

METHODS OF RESEARCH FOR DEVELOPING NEW SAFETY CRITERIA FOR AUTO VEHICLES

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KEYWORDS – lower extremity, injuries, intrusion, simulation, AATD

ABSTRACT – This paper presents experimental and simulation work used to study the injury patterns and mechanisms of the ankle/foot complex. The simulation effort has developed a segmented lower limb and foot model for an occupant simulator program to study the interactions of the foot with intruding toepan and pedal components. The experimental procedures include static tests, pendulum impacts and full-scale tests with AATD and human cadavers. The response of the lower extremities is characterized with analogous dummy and cadaver instrumentation packages that include strain gauges, electrogoniometers, angular rate sensors, accelerometers and load cells. Sled tests are performed with a toepna device that subjects the lower extremities to typical intrusion pulses. Based upon data from these tests, a risk function which correlates observed cadaver injury with dummy response is developed.

TECHICAL PAPER – Lower limbs injuries resulting from automobile accidents are a major cause of permanent disability and impairment. A search of the 1990-1992 NASS files determined the weighted distributions of lower extremity trauma shown in Fig. 1. The search criteria specified front seat occupants at least 16 years of age, in frontal cars or LTV collisions, without roll-over or ejection and with AIS \geq 2. The data indicate that lower extremity injuries account for 32% of all AIS \geq 2 injuries for belted occupants (25% for unbelted). Specifically injuries for the ankle/foot complex account for 33% of the AIS \geq 2 lower extremity injuries for belted occupants (24% for unbelted) and are the most prevalent injury. Based upon data for vehicle accidents in which there is improved head and torso protection from airbags, the relative importance of lower extremity injuries, and especially ankle/foot injuries, has increased as a result of the decline in head and chest injuries.

While there is agreement that ankle injuries are more frequent in frontal collisions than in other crash configurations, there is little agreement of the exact injury mechanisms involved. Originally, distal leg and ankle fractures were thought to occur due to a twisting or bending of the foot at impact (1). Recently, some researchers have conjectured that movement of the ankle beyond the normal range of motion (2, 3) is the source of injury. Still other research indicates that intrusion of the toepan (4), and subsequent foot contact with the pedals and floorpan (5) are significant factors. Accident data suggest that these contact ankle injuries occur regardless of the degree of intrusion and that they seem to be associated with the dynamic characteristics of the toepan acceleration. Supporting this hypothesis, 1990-1992 NASS data suggest that 62% of the lower limb injuries below the knee occur at intrusion level of less than 2.5cm (1in.).

Studying the mechanisms of ankle injury will determine which measurable engineering parameters are significant indicators of ankle trauma. An index of performance that describes a functional relation between an injury and these parameters can be then used to interpret data

from the general crash environment. Use of a good index which describes the data is fundamental to the development of a risk function (6). A good index predicts an increasing frequency of injury beyond of some threshold value of the recorded parameters. In other words, it tends to divide the data into three regions; an initial region, in which no injury is observed, a transition region in which a mix of injury and non-injury cases occur, and a region in which injury is the only response. Ideally, the transition region is relatively narrow, but in this study the breath will be a consequence of the variability in the strength of the biological tissues.

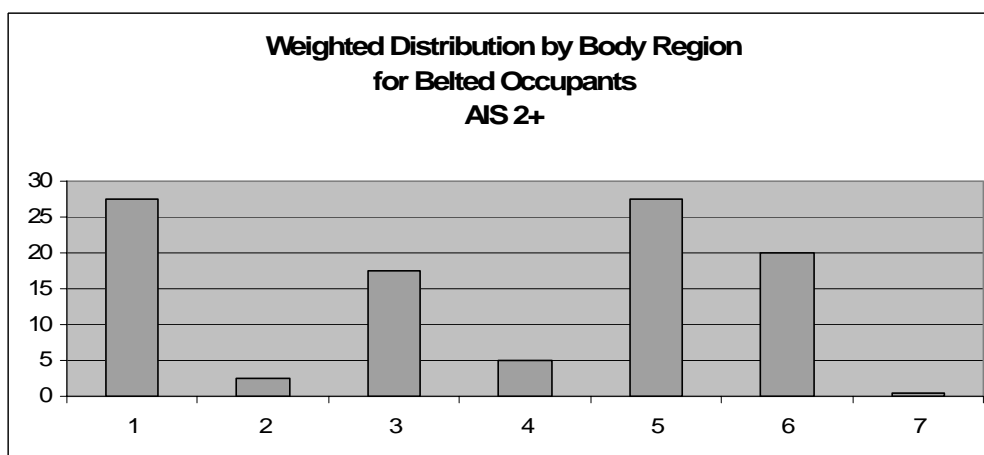
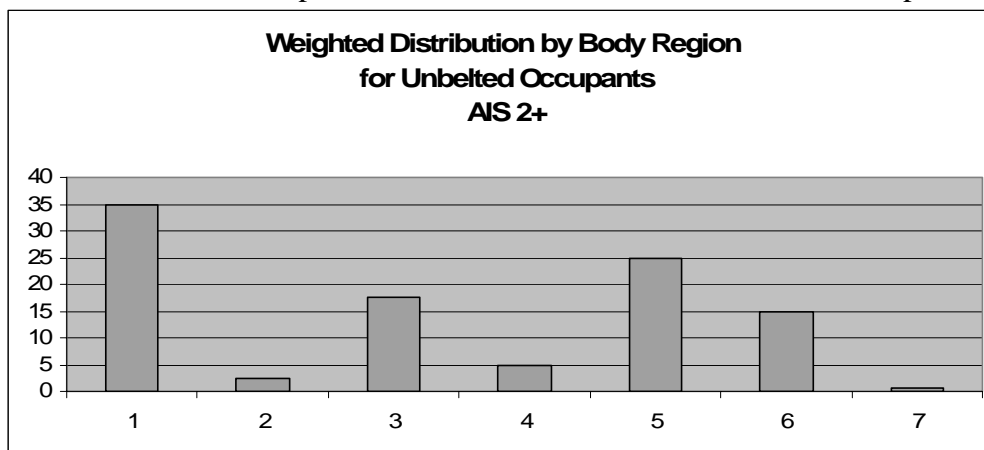
Since the data are categorical (i.e., injury or no injury) and independent, an objective function can be defined which is the probability of the entire sequence occurring, or

