EVALUATION OF LOWER LIMB INJURY MITIGATION FROM INFLATABLE CARPET IN SLED TESTS WITH INTRUSION USING THE THOR LX

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ABSTRACT

Real world crash investigations have suggested that lower limb injury risk is increased with the occurrence of toepan intrusion in a frontal collision. In order to more closely evaluate the effects of different modes of toepan intrusion, a rotational and translational intrusion device was built for the test sled at the University of Virginia. Sled tests were performed at a velocity of 56 km/h with a belted Hybrid III occupant and a simulated knee bolster and steering wheel air bag. Lower limb injury risk measures were obtained with Hybrid III and Thor Lx dummy lower extremities.

Dummy response variables of interest included tibia axial and shear loads, tibia bending moments, ankle rotations and foot and tibia accelerations. The tests were conducted with no intrusion and with a translational intrusion with a peak deceleration of approximately 175 g's with 14 cm of translation. A lower limb injury mitigation device, the Inflatable Carpet (InCa), was used in comparison tests to evaluate its efficacy in reducing loads imparted to the lower limb for varying initial foot positions. Results from the tests indicate that intrusion causes an increase in tibia axial load mainly due to acceleration, and ankle dorsiflexion mainly due to translation, both potentially increasing injury risk. The InCa resulted in large load reductions in the clearance position, and also reduced dorsiflexion angles. The design of the air bag used in this study was optimized for use in settings with toepan rotation in addition to translation. Occupant response was sensitive to a number of factors, such as knee bolster design and Inflatable Carpet geometry, which have to be taken into account in the tuning of the InCa design. Additional tests were conducted in a static setting, with various out-of-position lower limb configurations. These tests did not identify any potential harmful effects of accidental InCa deployment.

INTRODUCTION

Lower limb injuries occur frequently in frontal crashes, and restraint use has been shown to have little effect on the reduction of below knee injury risk (Crandall and Martin 1997). A study of National Automotive Sampling System (NASS) frontal crash cases from 1988-1995 found that the lower extremities were the most commonly injured AIS≥2 (Abbreviated Injury Scale) body region (40%) in front seat occupants with seat belt and air bag restraints. Several studies have shown that lower limb injuries are also very costly with painful long-term outcomes (Pattimore *et al.* 1991, Dischinger *et al.* 1994, Burgess *et al.* 1995, Morris *et al.* 1997, Taylor *et al.* 1997). Researchers have linked lower limb injury risk to structural deformation of the toepan during the crash event, however, many questions still remain about the role of intrusion.

In a study of offset frontal crashes, Zuby *et al*. (1994) found a positive relationship between tibia forces and moments and the amount of footwell intrusion. Another investigation of post-test deformation (Krüger *et al.* 1994) showed good correlation between footwell volume reduction and foot loads. This is in contrast to Kuppa and Sieveka (1995), who found that peak tibia forces correlated with peak toepan acceleration in vehicle crashes, but had little relation to the magnitude of the structural deformation. A study by Crandall *et al*. (1996) also found no relationship between intrusion magnitude and peak tibia loads, but claimed that tibia forces and moments were linked to the timing of the intrusion and other factors like knee bolster interaction.

Toepan intrusion can be characterized statically by post-impact deformation or dynamically using transducers mounted to the toepan during a crash. As evidenced by the lack of consistent correlations between static deformation and injury risk, the most accurate way to relate injury risk to intrusion parameters is by measuring the intrusion dynamically. Since accurate dynamic measurements of toepan deformation in vehicle crashes have been difficult to obtain, a sled system capable of producing various types of intrusion is an important element in discovering the relationship between intrusion parameters and injury risk.

Toepan intrusion systems for test sleds have been developed by a few organizations to examine the effects of toepan intrusion on occupant response. Crandall *et al.* (1996) developed a system capable of simulating translational intrusion. The intrusion simulator in their system consisted of separate footplates mounted to a translating carriage. Intrusion was powered by extracting energy from the sled's hydraulic decelerator, with the amount of translation being controlled in increments of 25 mm. Translational and rotational intrusion was recreated on a system described by Kallieris (1998). A honeycomb-covered impactor, which was fixed to the sled track, contacted the toepan at approximately 50 ms after impact and caused intrusion of 135 mm with 30 degrees of rotation. Håland *et al.* (1998) reported tests performed on a similar system, which was capable of producing varying amounts of intrusion based on honeycomb stiffness. The intrusion started at 32 ms after impact, and resulted in either 80 mm or 160 mm of translation with peak toepan accelerations of 140 g's and 70 g's, respectively. Another system capable of variable amounts of translation and rotation was designed and built by Thelen *et al.* (1998), and it is powered independently of the sled. A pneumatic impactor drives the intrusion system, which can be used in a static or dynamic setting. These sled-based intrusion systems have allowed researchers to prescribe an intrusion pulse and evaluate dummy and cadaver response, but there are currently only limited results in the literature.

Advancements in dummy technology have made it possible to more accurately measure injury risk in crash tests. Historically, production anthropomorphic test device (ATD) legs, such as the Hybrid III, have not been considered biofidelic from a response point of view (Welbourne and Shewchenko 1998). The recently developed Thor Lx appears to be a more human-like test device (Wheeler *et al.* 2000). It provides an Achilles tendon to simulate passive plantarflexion musculature, continuous ankle joint stops, more anatomically correct ankle joints, and a straight tibia shaft (Shams *et al.* 1999). In addition to a more biofidelic design, the Thor Lx comes with more standard instrumentation, which provides a more detailed account of crash behavior (Rudd *et al.* 1999). Since its design was held to strict biomechanical corridors, which were based on human volunteer and cadaver response, it serves as a better tool for crash testing in which biofidelic lower limb response is desired.

The combination of advanced dummy limbs and sled-based toepan intrusion systems gives researchers the ability to perform in-depth analyses of occupant responses to various intrusion parameters. This ability will also allow for the evaluation of injury countermeasure designs, without expensive vehicle tests from which intrusion parameters are difficult to quantify. One such countermeasure is the InCa, which is essentially an active padding which deploys in frontal crashes (Håland *et al.* 1998). The purpose of the InCa is to protect the feet, ankles and lower legs of front seat occupants in crashes with toepan intrusion.

This study provides a secondary evaluation of the InCa in crashes with toepan intrusion. The results from the tests will be used to determine whether or not the InCa provides adequate protection with intrusion, without increasing injury risk in non-intrusion situations. Additional tests of the InCa in a static setting helped to determine if the InCa increases risk to out-of-position occupants. Use of the Thor Lx advanced dummy lower extremity lends additional insight into the performance of the InCa.

METHOD – DYNAMIC TESTS

Frontal crash tests with toepan intrusion were simulated on a deceleration sled using separate decelerators for the toepan and the occupant compartment. The sled and intrusion deceleration profiles (Figures 1 and 2) were chosen based on full-scale vehicle tests. The buck (vehicle) crash pulse was prescribed using a hydraulic decelerator (VIA Systems 931-4000), and the intrusion pulse was achieved with a custom-built aluminum honeycomb decelerator. Peak intrusion accelerations were around 175 g's along the direction of sled travel, with approximately 80 g's measured normal to the toepan. This pulse produced 14 cm of translation.

Test Buck

The tests were performed in the driver-side seating position of a midsize vehicle test buck (Figure 3). Seat and knee bolster positions were adjusted to give the desired lower extremity positioning.

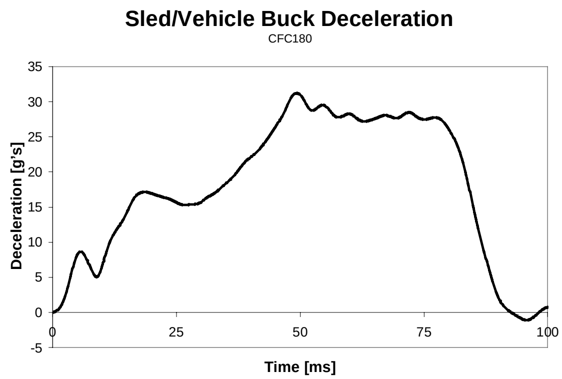

Figure 1. Sled pulse for dynamic tests

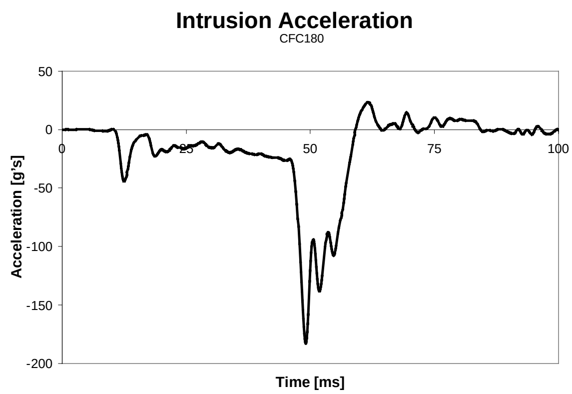

Figure 2. Intrusion pulse (global x-axis, along direction of travel) for dynamic tests.

