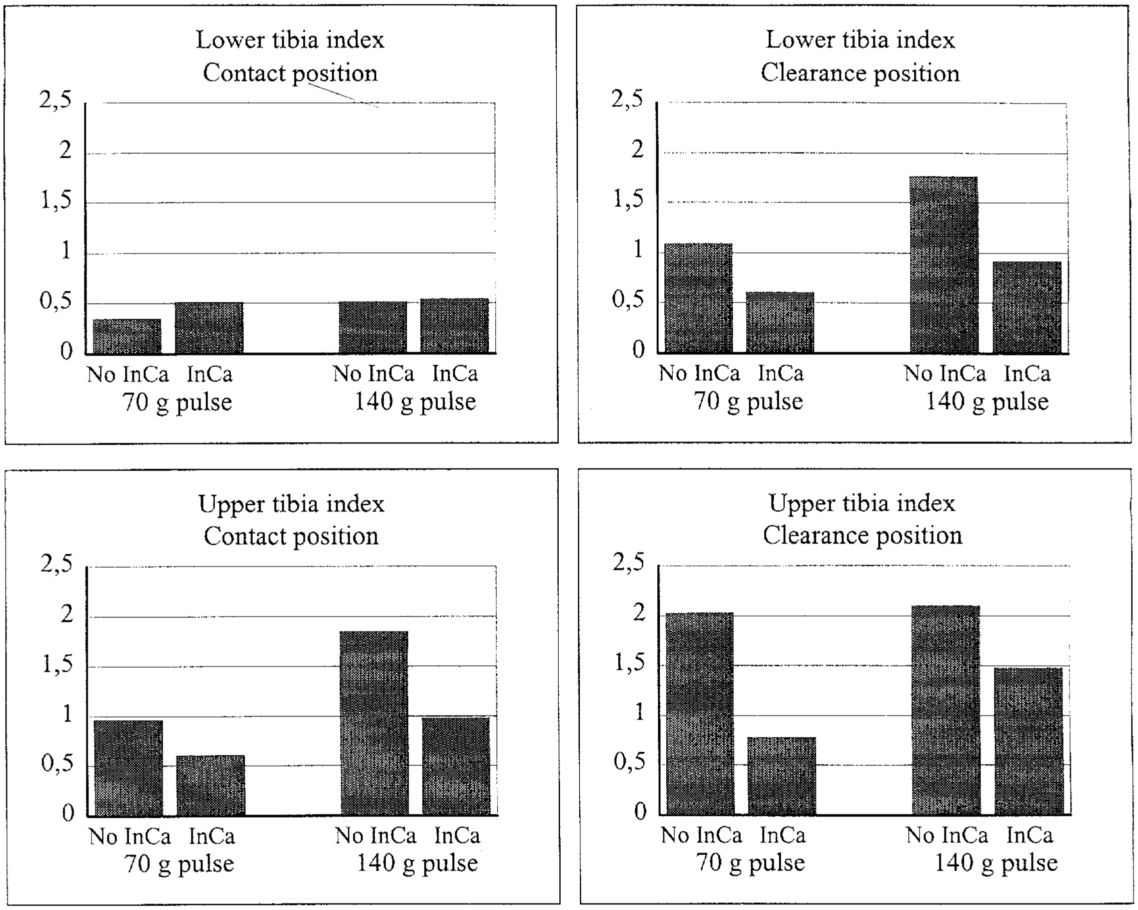


Figure 5. cont. The peak values of the foot acceleration, tibia force and tibia index (lower and upper tibia) for all tests.

Table 3
The peak values of tibia index (lower and upper tibia), tibia force and foot acceleration for all tests. The marked values are those which failed to pass the IARVs

Test no	Foot position	Toepan pulse (g)	Intrus. (mm)	InCa (Y/N)	Tibia Index lower tibia	Tibia Index upper tibia	Tibia force cfc600 (kN)	Foot acc cfc600 (g)
76	Contact	140	80	N	0.52	1.85	-9.18	141
77	Contact	140	80	Y	0.55	0.98	-4.65	95
*	Contact	70	160	N	0.35	0.97	-4.75	63
78	Contact	70	160	Y	0.51	0.61	-3.71	37
80**	Clearance	140	80	N	1.76	2.10	-11.1	401
79	Clearance	140	80	Y	0.88	1.43	-6 .34	134
90	Clearance	70	160	N	1.09	2.03	-8.23	204
89	Clearance	70	160	Y	0.61	0.78	-4.39	76

* Mean value, see table 4.
** Foot deformed in test no. 80 (repaired).

