SLED TESTS WITH TOEPAN INTRUSION USING POST-MORTEM HUMAN SURROGATES AND THE HYBRID III DUMMY

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ABSTRACT

A modified sled system was used to produce toepan intrusion characteristic of frontal offset crashes. Toepan intrusion was translational and varied between 0 cm and 22 cm. The buck was configured as a mid-size vehicle with the occupant seated in the driver position. The Hybrid III dummy and post-mortem human subject occupants were restrained by three-point belts for all tests and driver airbags for some. Lower extremity loads were recorded by load cells mounted on the toepan and implanted in the tibias. Post-test radiographs of the subject lower extremities were used to identify skeletal injuries while detailed necropsies were performed to detect soft tissue injuries. The lower limb response and injuries were compared for varying magnitudes of toepan intrusion. The results indicate that the presence of toepan intrusion may increase the likelihood of lower limb injury but the timing and magnitude of the intrusion are also determining factors.

REVIEWS OF ACCIDENT DATA base cases (Morgan, 1991; Crandall, 1995a; Thomas, 1995) and computer simulations of crashes (Henson, 1983; Pilkey, 1994) have shown that this structural deformation of the occupant compartment, frequently referred to as intrusion, greatly increases the severity of the impact response and the risk of injury for the occupant. Although current vehicle safety standards only require full frontal vehicle collisions against rigid barriers, offset frontal testing is currently being evaluated by the National Highway Transportation Safety Administration (NHTSA) (Hollowell, 1996), automobile manufacturers (Kallina, 1995), foreign vehicle testing organizations (Grosch, 1989; Planath-Skogsmo, 1994), and independent testing facilities (Lund, 1995). For research purposes, incorporating the characteristics of structural intrusion into the sled test environment offers several advantages over full-vehicle crash tests: less expensive, improved repeatability, and increased control of test parameters and conditions. This paper presents the results of a parametric study of toepan intrusion and the associated lower extremity response using a sled system with intruding toepan structure.

EQUIPMENT

The test sled (Via Systems Model 713) at the University of Virginia's Automobile Safety Laboratory was modified to reproduce the structural intrusion of the vehicle during frontal offset impacts (Crandall, 1995c; Bass, 1995). The system uses energy from the sled's hydraulic decelerator (Via Systems Model 931-4000) to power pistons that displace structural components of the buck. The test fixture, or "buck", utilized in this test series was an approximation of the front seating area of the passenger compartment of a 1993 model year Ford Taurus, a configuration deemed typical of current automotive technology in terms of the spatial relationship between the occupant and the passenger compartment, restraint design, and occupant response during the crash event.

The physical arrangement of the intrusion simulator is shown in side view in Figure 1 and in oblique view in Figure 2. The simulator consists of a toepan carriage with separate footrests for the left and right feet. This carriage travels in translation in the sled x-axis on two rods mounted to the test. The limit of travel of the toepan carriage is 22.9 cm from the reference Taurus footwell location. The rear mounting position of the hydraulic cylinder may be adjusted to limit total toepan travel in increments of 2.5 cm.