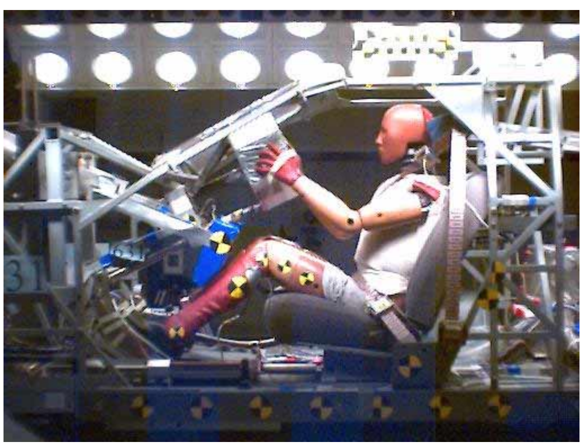

Figure 3. Buck setup with occupant and restraints

Intrusion Simulator

The toepan and floor were designed to displace relative to the occupant compartment. A toepan/floorpan assembly was fixed to a carriage, which rode along linear bearings mounted to the vehicle buck (Figure 4). During the sled crash pulse, the toepan experienced the same deceleration as the sled until a secondary decelerator was activated. This secondary decelerator stopped the intrusion carriage and toepan assembly independent of the sled once the pushrods contacted the decelerator pistons.

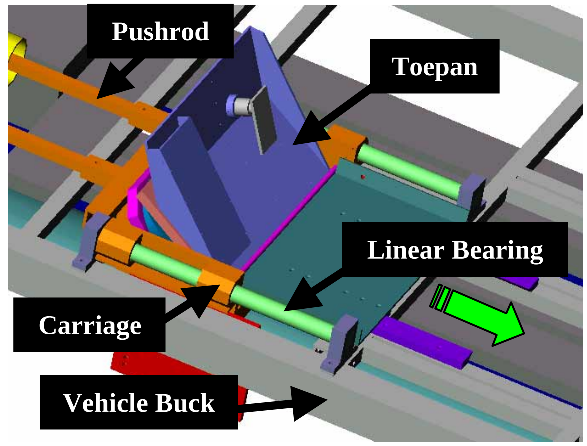

Figure 4. Sled buck mounted intrusion system.

The secondary decelerator consisted of telescoping cylinders mounted to the reaction mass, which were filled with aluminum honeycomb energy absorber. The honeycomb (Alcore DUR-5052-8.1-1/8-0.002-N-E) crush strength and area were tailored to provide the desired toepan deceleration levels. Spatial positioning of the secondary decelerator (Figure 5) relative to the primary sled decelerator determined the intrusion onset time and overall amount of intrusion.

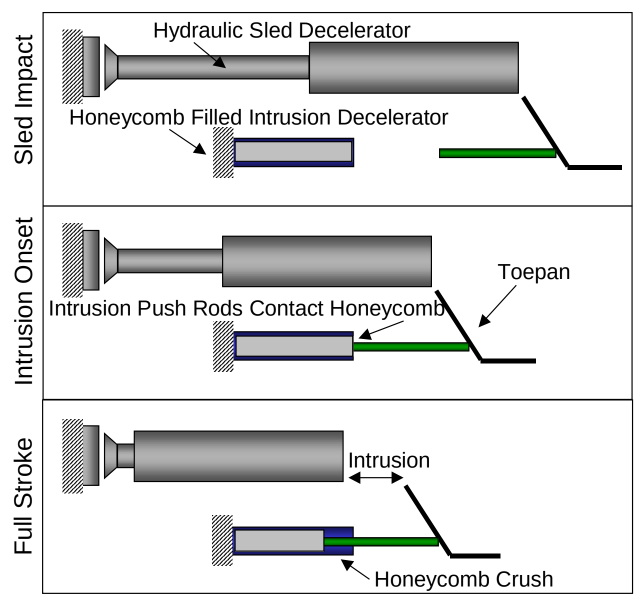

Figure 5. Sled and intrusion decelerator setup.

Occupant Restraints

Force limited and pretensioned belts were used to restrain the occupant in all tests. The buckle pretensioner was activated 9 ms after impact, and tightened the belt with a nominal force of 1.0 kN. Belt spool-out force was maintained at approximately 4.0 kN by the retractor. The belt restraint was supplemented by a simulated driver air bag, which consisted of a large block of DOW Ethafoam 220. The steering wheel was removed, and the foam block was fixed to a rigid plate in a plane perpendicular to the steering column. While serving simply as a restraint for the head, the block of foam was not intended to produce air bag-like responses for the upper body.

Instrument panel interaction with the lower extremities was achieved with the use of a knee bolster simulator. This adjustable system consisted of two piston and cylinder assemblies, each filled with energy absorbing aluminum honeycomb (crush force 310 kPa), mounted to the sled buck. The contact surface of the pistons was covered with a 52 mm thick contoured block of padding (DOW Ethafoam 400), with outer surfaces covered in a 3 mm thick polyethylene sheet.

Inflatable Carpet (InCa)

The Inflatable Carpet used in this testing is similar to that used in work by Håland *et al.* (1998). It inflates to a thickness of approximately 70 mm at the large central chamber and covers an area of about 450 x 350 mm (Figures 6 and 7). The InCa air bag is covered with a 4 mm thick sheet of acetal plastic, which is covered with the vehicle interior carpeting. Plastic tabs inserted through slots in the air bag fabric are used to hold the bag to the load distributor, and a piece of belt webbing is used to restrain the entire assembly to the toepan/floor. A hybrid gas generator (Autoflator H2010) was triggered 12 ms after impact to inflate the InCa to a pressure of about 150 kPa.

Instrumentation

Buck accelerations were measured with two uniaxial accelerometers mounted to the front of the sled (Entran EGC-500DS). The intrusion system was also instrumented with accelerometers; one on the toepan and one on the floor (Endevco 7264A). A string potentiometer was used to measure the linear translation of the toepan (SpaceAge 160-963). Restraint instrumentation included tension gauges (Eaton Lebow 3419-3.5k) on the lap, upper, and lower shoulder belt, and load cells (Sensotec D/7074-06) and accelerometers (Endevco 7264A) on the knee bolsters. A pressure transducer was connected to a pressure tap in the InCa (Kyowa PGM-5KC).

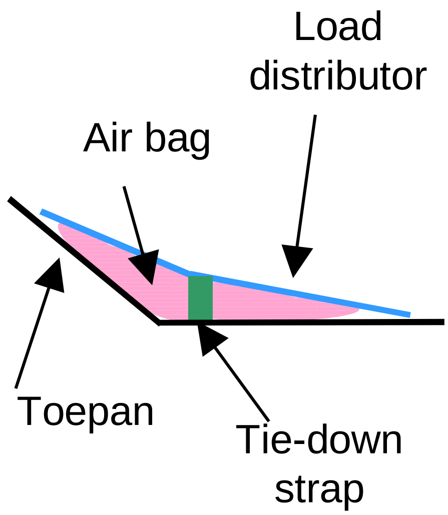

Figure 6. Lateral view of inflated InCa.