Table 4
Study of the repeatability of one tested configuration

Test no	Foot position	Toepan pulse (g)	Intrus. (mm)	InCa (Y/N)	Tibia Index lower tibia	Tibia Index upper tibia	Tibia force cfc600 (kN)	Foot acc cfc600 (g)
75	Contact	70	160	N	0.42	0.93	-4.44	60.4
85					0.36	1.10	-5.60	70.7
86					0.31	0.93	-4.55	66.4
87					0.29	0.90	-4.41	55.1
Mean Std. error of the mean (SE)*					0.35 +/- 0.025	0.97 +/- 0.039	-4.75 +/- 0.25	63.2 +/- 3.0

* $SE = SD/\sqrt{n}$, where SD = std. deviation and n=no. of tests (n=4).

The results of the repeatability study can be found in table 4. Tests (t-test) of statistical significance were done. These showed that the differences in measured peak values between all test configurations with and without the Inflatable Carpet were statistically significant ($p<0.001$-0.05) for upper tibia index, tibia force and foot acceleration. The differences for the lower tibia index were also significant ($p<0.001$-0.01) with exception for test no. 76 compared to test no. 77.

DISCUSSION

Kuppa and Sieveka (1995) found in a series of full-scale tests that high acceleration-short duration floor/toepan pulses led to a low level of intrusion but resulted in high axial loads through the dummy feet. Conversely, the data from the tests showed that low acceleration-long duration floor/toepan pulses led to high levels of intrusion but resulted in low axial loads through the dummy feet. These findings have been taken into consideration in the test method developed for this study. The two acceleration levels of the toepan, 70 g and 140 g, were chosen based on a recommendation from Crandall (1997b) that the acceleration of the foot in a position against the toepan should exceed 100 g (a severe test condition). A foot acceleration of 141 g was reached without the Inflatable Carpet in the "contact" position for the 140 g toepan pulse and 63 g in foot acceleration for the 70 g pulse. The test method thus simulates one toepan acceleration/intrusion condition that is worse than what Crandall suggested and one that is less severe. The tests confirmed the earlier findings by Kuppa and Sieveka (1995) that the loading of the foot and the lower leg (tibia) can vary considerably between tests with significantly different toepan acceleration/intrusion levels.

About half of all drivers, who sustain lower extremity injuries, are braking at the time of collision. The leg muscles are therefore tensed. The effect of this pre-impact bracing was investigated by Klopp et al. (1995) in a series of lower limb impact tests. A harness was placed over the knee and tensed to give a tibia load of about half the body weight. The tests showed that the forces and moments in the lower limb increased significantly due to this simulated pre-impact bracing. This type of simulation should therefore be included in further tests and evaluations of the effect of the Inflatable Carpet.

Several studies have shown that the risk of below-knee injuries for drivers is primarily the result of interaction with pedal controls (Morgan et al., 1991; Pattimore et al., 1997). When the foot is on the pedal and the heel is off the toepan, a velocity differential develops between the foot and toepan that makes the foot vulnerable to impact injury (Crandall and Martin, 1997a). The "clearance" position was therefore chosen as well. The results from the tests confirm that the distance between the foot and toepan has a very strong effect on both the foot acceleration and tibia force. The foot acceleration increased from 63 g in the test with "contact" position to 204 g in the test with "clearance" position for the 70 g toepan pulse. The tibia force increased from 4.8 kN to 8.2 kN (Figure 5). The results mentioned are from tests without the Inflatable Carpet. In the tests with the 140 g toepan pulse, the foot acceleration increased from 141 g to 401 g and the tibia force from 9.2 kN to 11.1 kN. The distance between the foot and the toepan in the tests with the "clearance" foot position developed a velocity difference of about 10 m/s for the 70 g toepan pulse and 12 m/s for the 140 g pulse. The contact between the foot and the toepan occurred, when the toepan still was undergoing acceleration. The loading of the foot and lower leg is thus caused by a combined effect of the toepan acceleration and the velocity difference between the foot and the toepan at the time of contact.