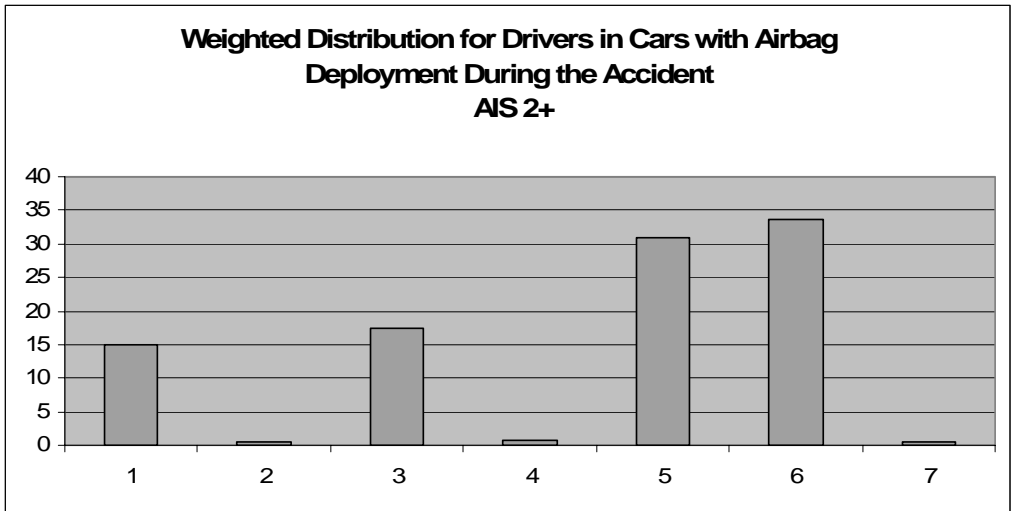
$$P = \prod_{j=1}^m \prod_{i=1}^n P_i(1 - P_j)$$