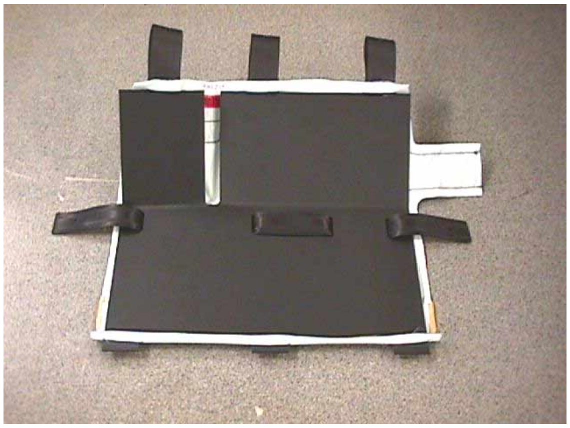

Figure 7. InCa with load distributor and strap.

A standard 50th percentile male Hybrid III dummy was used in this study. Triaxial accelerometer cubes (Endevco 7274A) were mounted at the head, chest and pelvis, and z-axis loads were measured from both femurs (GSE 112435). The left and right legs were different below the knee. A Hybrid III leg with 45° dorsiflexion soft joint stop with two-axis proximal (Denton 1583: Mx, My) and three-axis distal (Denton 1584: Fx, Fz, My) tibia load cells was mounted to the left knee. The right leg was a pre-production Thor Lx advanced dummy lower extremity. Thor Lx instrumentation included four-axis (Fx, Fz, Mx, My) load cells at the proximal (Denton 3115) and distal (Denton 2669) tibia, an Achilles tendon load cell (A.L.Design ALD-W-10), triaxial accelerometer cubes (Endevco

7267A) on the tibia and midfoot, and three ankle potentiometers (Contelec PD210-4B).

Sensor data were digitized at 10,000 Hz with a DSP TRAQ-P data acquisition system. High-speed digital video (1,000 frames/s) of the impact event was recorded using two Kodak Ektapro RO imagers and one Kodak Ektapro EM imager.

Foot Positioning

Two foot positions were examined in this series of tests. Tests were initially performed with both feet in contact with the toepan and/or pedal. The heels of both feet rested on the floor, and the feet were positioned without any initial inversion/eversion or internal/external rotation. Upon completion of the first series of tests with translational intrusion, a MADYMO model (Figure 8) was used to investigate alternate foot positions. It was desired to use a position that increased the injury risk without InCa, which was best achieved by creating a gap between the foot and toepan. The second set of tests was performed with the foot initially separated from the toepan by approximately 55 mm. This gap was maintained during sled launch by placing small paper spacers between the forefoot and toepan. Since the spacers sustained very little load, they had no effect during the impact event.

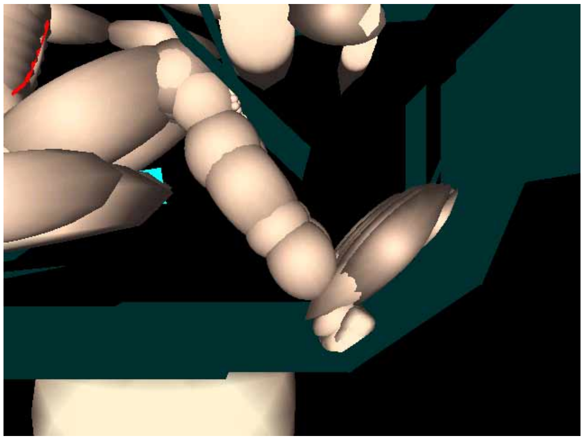

Figure 8. MADYMO model for positioning study.

Test Matrix

Tests were performed according to Table 1. The translational intrusion tests had a displacement of approximately 140 mm. Figure 9 shows the contact and clearance positions for the right foot placed on the pedal. The left foot position was similar to the right foot, except the forefoot rested on the footrest (in the contact position) or was lifted off with the spacer (in the clearance position).

Table 1.
Dynamic Test Matrix

Intrusion Type	InCa	Contact Position*	Clearance Position*
None	No	2 (22,23)	1 (35)
None	Yes	1 (34)	1 (36)
Translation	No	3 (18,19,20)	2 (37,39)
Translation	Yes	2 (31,33)	2 (38,40)

*Numbers in parenthesis refer to test numbers

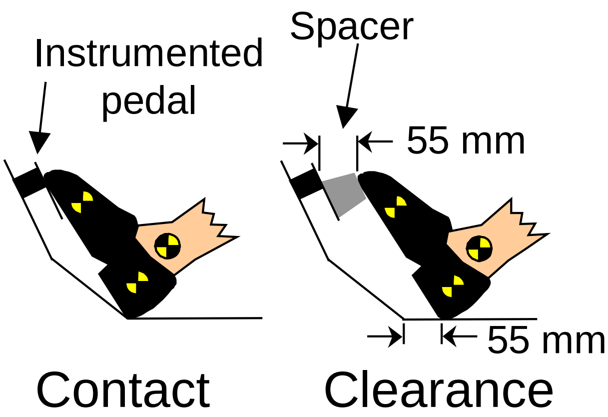

Figure 9. Right foot positions for dynamic tests.

METHOD – STATIC TESTS

Test Fixture

The static tests were performed in a modified vehicle buck, configured for four out-of-position occupant configurations. These positions were believed to be possible worst-case positions for accidental deployments. For two test cases, a modified instrumented brake pedal was used to measure foot reaction forces, and a simulated lower instrument panel was used to study entrapment effects.

Inflatable Carpet (InCa)

The Inflatable Carpet used in the static testing is the same as that used in the dynamic tests. The InCa was inflated in a manner similar to the dynamic tests, except two different hybrid gas generators were used. High pressure tests used an Autoflator H2010 inflator, and low pressure tests used an Autoflator H2003 inflator, producing peak bag pressures of 150 kPa and 100 kPa, respectively.

Instrumentation

Dummy instrumentation for the static tests included the lower extremity sensors described in the dynamic test section. Fixture instrumentation included a pressure transducer for the InCa and a six-axis pedal load cell. Test data were recorded as in the dynamic tests, and high-speed digital video was used in recording the events.

Foot Positioning

Position A had the forefoot on the brake pedal with the heel resting on the floor. The foot was internally rotated and inverted, in an attempt to investigate any roll propensity of the foot upon InCa deployment. Position B simulated an occupant in an extreme forward position, either sitting improperly or from pre-impact braking, with the knees against the lower instrument panel. The foot was placed on the floor, with the heel on the large central chamber of the air bag. Position C also represented an occupant in an extreme forward position, but without the instrument panel interaction. The forefoot was placed on the large central chamber of the air bag, so that deployment would force the foot into dorsiflexion. Position D simulated a foot trapped between the floor and pedal. The forefoot was placed on the toepan between the InCa and pedal, and the heel was placed on the floor. The large central chamber of the air bag was located at the midfoot. Figure 10 shows the positions.

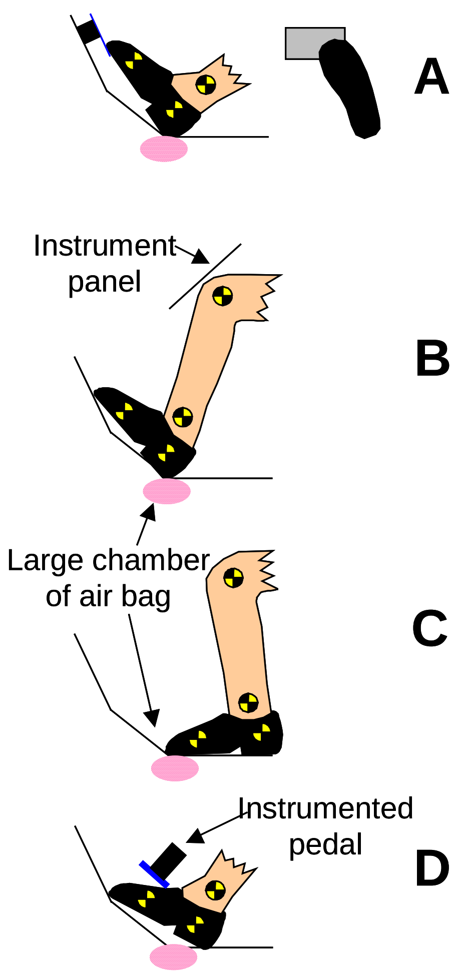

Figure 10. Right foot positions for static tests.

Test Matrix

Two static InCa deployments were performed with each inflator type for each position. Table 2 shows the sequence of tests.