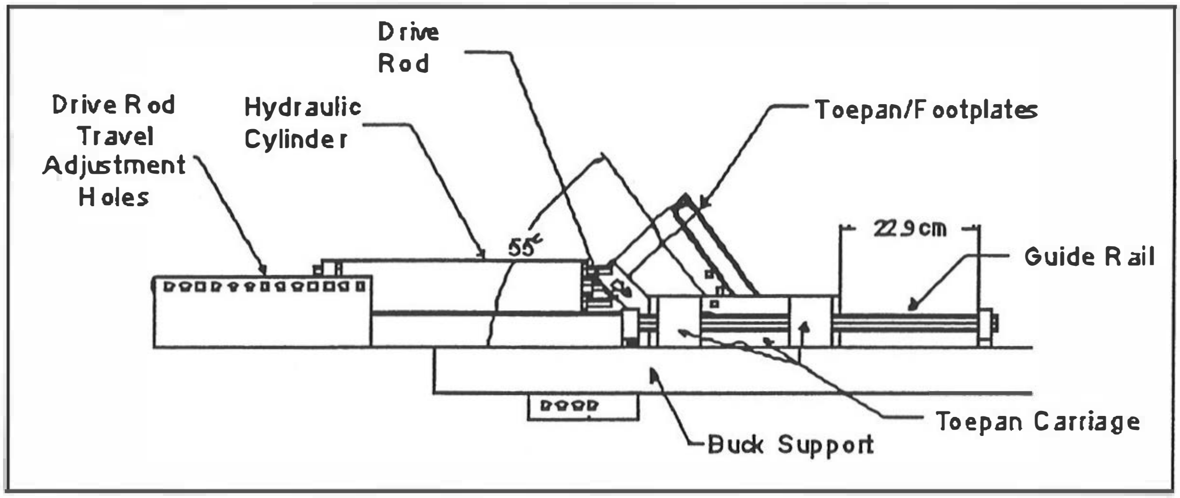

Figure 1: Intrusion Simulation Mechanism - Side View

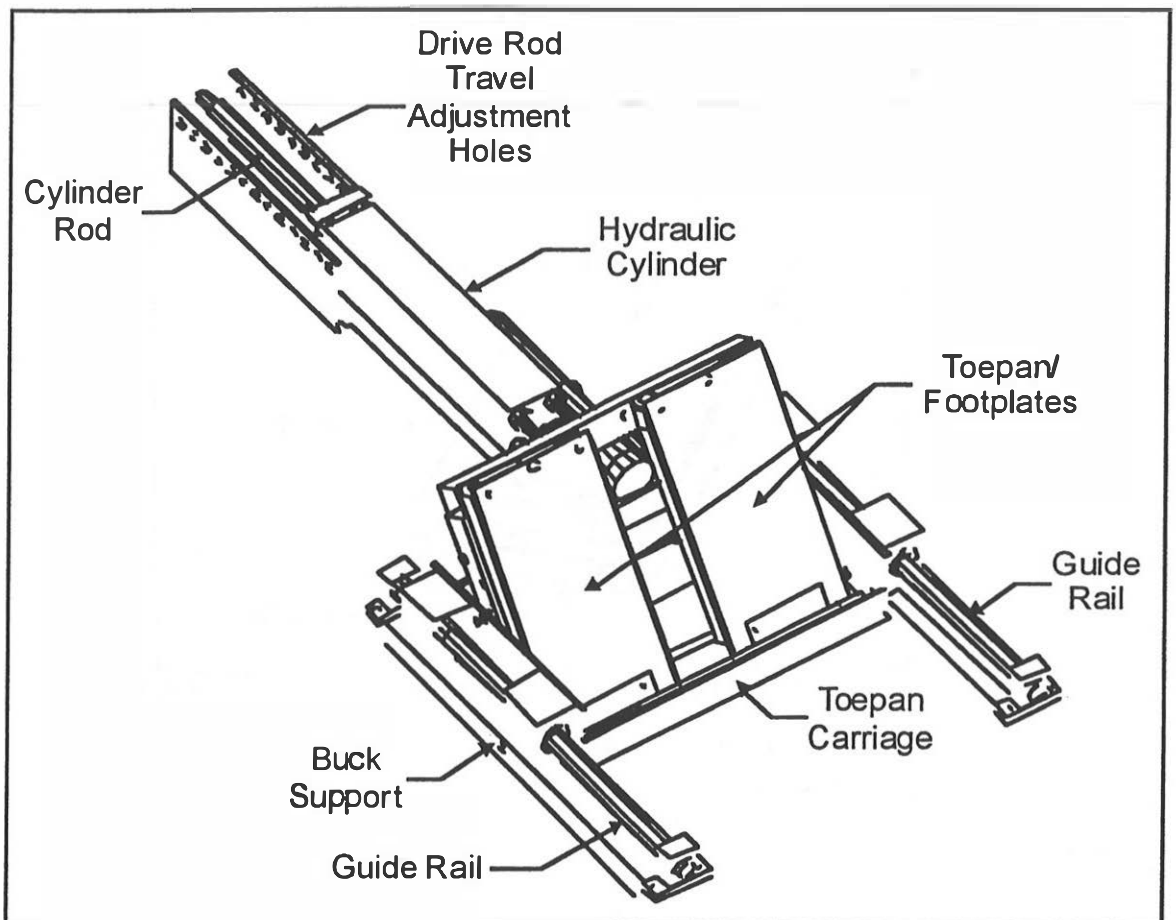

Figure 2: Intrusion Simulation Mechanism - Oblique View

The toepan carriage is instrumented with footplates mounted on the toepan carriage at 55 degrees from the horizontal, consistent with the Ford Taurus driver-side foot-rest. Each footplate consists of a rectangular unit, approximately 18 cm by 36 cm and 3.5 cm thick, mounted on the angled portion of the crash simulator toepan. The footplates are located so that each of the occupant's feet, when correctly positioned, is approximately centered on a footplate. A small horizontal platform supports each heel. Each footplate contains a load cell at each corner and a single miniature accelerometer, with a damped mounting, at the center of the bottom surface (Figure 3). The active axis of the footplate, perpendicular to the top surface, is defined as the local Z-axis of the device. Accelerometers are mounted on the rear center of the plate to assist in mass compensation of the measured forces.