In an earlier investigation performed within Autoliv Research, a complete leg of a Hybrid III dummy was used in drop tests against a concrete floor. It was found that the foot acceleration, as well as the tibia force, was almost linearly proportional to the contact velocity with the floor. The highest velocity tested was 6 m/s. This was the first indication from own test results that the contact velocity is a very important factor. The drop tests with the Hybrid III leg also showed the effect of various paddings and of the Inflatable Carpet. An Inflatable Carpet of 70 mm thickness and with a pressure of about 150 kPa (1.5 bar) reduced the foot acceleration and the tibia force by 40 - 60 %. The current study also shows considerable reductions in these loads by the Inflatable Carpet. The largest reductions were found in the tests with the "clearance" position of the foot. The foot acceleration was reduced by about 3/4 by the Inflatable Carpet in tests at both toepan accelerations levels. The tibia force was reduced by almost 1/2. In the most severe test condition, with the foot in "clearance" position and with the 140 g toepan pulse, the foot acceleration was reduced by the Inflatable Carpet below the suggested injury assessment reference value (IARV) of 150 g, down to 134 g. Without the Inflatable Carpet, the maximum foot acceleration was much higher, 401 g. The tibia force was also reduced below the IARV of 8 kN, down to 6.3 kN. Without the Inflatable Carpet the maximum value was 11.1 kN. The Inflatable Carpet thus seems to act as a very efficient shock absorber, when there is a violent toepan intrusion.

The tibia index is an official lower leg criterion in the new European frontal test procedure (EU, 1996). The maximum allowed level is 1.3. The index measured for the upper tibia was higher for all tested configurations than the index for the lower tibia. The highest tibia index, of 2.1, was reached with the 140 g toepan acceleration, "clearance" foot position, and without the Inflatable Carpet (Figure 5). The upper tibia index was reduced by the Inflatable Carpet down to 1.4, close to the acceptable level. For all other test conditions, the tibia index was reduced well below 1.3 by the Inflatable Carpet. The device could therefore be one of the measures car makers can take in order to meet the requirements of the new European frontal test procedure, to minimize the tibia index.

This study has not evaluated any more interaction between the foot and a pedal, for example the brake pedal, than the effect of the contact velocity between the foot and the toepan. There can also be other effects that contribute to the loading of the foot/ankle and the lower leg. A few tests with the right foot of the dummy on a fully depressed brake pedal (rigidally attached to the toepan) were run in addition to the tests according to the test matrix. The toepan acceleration was 70 g. The results indicate that the loadings to the foot and tibia were not worse than at the "clearance" position of the foot, rather the opposite. However, more testing is needed before any conclusions can be drawn.

Klopp et al. (1997) found that the peak contact plantar force, its onset rate, and the peak heel acceleration were good predictors of injury to the lower limb. The fifty percentile probability of injury were found to be at 9.3 kN peak contact force, 5 kN/ms peak contact force onset rate, and 216 g peak heel acceleration. If it can be assumed that the tibia force, measured with the Hybrid III dummy lower leg, can substitute the plantar contact force, it is noticeable that not only is the tibia force significantly reduced by the Inflatable Carpet but also the onset rate. Figure 6 shows the tibia force time histories for test no. 79 and test no. 80, with and without the Inflatable Carpet respectively, with the "clearance" foot position and 140 g toepan acceleration. The maximum onset rate of the tibia force was reduced from a maximum of 6 kN/ms without the Inflatable Carpet to only 2 kN/ms with it. This reduction of the onset rate due to the Inflatable Carpet should therefore also contribute to the reduction of the risk of receiving an injury to the lower limb in collisions with violent footwell intrusion.