Table 2.
Static Test Matrix

Test Number	Position	InCa Inflator
3	C	H2010-High Pressure
4	C	H2010-High Pressure
5	C	H2003-Low Pressure
6	C	H2003-Low Pressure
7	A	H2010-High Pressure
8	A	H2010-High Pressure
9	A	H2003-Low Pressure
11	A	H2003-Low Pressure
12	D	H2003-Low Pressure
13	D	H2003-Low Pressure
14	D	H2010-High Pressure
15	D	H2010-High Pressure
16	B	H2003-Low Pressure
17	B	H2003-Low Pressure
18	B	H2010-High Pressure
19	B	H2010-High Pressure

RESULTS – DYNAMIC TESTS

In tests with toepan intrusion, the InCa reduced foot accelerations, tibia axial load, distal tibia index and ankle dorsiflexion. The effect of the InCa in the non-intrusion tests was not as pronounced. In some cases, the InCa actually increased the acceleration or force without intrusion.

The midfoot acceleration in the contact tests (Figure 11) was much higher in the intrusion cases than in the non-intrusion cases. The onset of intrusion and the presence of InCa was not a factor in the clearance position, since the inertial slap of the forefoot on the pedal happened before intrusion began. Because midfoot acceleration was also influenced by foot contact with the pedal (which was not covered by InCa), there may not be reductions in foot accelerations with the InCa. Foot accelerations in the clearance tests (Figure 12) were more sensitive to initial positioning, which is believed to be the cause for the increased variability in peak values.

Thor Lx (right leg) distal tibia axial loads (Figures 13 and 14), which include the superimposed compression from the passive musculature in the Thor Lx, increased by more than a factor of two in the presence of intrusion without InCa. When InCa was used, the loads were reduced slightly in the contact position and more noticeably in the clearance position. The difference between non-intrusion tests with and without InCa is negligible for either position.

The Tibia Index (Figures 15 and 16), which is a combination of axial load and bending moment, followed the same trend as the tibia axial loads. The Thor Lx Tibia Index is based on human data, and is calculated using different critical values than the Hybrid III. The Tibia Index critical values are described in the Discussion section.

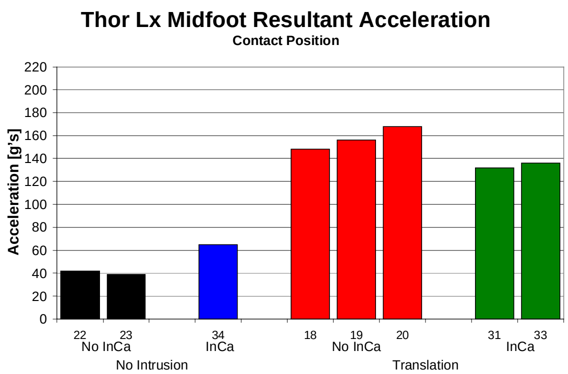

Figure 11. Contact position right midfoot acceleration.

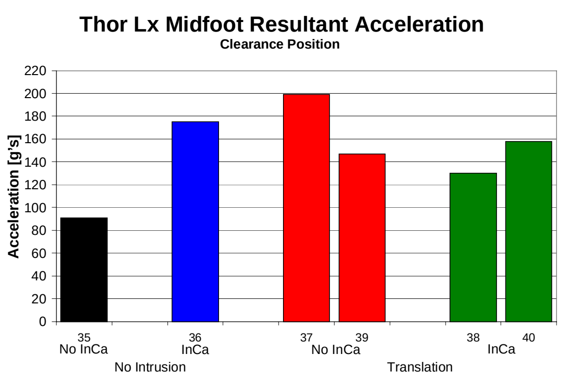

Figure 12. Clearance position right midfoot acceleration.

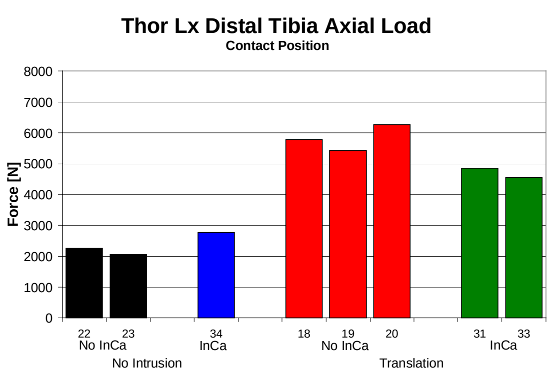

Figure 13. Contact position right tibia load.

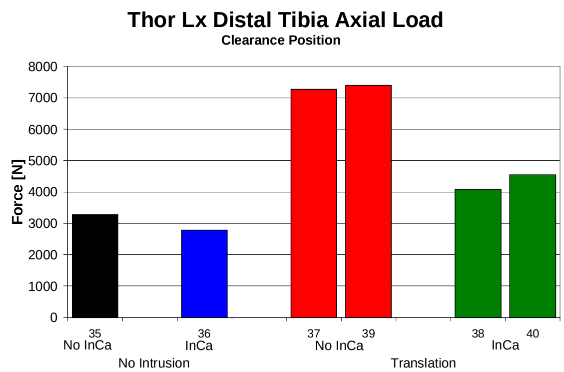

Figure 14. Clearance position right tibia load.

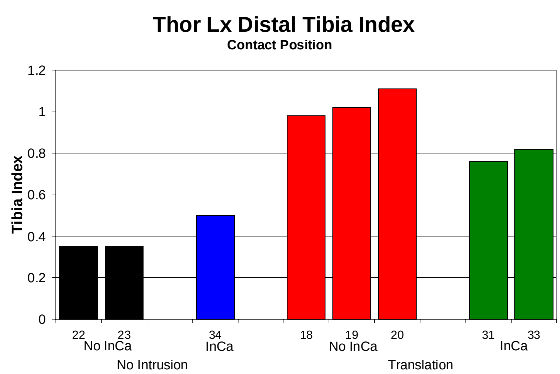

Figure 15. Contact position right Tibia Index.

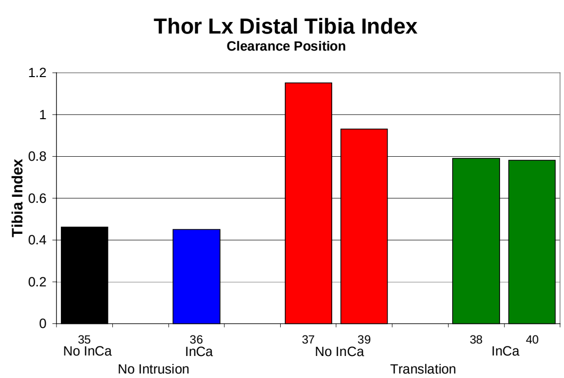

Figure 16. Clearance position right Tibia Index.

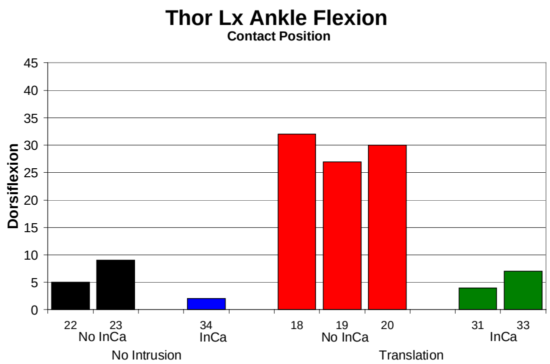

Figure 17. Contact position right ankle flexion.

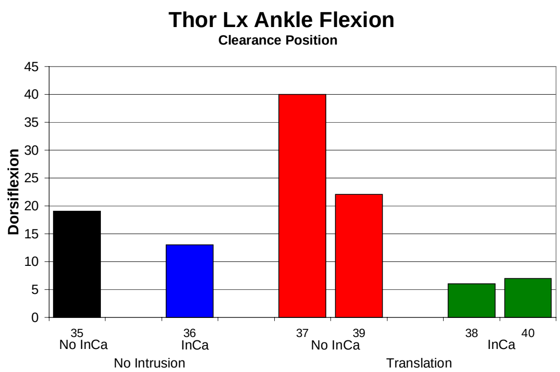

Figure 18. Clearance position right ankle flexion.