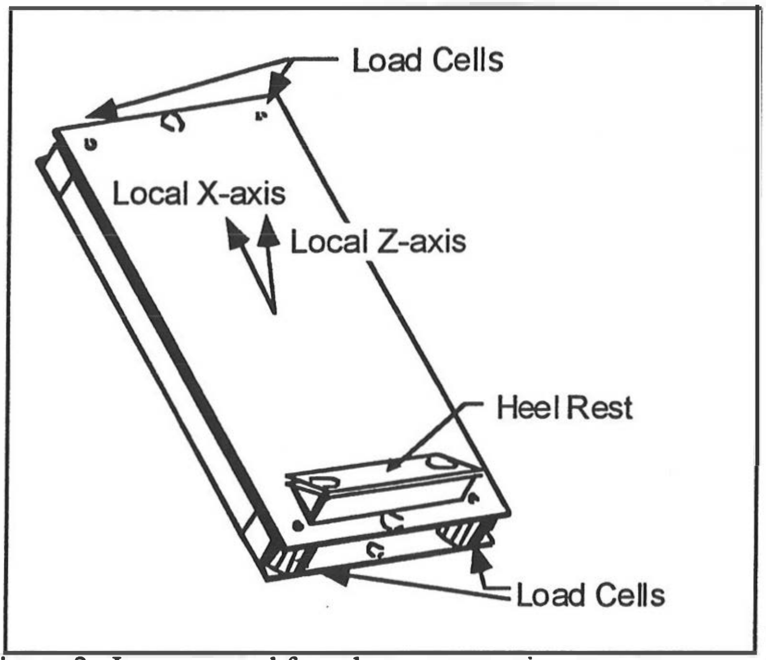

Figure 3. Instrumented footplate representing toepan structure

An adjustable knee bolster device was used to simulate the energy-absorbing characteristics of production knee bolster/dash assemblies while allowing a range of adjustment of position, angle, and energy-absorbing capability along with the ability to measure the forces involved. It consists of two piston and cylinder assemblies, one for each knee, mounted to the sled buck in the fire wall area. Each cylinder contains a column of aluminum honeycomb (Hexcel Corporation ACG -3/4-310 kPa) which functions as the energy absorbing medium. The contact surface of the cylinders was covered with 3.8 cm thick sorbothane rubber. Load cells (Sensotec Model D/7074-06-01) mounted in the cylinder assemblies measure the forces along the axis of the bolster stroke and accelerometers mounted on the push rod assembly provide data which is utilized to compensate for the inertial effects of the push rod assembly mass on the measured force levels.

SURROGATES

The Hybrid III 50th percentile male dummy was used in baseline sled runs for all test conditions prior to testing of the post-mortem human surrogates (PMHS). The initial series of tests were conducted with the dummy ankle that allowed only 30 degrees of dorsiflexion motion. However, it became evident that this ankle prematurely contacted the rigid joint stop and potentially resulted in irregular sensor data. Therefore, subsequent testing used the dummy ankle with 45 degrees of dorsiflexion motion. The lower extremities of the dummy were instrumented with uniaxial femur load cells and proximal and distal tibial load cells that recorded the inferior/superior axial load, medial/lateral shear load and anterior/posterior shear load.

The PMHS were obtained through the Virginia State Anatomical Board with explicit permission given by the family to conduct biomechanics research. All test were approved by the Human Use Review Panel (HURP) of the NHTSA and all personnel involved in PMHS testing read and signed Ethical Treatment of Human Surrogate Forms supplied by the HURP. Screening of blood for Hepatitis A, B, C, and HIV was conducted with each PMHS prior to acceptance into the research program. The PMHS were tested either in the fresh condition or preserved using freezing or a custom embalming technique (Crandall, 1991).

INSTRUMENTATION

In order to determine torso kinematics, triaxial accelerometers (Endevco Model 7267) were mounted on the first and twelfth thoracic vertebrae and the pelvis. A instrumentation package for the lower extremities was developed for the PMHS in order to have comparable response measurements for the PMHS and the Hybrid III dummy. The PMHS and dummy instrumentation package consists of angular rate sensors on the leg and foot to determine ankle motion, accelerometers on the leg and foot to evaluate shock transmission to the lower limb, and a load cell in the tibia.

Magnetohydrodynamic (MHD) angular rate sensors (Applied Technologies Associates, ARS-04E) were used to determine relative motion of the foot and leg (Klopp, 1995). For three-dimensional rotational information with the PMHS, an set of triaxial MHD sensor cubes was externally mounted to the medial sides of the distal tibia and the calcaneus. For the dummy, the sensors were mounted to the metallic plate in the foot and to the ankle joint housing. Uniaxial accelerometers (Endevco Model 7264A) are mounted to each face of the sensor to determine deceleration pulse transmissibility across the ankle joint.

For the PMHS, five-axis implantable tibia load cells were developed jointly by the Automobile Safety Laboratory and Robert A. Denton, Inc. A segment of the tibia was removed and the load cell was inserted with the leg musculature and fibula in tact. Forces were measured along three orthogonal axes and moments about two axes. The forces measured were inferior/superior axial load, medial/lateral shear load and anterior/posterior shear load. Bending moments were measured about medial/lateral and anterior/posterior axes. The five-axis load cell provides comparable PMHS measures to the distal and proximal tibial load cells in the instrumented dummy legs.

Electronic data collection was acquired at 10,000 samples/sec. using a DSP Technology Transient Acquisition and Processing System, model TRAQ P. In addition to the sensor data, high speed photographic data was recorded by servo-controlled 16 mm high speed rotary prism movie cameras (Photosonics 16mm-1B) arranged to provide driver and passenger side views of the testing. An additional camera was positioned to record views of the knee bolster and toe board areas. All cameras were operated at a speed of 1,000 frames/sec.

METHODOLOGY

The objective of the research was to examine the response of the PMHS and Hybrid III dummy subject to varying levels of toepan intrusion. Since limited detailed information of the footwell intrusion from crash tests and real-world crashes existed, the complexities of the intrusion event were simplified and modeled as a linear translation of the toepan structure. The acceleration profiles for the intruding toepan were obtained from a paper by Kuppa and Sieveka (1995).

A test matrix was established to provide the lower limb response at three conditions: no intrusion (0 cm), moderate intrusion (7 cm), and severe intrusion (22 cm). For each condition, dummy and PMHS were run under comparable conditions with lower extremity instrumentation present in all tests with toepan intrusion. For injury and kinematic reference, a series of PMHS tests with no intrusion were included but did not provide detailed instrumentation in the leg, foot, and ankle. The restraint systems for all tests involved a three-point belt system with a supplemental driver used in several tests. All tests were conducted with a nominal velocity of 50 - 60 km/h. The test matrix is shown in Table 1 with the dummy tests (HIII) categorized by the ankle range of dorsiflexion motion and the PMHS by gender (male - M, female - F).