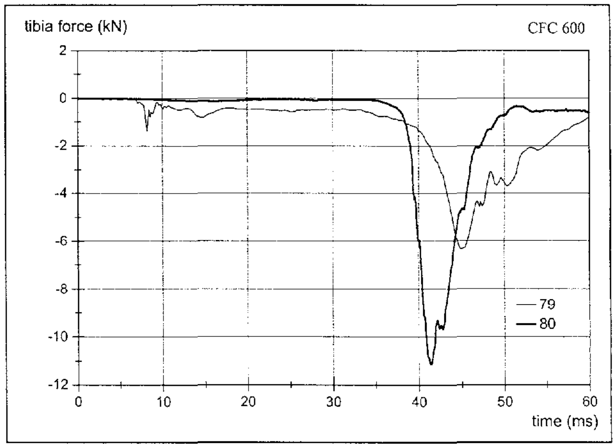
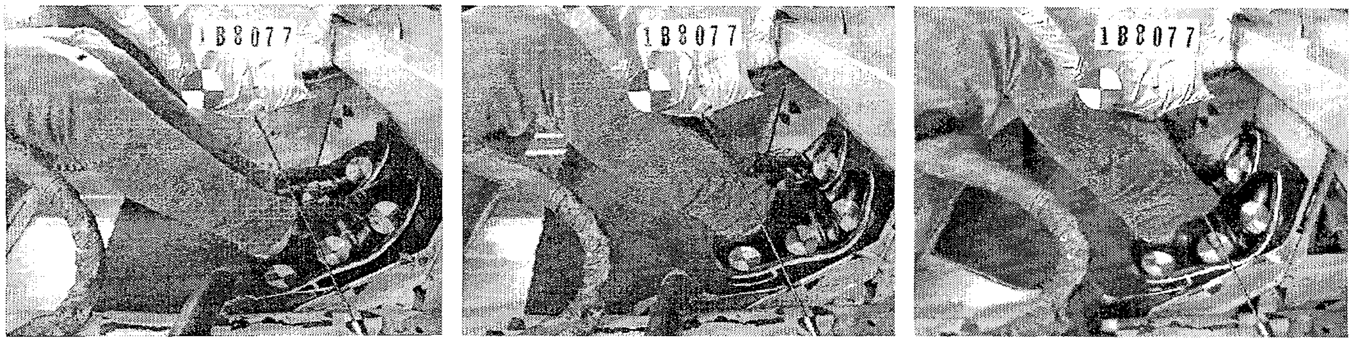


Figure 6. Examples of tibia force onset rates. In test no. 79 (with InCa) max 2 kN/ms at 43 ms and in test no. 80 (without InCa) max 6 kN/ms at 41 ms.

The dorsiflexion motion of the foot could be evaluated from the high speed video recordings from the tests. It was found that the motion was at maximum 20 degrees from the start position (Figure 7, left picture) in tests with the Inflatable Carpet. The motion was somewhat less in tests without the Inflatable Carpet. Inversion and eversion motions were very small. Parenteau (1996) found in her research that the dorsiflexion motion could be up to 44° (+/- 10°) without failure in the ankle joint. The results from the tests in this study thus indicates that the Inflatable Carpet does not increase the risk of injury to the ankle. The motion of the toes were large (Figure 7, right picture). It was not possible to evaluate whether this could be injurious to the mid foot bones and ligaments. However, the bending of the toes was not larger with the Inflatable Carpet than without.

Typical values for the femur loads were 2 to 4 kN. They were not significantly influenced by the different toepan accelerations or the use of the Inflatable Carpet.



Initial position (0 ms) | InCa fully inflated (35 ms) | Max. toepan intrusion (45 ms)

Figure 7. The sequence of pictures from test no. 77 shows the inflation of the Inflatable Carpet and the toepan intrusion (80 mm).

Static deployment tests of the Inflatable Carpet have previously been performed at Autoliv Research, to study the effect on the feet and lower legs, when the feet are placed against the toepan, a kind of out of position (OOP) situation. In these tests, foot accelerations and tibia forces of maximum 20 g and 1 kN respectively were measured. These values are low compared to known IARVs, hence the Inflatable Carpet itself should be harmless.

CONCLUSIONS

The study has shown that the test method with a mechanical simulation of toepan intrusion works well. The acceleration of the toepan, the position of the foot relative to the toepan and the use of the Inflatable Carpet, all significantly influenced the load on the foot and the lower leg:

- An increase of the toepan acceleration from 70 g to 140 g doubled the foot acceleration, and the tibia force increased 35 to 90 % (without the Inflatable Carpet).
- A clearance between the foot and the toepan (simulating a foot on a pedal), instead of in contact with the toepan, increased the foot acceleration by 2 to 3 times and the tibia force by up to 70 % (without the Inflatable Carpet).
- The use of the Inflatable Carpet reduced the foot acceleration by up to 65 % and the tibia force by up to 50 %.
- The tibia index (upper tibia) was reduced by 30 to 60 % by the Inflatable Carpet.