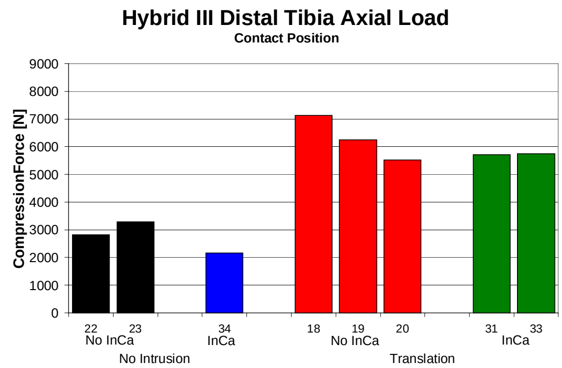

Figure 19. Contact position left tibia load.

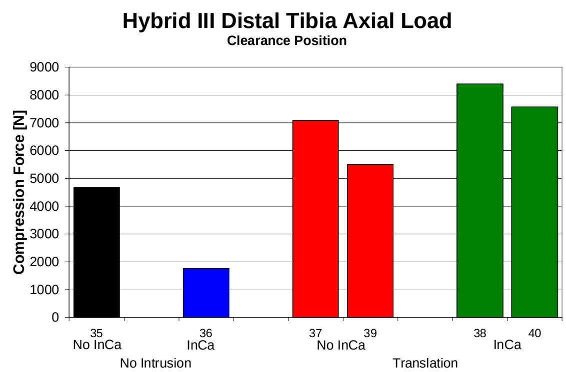

Figure 20. Clearance position left tibia load.

The ability to directly measure the flexion angle (Figures 17 and 18) in the Thor Lx allows for the evaluation of potential ankle injury risk. Because of the heel-lifting action of the InCa, the overall amount of dorsiflexion experienced in tests with InCa was greatly reduced in the intrusion tests. Again, the effect was not as pronounced in the non-intrusion tests, but there were no potential harmful effects.

Hybrid III (left leg) distal tibia axial loads (Figures 19 and 20) were higher for intrusion tests, but did not typically show significant reductions when InCa was used. In some cases, the axial load was increased in tests with InCa.

RESULTS – STATIC TESTS

Illustrative sensor time-history curves are presented for the four positions with the high pressure inflator; all measured from the Thor Lx dummy lower extremity. Midfoot resultant accelerations (Figure 21) were greatest in Position D, with the foot under the pedal. The simulated entrapment (Position B) produced the largest axial loads, with other positions producing very minor forces (Figure 22). Ankle rotations (Figures 23 and 24) were small, even in the cases designed to produce excessive rotations (Position A and C). Pedal forces are only reported for position D, and the resultant is shown in Figure 25, which corresponds to the compressive load on the forefoot and midfoot.

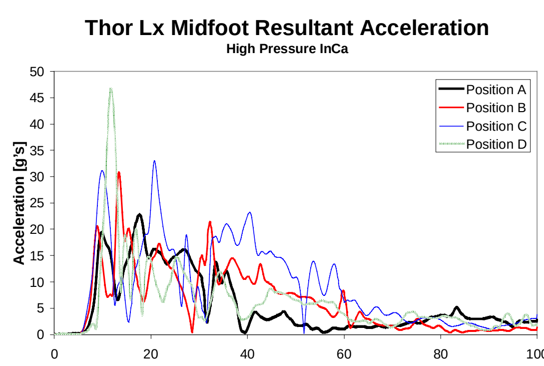

Figure 21. Static test right midfoot acceleration.

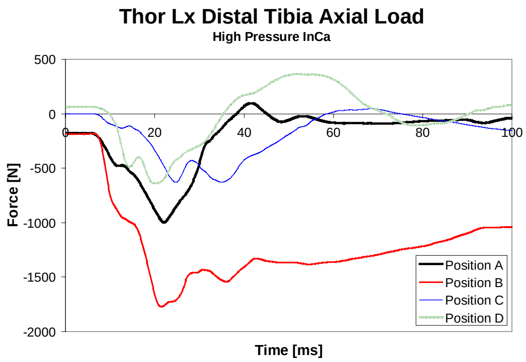

Figure 22. Static test right tibia load.

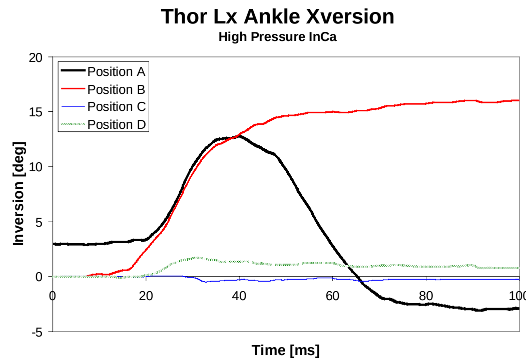

Figure 24. Static test ankle xversion.

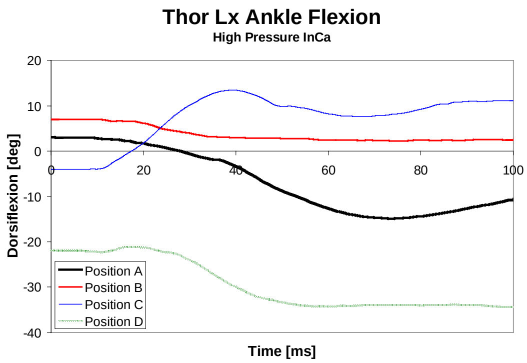

Figure 23. Static test right ankle flexion.

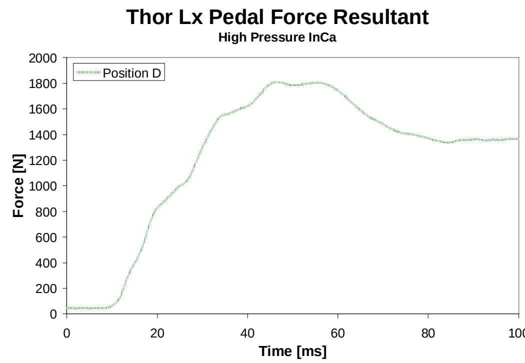

Figure 25. Static test pedal load.

DISCUSSION

Toepan pulses found in real-world crashes are likely to cover a broad range of acceleration levels, deformation amounts and onset times. To recreate every possible toepan intrusion scenario in the laboratory would require a significant amount of time and effort. The tests presented in this paper were performed with only one toepan intrusion pulse, but they do offer insight into the effects of toepan intrusion on lower limb response.

Given the same vehicle or sled pulse, the response of the lower limbs should be identical prior to the onset of toepan intrusion when comparing an intrusion test to a non-intrusion test (Figure 26). As the sled begins to decelerate, the occupant will continue moving forward at the initial speed until restraints or contact with vehicle structures begins to decelerate the occupant. This is the case with the legs, which begin to experience inertial loading approximately 25 ms after impact (i.e., after carpet and heel compression in contact tests). In a non-intrusion test, the knee bolsters eventually pick up a significant amount of inertial load, which causes the tibia load to decrease (at approximately 50 ms). Intrusion onset occurs at 46 ms, which causes a significant rise in tibia load due to the acceleration of tibia mass (peaks at 56 ms). The tibia rebounds slightly in non-intrusion at 75 ms, and also experiences a rebound load in the intrusion tests at approximately 95 ms. As the knee is essentially fixed fore-aft against the knee bolster, the rearward motion of the toepan causes the foot and tibia to move in such a way as to force the ankle into dorsiflexion. Residual tibia axial load (between 70 ms and 125 ms) in the intrusion test is due to the superimposed compression from the Achilles tension in the Thor Lx.