Test	Surrogate	Height (cm)	Mass (kg)	Age (years)	Delta-V (km/h)	Restraint System	Intrusion (cm)
299	HIII/45° Ankle	173.0	78.2	NA	58.6	3pt belt	0
300	HIII/45° Ankle	173.0	78.2	NA	58.2	3pt belt	0
61	PMHS-M11	172.0	66.8	62	49.4	3pt belt	0
66	PMHS-M12	169.0	51.4	53	48.3	3pt belt	0
79	PMHS-M14	171.0	66.8	58	46.7	3pt belt	0
293	HIII/30° Ankle	173.0	78.2	NA	56.8	3pt belt	7
294	PMHS-F44	148.1	55.4	68	56.8	3pt belt	7
295	PMHS-M42	186.5	104.4	57	58.2	3pt belt	7
296	PMHS-M45	180.8	73.9	59	59.8	3pt belt	7
302	HIII/45° Ankle	173.0	78.2	NA	57.5	3pt belt/AB	7
303	PMHS-M34	154.3	50.0	64	57.5	3pt belt/AB	7
304	PMHS-M47	167.7	56.8	65	59.4	3pt belt/AB	7
305	PMHS-M48	160.9	58.1	48	59.4	3pt belt/AB	7
332	HIII/45° Ankle	173.0	78.2	NA	57.5	3pt belt/AB	22
333	PMHS-M51	170.0	63.6	50	58.6	3pt belt/AB	22
334	PMHS-M49	186.0	79.5	47	58.2	3pt belt/AB	22
335	PMHS-M50	172.0	66.4	69	58.6	3pt belt/AB	22

Table 1. Test matrix of sled runs with occupant anthropometry and restraint systems

Pre-test radiographs were obtained for all PMHS and used for comparison with post-test x-rays. Following the sled tests, standard autopsy procedures were performed by a pathologist and autopsy specialist who examined the cardiovascular system, abdomen, viscera, brain, head and neck, spine, and other skeletal elements. To supplemental the hard tissue trauma detection by radiography, a detailed necropsy of the lower extremities was conducted by an orthopedic surgeon to determine soft tissue injuries.

RESULTS AND DISCUSSION

Analysis of the sensor and film data suggested that the lower extremity response of the occupants could be divided into three general events: inertial slap, intrusion event, knee bolster interaction. Figures 4 and 5 divide the sensor time histories for the intrusion tests into these three events. Figure 4 shows the dummy response to 7.0 cm of toepan intrusion while Figure 5 shows the dummy response to 22.0 cm of intrusion. Both plots show the response for only the left foot but both right and left aspects are comparable since no brake pedal was included in the tests and the intrusion is uniform for the entire toepan.

Event 1. Inertial Slap - The acceleration of the sled up to the impact velocity resulted in a gap developing between the footplate and the occupant's heel. This gap was generally greater for the dummy (1 cm to 2 cm) than the cadaver (0.5 cm to 1.0 cm). During initial deceleration of the buck, the heel of the foot struck the decelerating footplate and resulted in a peak in the cadaver tibia force (Fz) and the dummy tibia force (Fz) and moments (My). Typical values for the dummy peak were 2.0 to 3.0 kN depending on the magnitude of the initial gap. It was observed that taping of the feet with tape would minimize the gap and would mitigate the loading peak (less than 1.0 kN). Taping of the feet to the footplates was performed for tests 332-335.