The Inflatable Carpet therefore seems to be able to significantly reduce the risk of receiving an injury to the foot/ankle and lower leg in collisions, where violent footwell intrusion occurs.

ACKNOWLEDGEMENT

The authors wish to thank Dr. Bengt Pipkorn, Autoliv Research, for valuable mathematical simulations.

REFERENCES

Bass, C.R., Dekel, E., Crandall, J.R., Lange, M., Pilkey, W.D., "Experimental devices to simulate toepan and floorpan intrusion", SAE paper 970574, Intl. Congress & Exposition, Detroit, 1997.

Crandall, J.R., Martin, P.G., "Lower limb injuries sustained in crashes and corresponding biomechanical research", Proc. of the International Symposium on Real World Crash Injury Research, Leicestershire, England, 1997a, pp. 3.5:1-3.5:16.

Crandall, J.R., "Personal communication", 1997b.

Crandall, J.R., Martin, P.G., Sieveka, E.M., Klopp, G.S., Kuhlmann, T.P., Pilkey, W.D., Dischinger, P.C., Burgess, A.R., O'Quinn, T.D., Schmidhauser, C.B., "The influence of footwell intrusion on lower extremity response and injury in frontal crashes", Proc. 39th AAAM Conference, Chicago, 1995, pp. 269-286.

European Union (EU) Directive 96/79/EC, "On the protection of occupants of motor vehicles in the event of a frontal collision", 1996.

Fildes, B., Lenard, J., Lane, J., Vulcan, P., Seyer, K., "Lower limb injuries to passenger car occupants", Proc. 39th AAAM Conference, Chicago, 1995, pp. 47-58.

Forsell, J., Jakobsson, L., Lund, Å., Tivesten, E., "Foot and leg injuries in frontal car collisions", Proc. 15th ESV Conference, Melbourne, 1996, pp. 422-437.

Frampton, R., Mackay, M., Hill, J., "Leg injury risk in frontal collisions", SAE Intl. Congress and Expo, Paper 950499, SP-1072, 1995.

Klopp, G.S., Crandall, J.R., Hall, W.H., Pilkey, W.D., Hurwitz, S.R., "Mechanism of injury criteria for the human foot and ankle in dynamic axial impacts to the foot", Proc. of the IRCOBI Conference, Hannover, 1997, pp. 73-86.

Kuppa, S.M., Sieveka, E.M., "Dynamic motion of the floor pan and axial loading through the feet in frontal crash tests", Proc. 39th AAAM Conference, Chicago, 1995, pp. 389-402.

Morgan, R.M., Eppinger, R.H., Hennessey, B.C., "Ankle joint injury mechanism for adults in frontal automotive impact", Proc. 35th Stapp Car Crash Conference, San Diego, 1991, pp. 189-198.

Parenteau, C.S., "Foot-Ankle Joint Responses; Epidemiology, Biomechanics and Mathematical Modeling", Doctoral thesis, Department of Injury Prevention, Chalmers University of Technology, Gothenburg, 1996.

Pattimore, D., Ward, E., Thomas, P., Bradford, M., "The nature and cause of lower limb injuries in car crashes", Proc. 35th Stapp Car Crash Conference, San Diego, 1991, pp.177-188.

Pipkorn, B., "Personal communication", 1998.

Thomas, P., Bradford, M., Charles, J., Fay, P., "Lower extremity injuries and their causation in frontal car crashes: real world accident data collection", Pelvic and Lower Extremities Conference, Washington D.C., 1995.

Zeidler, F., Pletschen, B., Mattern, B., Alt, B., Miksch, T., Eichendorf, W., Reiss, S., "Development of a new injury cost scale", Proc. 33rd AAAM Conference, Baltimore, 1989, pp.231-247.

Öhlund, A., Palmertz, C., Korner, J., Nygren, M., Bohman, K., "The Inflatable Curtain (IC) - a new head protective system in side impacts", Paper 98-S8-W29, 16th ESV Conference, Windsor, 1998.