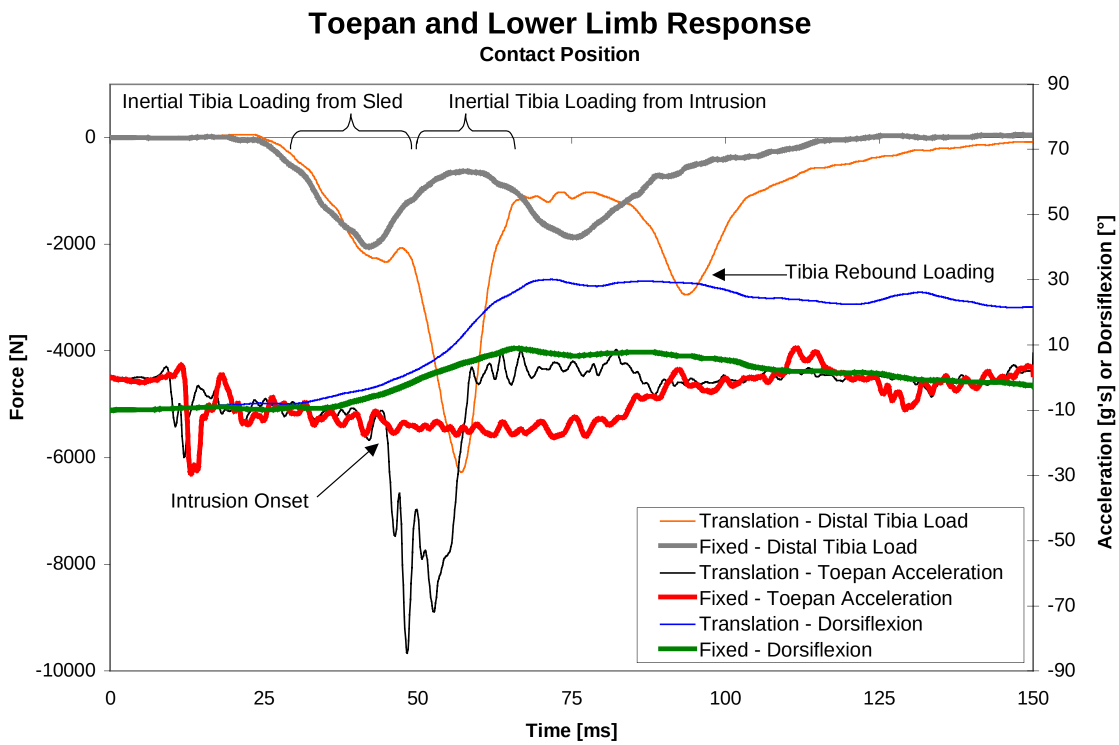

Figure 26. Time-history of toepan acceleration and lower limb response for fixed toepan and translational intrusion.

Toepan intrusion introduces many factors which complicate occupant kinematics and add potential injury risks. Depending on the timing of the intrusion event and occupant positioning relative to the knee bolster, interaction of the lower limbs with the lower instrument panel can either increase or decrease the injury risk. As the occupant moves forward during the crash, the knees come closer to, and eventually compress into the knee bolster. If the onset of intrusion occurs before there is significant "pocketing" of the knee in the bolster, the knees may just slide along the lower instrument panel. A later onset may allow sufficient force build-up between the knee and bolster, which would lead to an entrapment situation. If the force required to overcome the friction is very high, the intruding toepan can cause injurious axial loads to develop in the leg. Sufficient padding and altered kinematics from the InCa may alleviate the buildup of tibia axial load, but such effects would require more in-depth study with a multi-variable test matrix.

The graphs of knee bolster and tibia axial load (Figure 27) show a higher magnitude and longer duration knee bolster load for the non-intrusion case. After the initial inertial loading from the onset of intrusion, the knee and tibia slide along the bolster before any pocketing starts, which results in low sustained tibia axial loads. In tests with the lifting action of the InCa, the bolster load is even lower. The bolster load drops off since the intruding toepan is forcing the knee in a vertical direction. In the non-intrusion case, the knee bolster load remains high, because the knee remains in contact with the bolster, transmitting the inertial loads from the pelvis and femurs. This interaction is highly dependent on timing, occupant positioning, bolster friction and vehicle/toepan pulse.

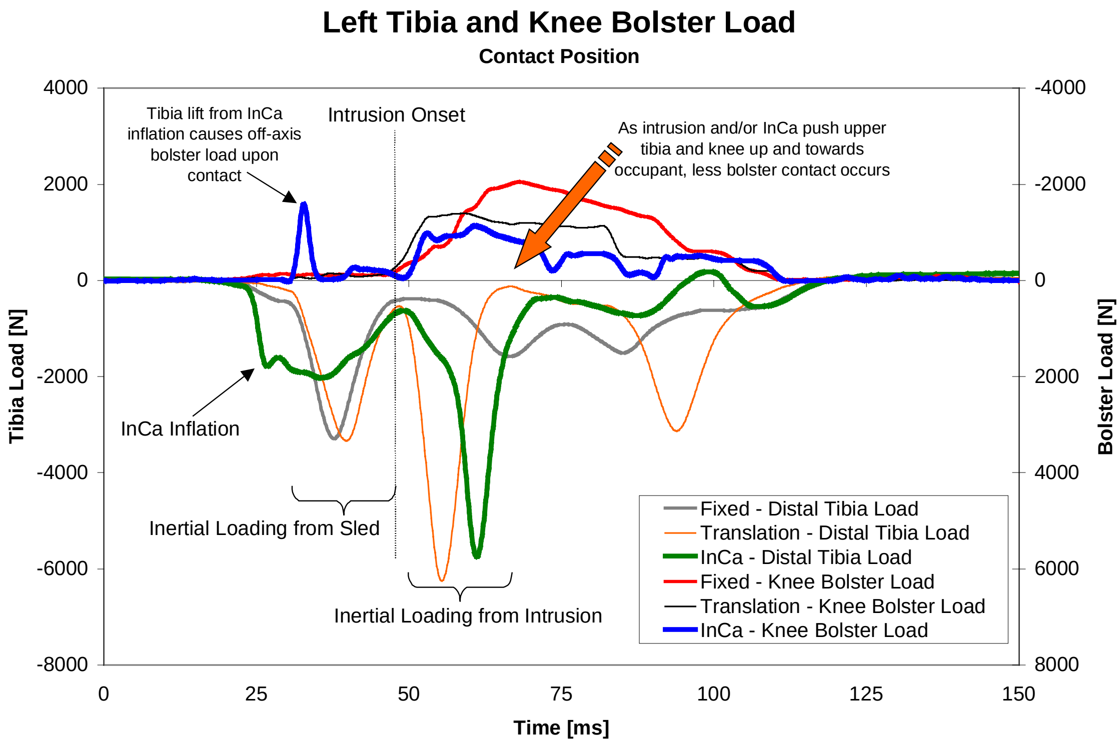

Figure 27. Time-history of left tibia and knee bolster loads for fixed toepan and translational intrusion with and without InCa. The curves labeled "InCa" are with translational intrusion.

The dynamic testing presented in this paper does not include results from all of the planned tests. A series of tests with combined translation and rotation of the toepan were conducted too late to be included in this publication. The design of the air bag used in this study was optimized for use in settings with toepan rotation in addition to translation. Positioning of the large chamber of the InCa was such that excessive dorsiflexion was minimized more so than axial loading to the tibia. The effectiveness of the InCa in reducing dorsiflexion is clearly exhibited in both foot positions, but there is less of an effect on tibia axial load. InCa-induced kinematics caused the left heel to lift and contact the toepan at a thinner cross-section of the air bag as shown in Figure 28 through 30 (the foot and toepan have been highlighted).

The first photo (Figure 28) is from a test in the contact position without the InCa at 46 ms, just before the onset of intrusion. Figure 29 is also at 46 ms, but is from a test with the InCa. As the InCa inflates, the heel is lifted, which moves the forefoot higher on the toepan to a thinner part of the InCa. After intrusion starts, the translation only aspect causes the heel and forefoot to slide up the toepan, such that the heel also contacts at a thinner section of the InCa (Figure 30, at 60 ms), which results in less mitigation of the transmitted load. If toepan rotation were superimposed, the foot would not have a tendency to slide up the toepan. Moving the large central chamber of the InCa farther forward and up the toepan would be more suitable in a translation only situation, since there would be less heel lift and more thickness of air bag for compression once intrusion initiates inertial loading of the tibia. Knee bolster design also influences this phenomenon. If the lower instrument panel can restrain the leg from lifting, this effect could be eliminated.

Slightly different foot positioning for the right leg resulted in less sliding action, and the presence of the pedal helped to keep the heel on the large chamber of the InCa. Figure 31 shows the right (Thor Lx) foot at 85 ms without and with an inflated InCa. The forefoot remains in contact with the pedal after InCa deployment even as the heel is lifted and the foot is forced into plantarflexion. Tibia axial load reduction was more noticeable on the right leg, since the heel remained in contact with the large portion of the airbag during the inertial loading.