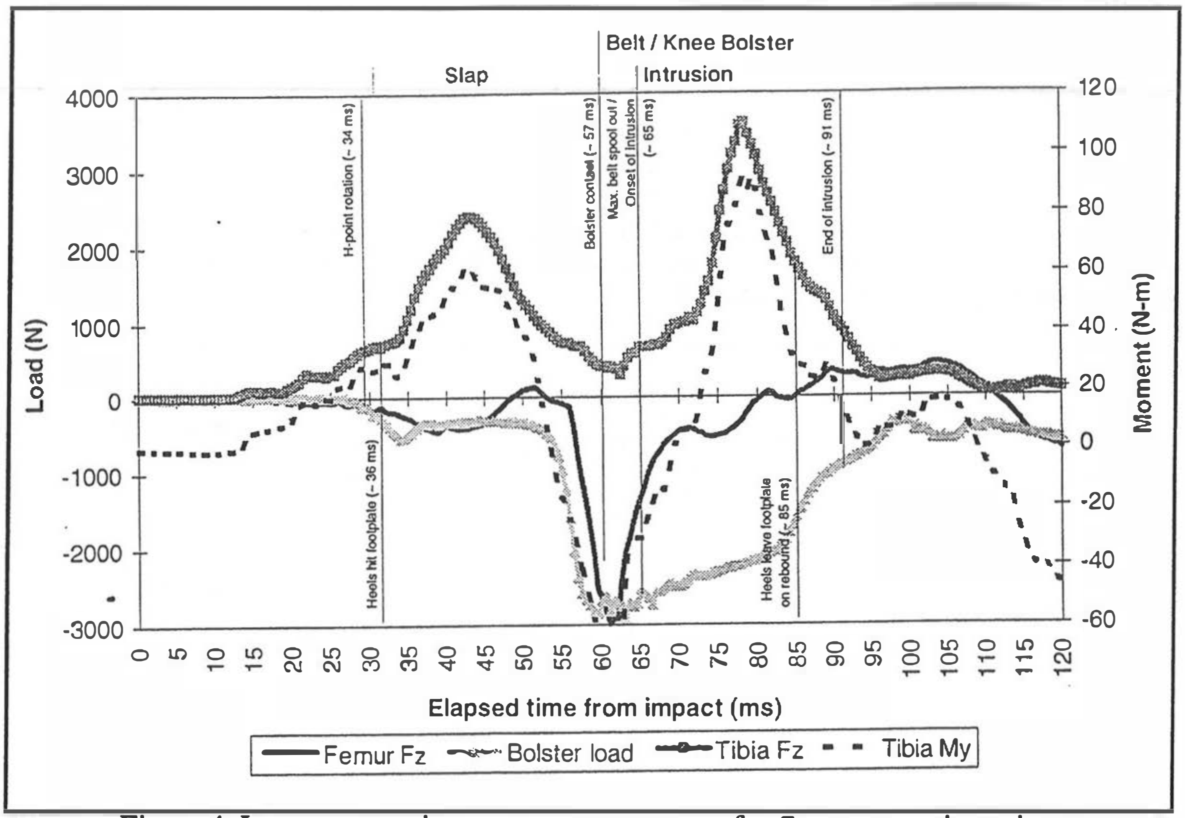

Figure 4. Lower extremity response parameters for 7 cm toepan intrusion

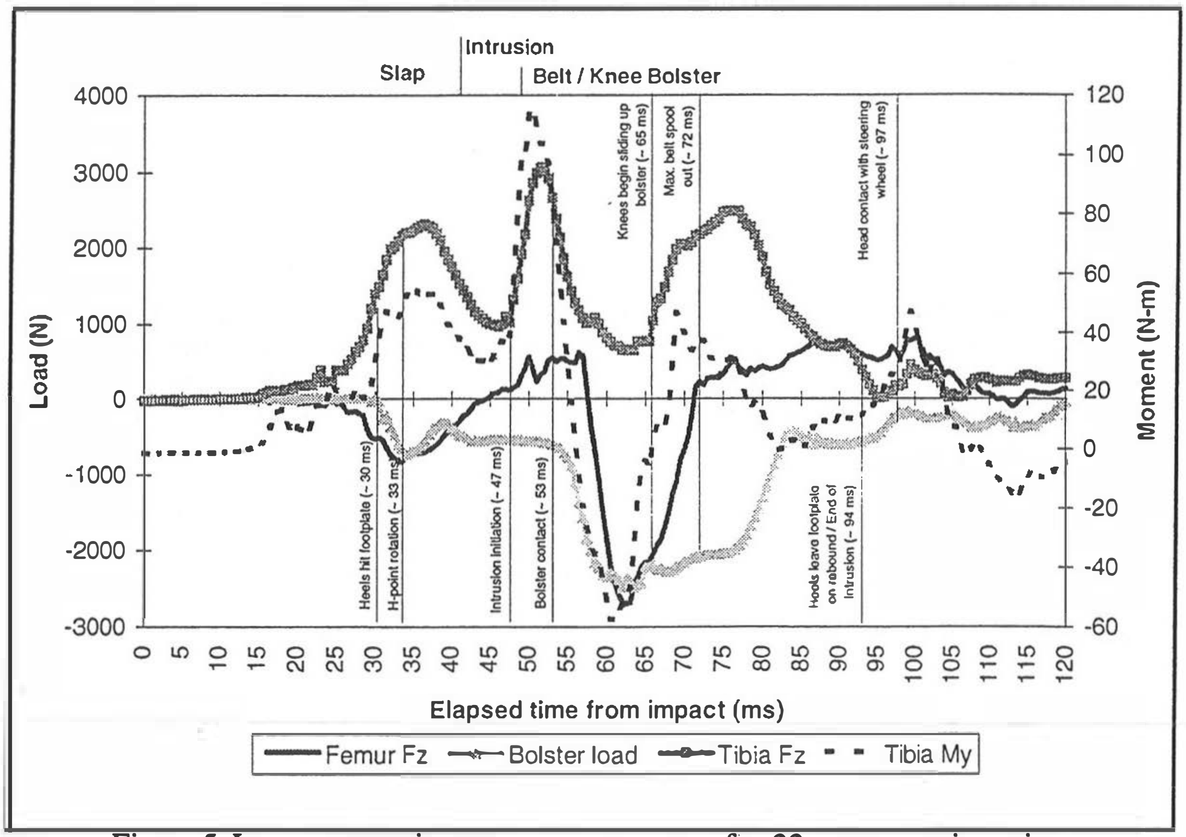

Figure 5. Lower extremity response parameters for 22 cm toepan intrusion

To further investigate the inertial slap behavior, a parametric study was conducted using the Articulated Total Body (ATB) simulation program. An advanced model of the lower extremities was used that provided forces at locations equivalent to those in the Hybrid III dummy. For the impact environment used in the 22 cm intrusion tests, the initial heel to toepan spacing was varied from 0 cm to 6 cm. The results of the study show a progressive increase in the magnitude of the tibia force due to the foot and toepan contact with increasing gap distances (Figure 6).