Since the InCa gas generator was fired at 12 ms after impact, and the expanding gases must travel through a two meter long hose before filling the bag, the InCa does not begin to affect the lower extremities until about 25 ms. As the InCa fills, it

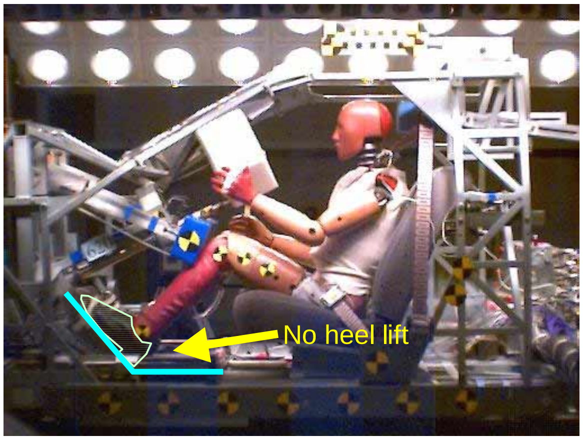

Figure 28. No InCa test at 46 ms after impact. The heel rests on the floor and the forefoot is on the toepan. Toepan intrusion begins at 47 ms.

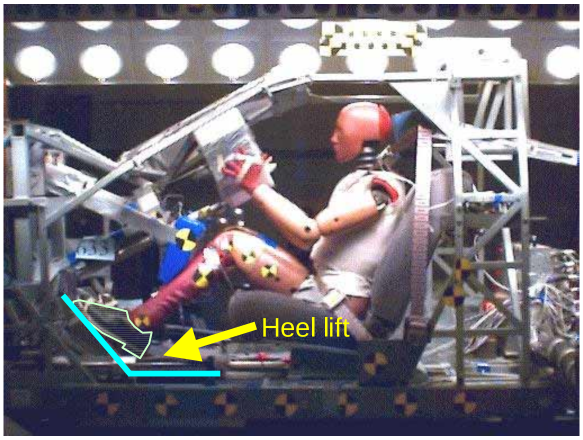

Figure 29. InCa test at 46 ms after impact. The heel is lifted by the large central chamber of the air bag, and the forefoot slides up the toepan.

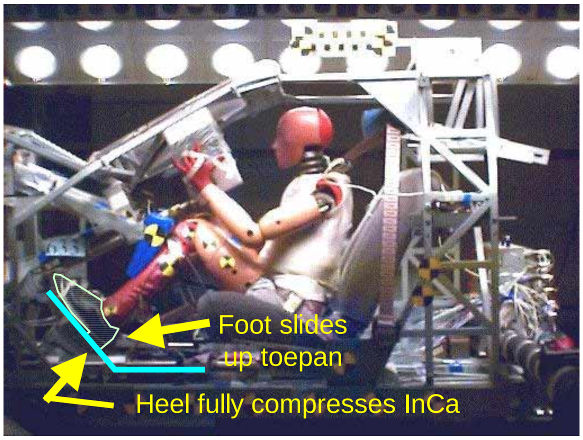

Figure 30. InCa test at 60 ms after impact. The toepan has translated approximately 60 mm. As the toepan translates, the forefoot slides along the carpet and up the sloped toepan until the heel presses through the thin section of the air bag.

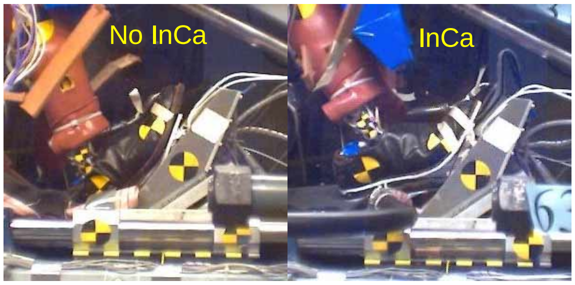

Figure 31. Right foot at 85 ms with and without InCa.

accelerates the feet and legs up and towards the occupant while the legs are beginning to decelerate as a result of sled deceleration. This superposition of inertial loading causes a faster rise time for distal tibia axial load (Figure 32) between 25 ms and 40 ms. Once intrusion starts, the tibia axial load increases again from the inertial loading, with or without the InCa (50 ms to 58 ms). The padding effect of the InCa helps minimize the tibia load, although the onset rates of tibia load are similar with or without InCa. The InCa was not vented, so therefore, it did not provide much ride-down effect for the lower limb during the toepan translation. Again, the InCa prototype used for this study was optimized for translation and rotation, where it is desirable to maintain heel lift throughout the entire intrusion event to minimize dorsiflexion. Faster venting of the bag would lower the tibia load onset rate, which would also result in even lower peak tibia loads under certain circumstances. The right ankle was initially in ten degrees of plantarflexion, which was increased to about 14 degrees after InCa inflation. The ankle rotated through about 40 degrees to reach a peak dorsiflexion angle of 30 degrees of dorsiflexion without InCa, but only rotated about 14 degrees to reach a peak of 4 degrees of dorsiflexion with InCa. This significant reduction in rotation may decrease injury risk in some circumstances.

The presence of the brake pedal affected the results in the clearance tests by causing higher midfoot accelerations in non-intrusion cases with InCa (Figure 33). Since the Thor Lx midfoot accelerometer was mounted between the ankle and toe, it was more sensitive to the contact of the foot with the pedal (which was not covered by InCa). In the clearance tests, the right foot was lifted by the InCa such that the middle of the foot contacted the pedal resulting in a large recorded acceleration. The loads transmitted to the tibia were not increased by this effect, since the heel was cushioned by the InCa. A deformable brake pedal would likely help to reduce the brake pedal influence both with and without the InCa.

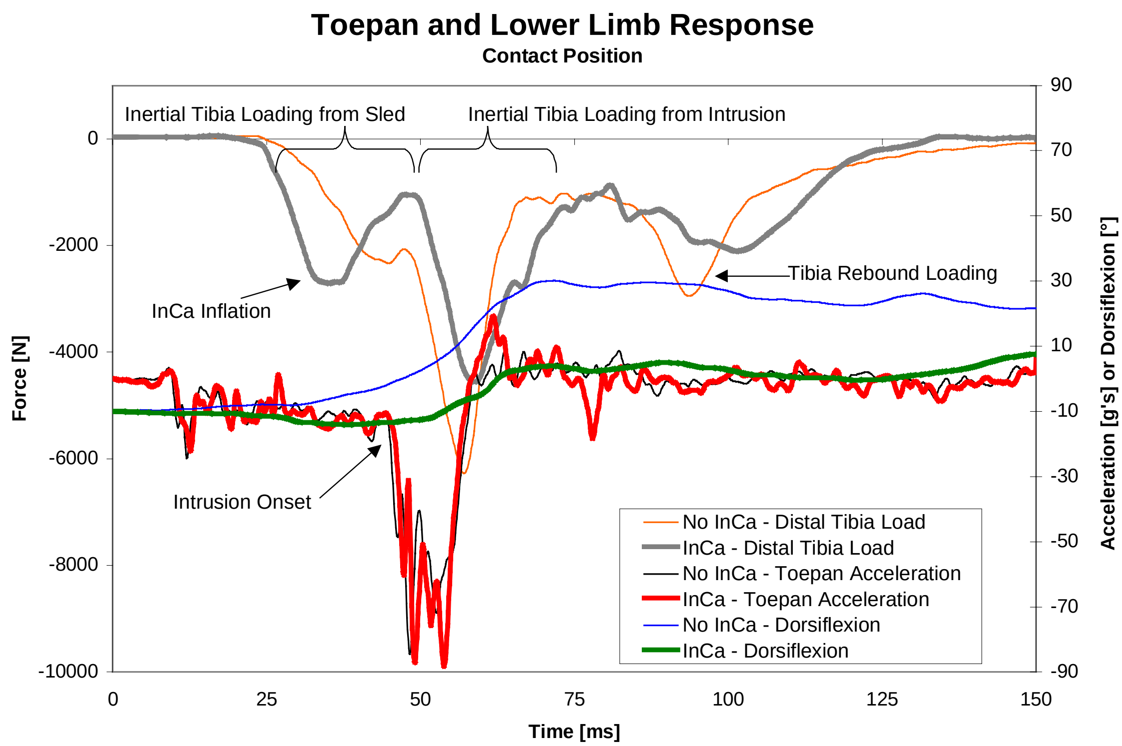

Figure 32. Time-history of toepan acceleration and lower limb response for translational intrusion with and without InCa.