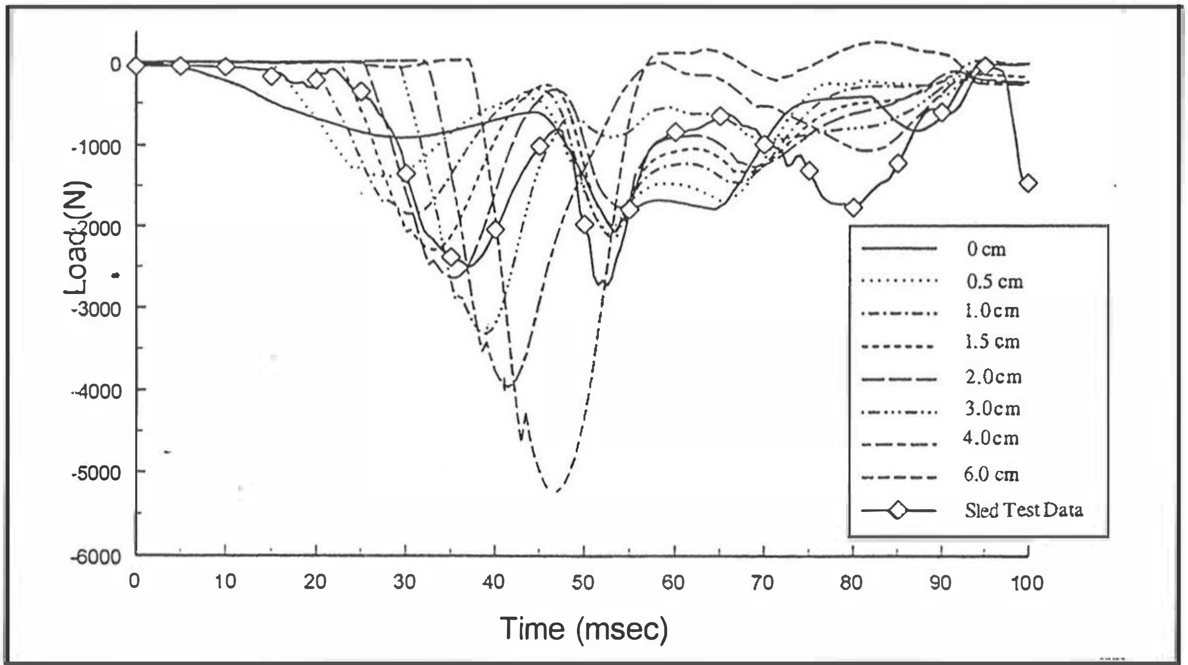

Figure 6. Parametric ATB study of initial heel to toepan spacing

Event 2. Toepan Intrusion - The onset of the intrusion event was evident in both the kinetic and kinematic data. Since the intrusion was creating by arresting the toepan in the laboratory reference frame and allowing the buck to continue decelerating, timing of the intrusion onset was dependent on the desired toepan displacement. In particular, the tibia inferior/superior forces (Fz) and the ankle flexion angles showed sharp rises with intrusion. This behavior is attributed to both the high deceleration values of the toepan structure (from 80 g's to 100 g's) and the increased ankle rotation caused by overall motion of the toepan.

Event 3. Knee Bolster Interaction - The coordination of the toepan intrusion with knee bolster contact can result in entrapment of the foot, leg, and ankle between the toepan and bolster. This entrapment can result in both increased magnitude and duration of the lower extremity loads. The likelihood of this occurrence depends on the initial position of the occupant, the timing of the toepan intrusion, the surface geometry of the knee bolster, and the force-deformation properties of the bolster.

In the sled tests, the knee bolster was a laboratory device rather than a production knee bolster. Therefore, the geometry and loading properties may differ slightly from those obtained in vehicle crash tests but were consistent within the series of sled tests. Penetration of the occupant's knees into the bolster was greatest for the no intrusion tests with maximum permanent crushes of 1.5 cm to 4.0 cm. The timing of the intrusion coincided with the intrusion event for the tests with 7 cm toepan intrusion. The toepan began intruding approximately 5 ms after the knees had contacted the bolster. Measurement of permanent knee bolster crush were generally small (less than 1.0 cm for dummy and PMHS) with the exception of PMHS-M42 (3.5 cm of bolster penetration) who had a mass of nearly 105 kg. The intrusion event for 22 cm of toepan translation began much before the occupant's interaction with the knee bolster. Consequently, the lower extremities were arrested by the intruding toepan and knee bolster penetrations were very small (less than 0.5 cm for dummy and PMHS).

To determine the sensitivity of the tibia loads to entrapment behavior, a series of simulations was conducted using the ATB model. The frictional coefficients of the bolster surface, an additional horizontal plane to prevent vertical sliding of the knees, and the force required to penetrate this horizontal plane (Yield Force) were altered in the model. This additional plane was intended to represent "pocketing" of the knees in the bolster. The location of this plane was referenced from the bottom surface of the knee bolster. The yield forces were varied between 2.5 kN (i.e., the force required to penetrate the bolster in during normal contact by the knees) and 25 kN. All changes to the bolster system were superimposed on the baseline file for 22 cm of toepan intrusion. The parameters for the simulation series are shown in Table 2.

Simulation	Plane Position (cm)	Friction Coefficient	Yield Force (kN)
P1	12.9	0.3	2.5
P2	10.9	0.3	2.5
P3	9.9	0.3	2.5
P4	10.9	0.3	25
P5	9.9	0.3	25
P6	12.9	0.8	2.5
P7	9.9	0.8	25

Table 2 Knee bolster parameters used in simulation study of leg entrapment

The results of the simulation study show that the addition of the plane representing pocketing behavior increases the peak loading of the tibia after contact with the bolster occurs. For simulations P3 and P5, contact with the top plane coincided with the anterior face of the bolster and would represent pocketing occurring at the onset of bolster contact. Comparing tests P5 and P7, it is evident that the surface coefficient of friction produced negligible changes in the tibia loads. When the yield force of the plane was increased to ten times that of the bolster, however, the peak tibia force showed large increases to nearly 45 kN. It should also be noted that phasing of the peak shifted as the magnitude of the tibia force increased.

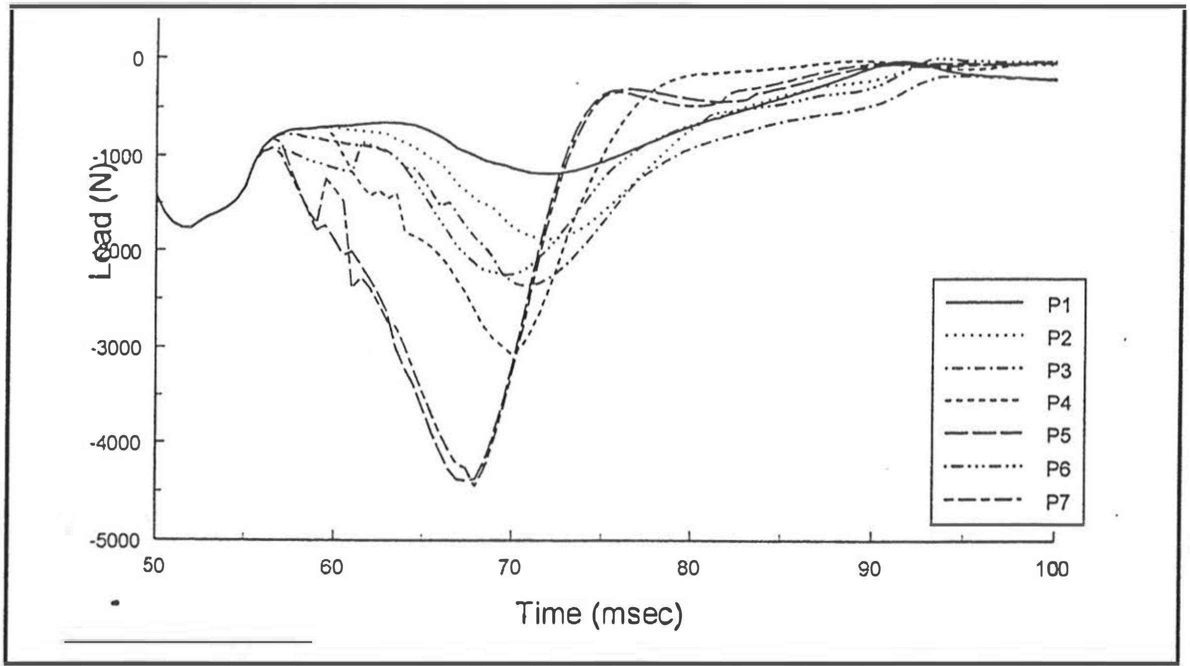

Figure 7 Parametric study of tibia force variation with knee bolster properties

The lower extremity responses for the PMHS and dummy are shown in Table 3. Compressive values for the tibia and femur are assigned positive polarities as are dorsiflexion and eversion. Injury to the lower limb occurred in only one test (294) despite the introduction of toepan intrusions up to 22 cm. This test exhibited extreme dorsiflexion and may have resulted in a tensile fracture of the calcaneus due to stress from the plantar tendons and the Achilles tendon. Although the no intrusion PMHS tests are not listed in Table 3 since no lower extremity instrumentation was present, none of the cadavers in these tests sustained any lower limb injury.

Axial loads in the PMHS tibia were below published injury thresholds of 6.0 kN to 8.0 kN (Yoganandan, 1995; Crandall 1995b). Axial loads and ankle flexion were consistently higher for the dummy tests than the PMHS. The increased axial loads were attributed to greater stiffness of the dummy relative to the PMHS while the lack of a continuous joint stop in the dummy ankle results in greater rotations. In tests 293, 302, and 332 with the dummy, the ankle contacted the rigid joint stop and this may have resulted in increased bending moments (My). In several of these tests, the calculated ankle flexion actually exceeded the design range of motion by up to 2 degrees. This excess was attributed to errors in the measurement of the initial ankle position taken while the dummy was seated in the buck.

Test	Surrogate	Intrusion (cm)	Femur Left Fz (kN)	Femur Right Fz (kN)	Ankle Left Flexion (°)	Ankle Right Flexion (°)	Ankle Left Xversion (°)	Ankle Right Xversion (°)	Tibia Left Fz (kN)	Tibia Right Fz (kN)	Tibia Left My (Nm)	Tibia Right My (Nm)	Lower Limb Injury
299	HIII/45° Ankle	0	3.6	2.4	25.4	22.6	1.35	3.4	3.4	2.7	85.1	69.4	NA
300	HIII/45° Ankle	0	3.0	2.4	25.9	21.9	4.6	0.0	3.5	2.7	84.5	69.2	NA
293	HIII/30° Ankle	7	2.6	2.2	29.8*	NA	-18.0	NA	2.8	2.8	110.1	95.6	NA
294	PMHS-F44	7	3.2	2.2	58.9	25.7	18.3	NA	1.0	1.0	48.2	41.0	Calcaneus Fracture
295	PMHS-M42	7	3.0	3.0	31.3	30.2	24.4	30.0	1.6	2.3	99.0	82.0	None
296	PMHS-M45	7	0.6	0.5	28.4	NA	16.4	NA	2.0	2.0	66.5	54.9	None
302	HIII/45° Ankle	7	3.5	3.7	46.0*	34.7	14.3	-5.2	3.6	3.2	92.8	84.8	NA
303	PMHS-M34	7	2.7	2.6	43.6	31.0	14.2	17.1	1.0	0.9	40.8	51.3	None
304	PMHS-M47	7	0.5	NA	29.6	28.3	15.7	14.4	0.8	1.0	63.8	78.2	None
305	PMHS-M48	7	NA	NA	39.8	37.7	16.5	22.2	1.0	1.2	46.8	45.7	None
332	HIII/45° Ankle	22	2.7	2.2	45.0*	47.0*	-9.1	13.8	3.1	2.6	147.0	83.1	NA
333	PMHS-M51	22	0.7	0.7	23.4	30.9	9.8	8.4	1.8	1.6	87.6	84.5	None
334	PMHS-M49	22	1.7	0.5	26.8	28.1	4.7	8.8	2.7	2.6	99.2	81.5	None
335	PMHS-M50	22	2.6	2.9	38.3	29.3	10.6	14.5	2.3	2.2	64.3	66.1	None