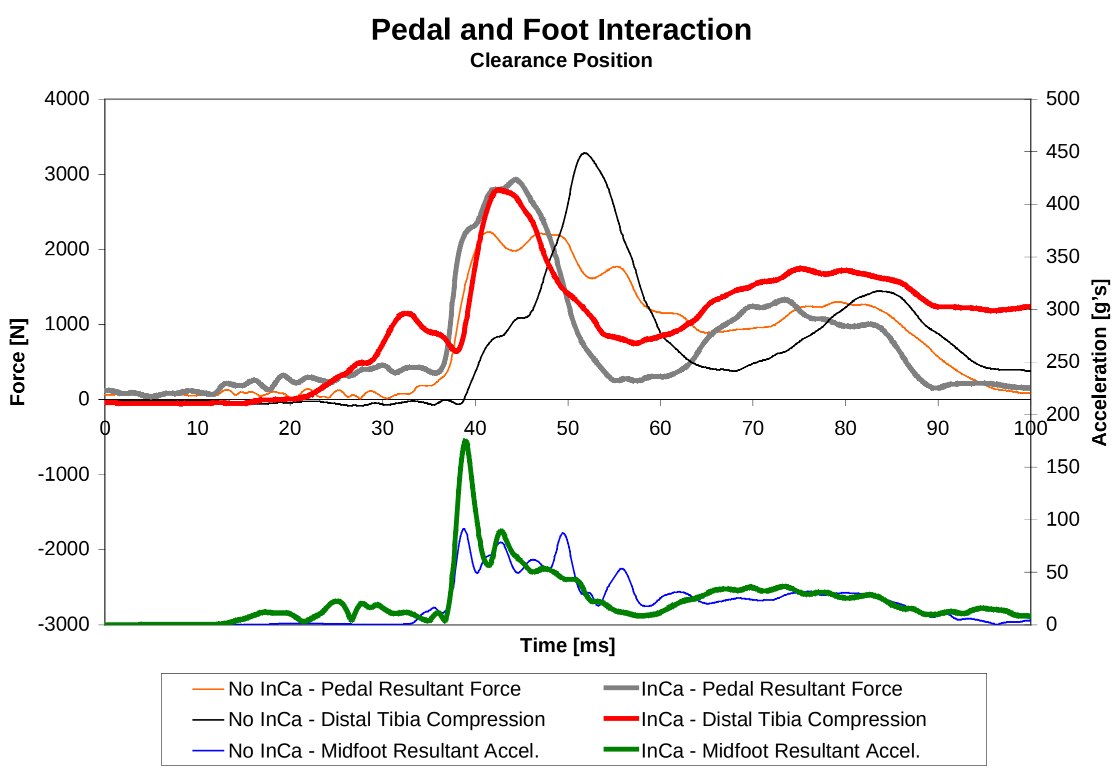

Figure 33. Non-intrusion clearance test pedal and foot interaction with and without InCa.

Static testing of the InCa produced no results which brought into question the safety of the device during inadvertent deployments. While the entire range of out-of-position configurations would potentially include more vulnerable positions, none of the worst-case scenarios studied here should raise any concern. One factor, which could significantly affect the results from this type of testing, is muscle tension in the lower limbs. Human limb response could differ in the presence of muscle tension.

One unique aspect of this testing was the use of the Thor Lx advanced lower extremity. Because of slight differences in the position of the left versus right leg, a direct comparison between Thor Lx and Hybrid III legs cannot be made. The additional instrumentation in the Thor Lx was useful in the interpretation of the results, and the design and construction proved to be durable. The only failure was a bad Mx channel in the upper tibia load cell.

Assuming biofidelic response from the Thor Lx, injury limits from human data in the literature can be applied to the responses measured in this testing. A reasonable approach is to compare the measured values to the ranges of values considered injurious from static and dynamic human cadaver testing. While providing no absolute answers on the ability of the InCa to reduce response values below legislative limits, evaluation of projected injury thresholds based on existing data proves that the InCa brings dummy response values to more tolerable levels in dynamic tests.

An analysis of tibia axial load tolerances in the literature indicates fracture forces range from around 5.3 kN to 8.7 kN. Kitagawa *et al.* (1998) found average fracture forces to be 7293 N for Pilon fractures, and 8115 N for calcaneus fractures. Yoganandan *et al.* (1996) impacted limbs and found the range of fracture forces to be from 6.9 kN to 8.7 kN. More recent work by Funk *et al.* (2001) produced a survivor function which predicts a 5.3 kN reference value for a 65 year old 50th percentile male with no Achilles tension. The same survivor function predicts a 7.3 kN value for a 45 year old. Using the lowest value in the range (5.3 kN) as a reference, the InCa reduced the tibia load below the tolerance level for both positions (Figure 13 and 14).

The Tibia Index calculation used for the Thor Lx was derived from the discussion by Crandall *et al.* (1999). The critical force and moment values represent those of human legs, and a threshold value of 1.0 can be assumed for this study. Tibia Indices from tests with the InCa were below 1.0, while tests without InCa produced Tibia Indices near or above 1.0 (Figures 15 and 16).

Human tests of the ankle in dorsiflexion have shown a range of motion from 30 degrees to 45 degrees before injury occurs. Petit *et al.* (1996) performed static rotation tests, and found 45 degrees of dorsiflexion to be the limit for occurrence of injury. Dynamic tests performed by Portier *et al.* (1997) found the limit to be closer to 30 degrees. Thor Lx dorsiflexion angles in intrusion tests without InCa approached and exceeded the 30 degree level, but were greatly reduced with InCa (Figures 17 and 18). The static InCa deployments did not produce dorsiflexion angles near the injurious level (Figure 23).

Inversion and eversion were not sources of concern in the dynamic tests, but were considered to be potentially harmful in the static tests. Parenteau *et al.* (1998) found the rotational tolerance in inversion and eversion to be around 34 degrees and 32 degrees, respectively. Applying this level of rotation as an evaluation criteria would indicate a low risk of injury in the static InCa deployments, with a maximum inversion of around 15 degrees (Figure 24).

CONCLUSIONS

The evaluation of intrusion and Inflatable Carpet effectiveness in this study revealed many important conclusions. The tests performed on the new toepan intrusion system proved to be successful, in that a repeatable intrusion pulse was delivered test after test. Intrusion alone significantly influenced the loads transmitted to the occupant's lower extremities, and under certain conditions, the Inflatable Carpet was able to lower the tibia loads and minimize ankle rotations.

- Intrusion alone increased foot accelerations by 288%, tibia axial load by 170%, lower tibia index by 196% and maximum dorsiflexion angle by 324% in tests without InCa.
- Inclusion of InCa in intrusion tests lowered the foot accelerations about 16%, lower tibia index by 24% and dorsiflexion angle by about 80% with either initial position. Tibia axial load was lowered 19% in the contact position and 41% in the clearance position with the use of InCa.
- An initial gap between the foot and toepan causes inertial slap of the feet on the toepan and pedal. This resulted in a 26% increase in distal tibia axial load, and a 10% increase in foot acceleration.
- The performance of the InCa is dependent upon the type of intrusion, and the InCa should be tuned properly to account for all types of intrusion

- Proper knee bolster design is crucial to InCa performance, and inferior design properties of the InCa and/or knee bolster may allow the foot to kick up upon deployment resulting in different toepan interaction. The foot can become separated from the InCa, which makes the InCa less effective.
- The heel lifting action of the InCa helps to prevent excessive dorsiflexion which may occur during toepan intrusion.
- Thor Lx responses in intrusion tests without InCa were near or above injurious levels based on human data in the literature; the use of InCa brought these responses down to lower risk levels
- The Thor Lx performed with repeatable results, and was durable during the series of intrusion tests.

Although the InCa reduced loads in some cases, maximizing its effectiveness requires careful tuning. Knee bolster interaction must be considered in implementation of the InCa, since controlling leg kinematics is crucial to effective InCa protection. The InCa has the potential to reduce lower limb injury risk from footwell intrusion, however, further design work should be considered to optimize the InCa to be capable of handling translational as well as combined translational and rotational toepan motion.

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