Table 3. Lower extremity response data for PMHS and dummy

Comparison of the sled test results with test data from NHTSA frontal offset tests with the Ford Taurus showed similar behavior. Three distinct regions could also be identified on a crash test conducted at comparable velocities (56.3 km/h) to the sled tests (Figure 8). Figure 8 shows the response data for the left (outboard) foot of the Hybrid III dummy placed against the toepan footrest. Since the right foot was placed on the accelerator prior to the crash, the left foot was considered more representative of the sled test condition. The reduced tibia loads during the inertial slap event were attributed to the attenuation effects of padding and carpeting on the toepan structure. The peak tibia forces, however, are comparable in magnitude to those recorded in the sled tests.

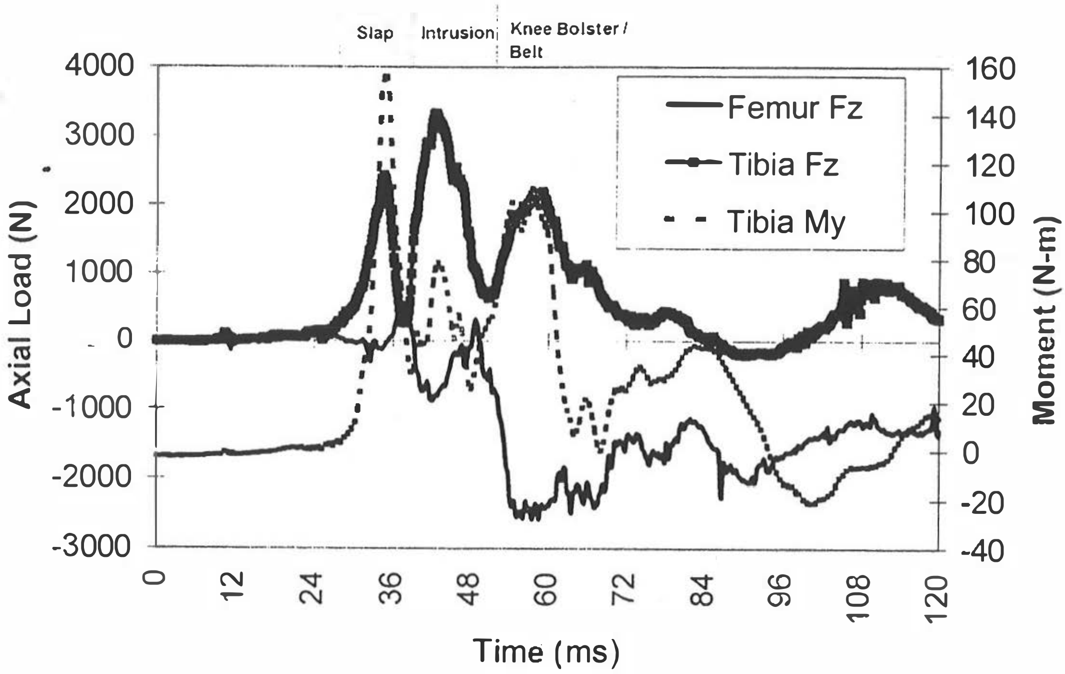

Figure 8. NHTSA offset frontal crash test of Ford Taurus

CONCLUSIONS

The results of the intrusion tests suggest the following conclusions:

1. The Hybrid III dummy records greater axial tibia loads and ankle dorsiflexion than the PMHS in comparable test conditions. In addition, the dummy contacted the rigid joint stop of the ankle while the cadavers did not sustain injury under equivalent test conditions. While the axial loading data can likely be scaled to predict injury, the dorsiflexion response suggests that the current design of the Hybrid III may not be capable of predicting rotational injury.

2. Despite levels of intrusion up to 22 cm, only one of the 12 PMHS sustained injury. This indicates that factors other than the magnitude of intrusion (e.g., rate and timing of the intrusion event) must be considered.

3. Care must be taken to eliminate a gap between the feet and toepan structure during sled and full-scale vehicle tests. This gap can result in a inertial slap of the feet against the toepan. If coincident with the intrusion event, this behavior could result in erroneously high values of tibia load.

4. Tibia load is highly dependent on the level of knee pocketing in the bolster. Entrapment of the legs between the bolster and intruding toepan can result in extremely high axial loads in the leg.

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