P_i = probability of injury for the i -th data point

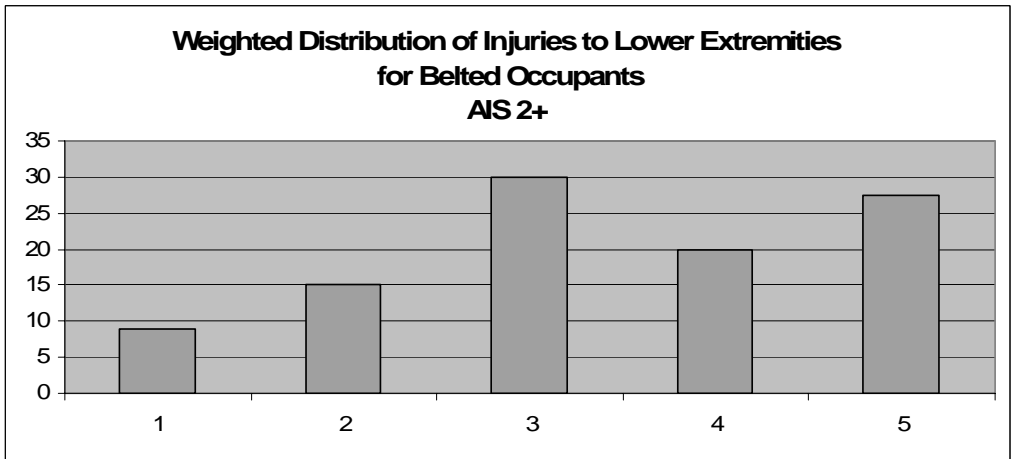
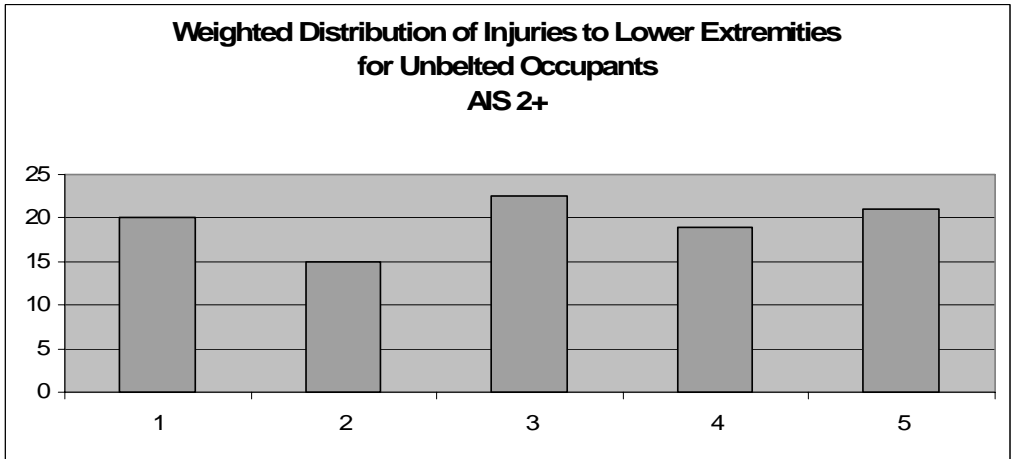
P_j = probability of non-injury (for $n+m$ total data points)

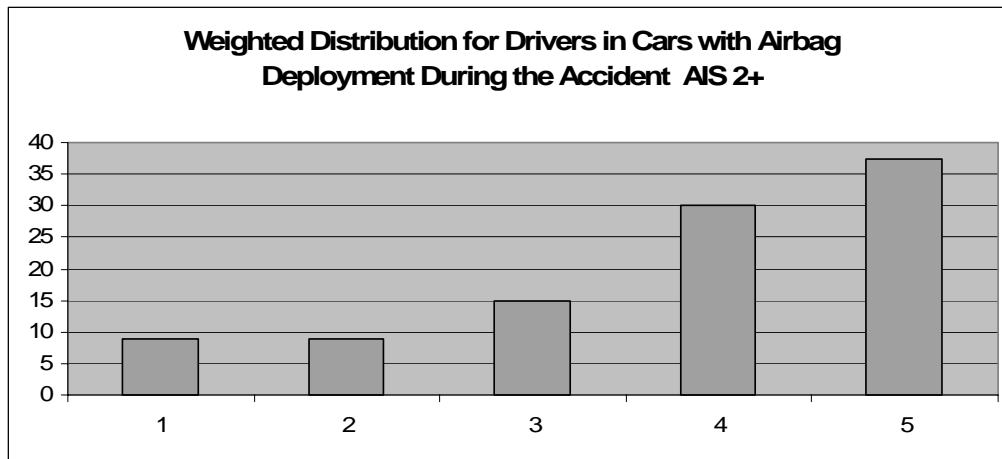
One must assume a probability density function for a particular set of data such that P_i and P_j can be calculated if the necessary parameters are known. In general, these parameters are not known a priori and must be estimated so that the overall probability for the set is maximized. Numerous random samples of test data are used to estimate the model parameters.





1=Head/Face; 2=Neck; 3=Chest; 4=Abdomen; 5=Lower Extremities; 6=Upper Extremities;
7=Other





1=Pelvis; 2=Thigh; 3=Knee; 4=Lower Leg; 5=Ankle and Foot

Figure 1 Survey of NASS Database (11)

TEST ENVIRONMENT

Since contact with the pedals and the floorpan are the primary mechanisms of ankle/foot injury in automobile collisions, intrusion parameters are being incorporated into the cadaver and dummy sled testing. Intrusion is defined as the inward crushing motion of a vehicle's interior structures toward the occupant. This is of special concern in offset frontal collisions where less than the full frontal area of the vehicle is engaged in energy absorption. Current vehicle safety standards only test full frontal collisions against rigid barriers an intrusion is generally minor. In offset collisions greater vehicle deformations and intrusions occur on the struck side. European advanced ATB Foot Model researchers (7, 8) have emphasized this as a rationale for specifying an offset frontal test since tests limited to full frontal crashes may produce a false sense of security.

In order to simulate the primary mechanisms of ankle injury (pedal and floorpan contact (5)), sled and component tests must simulate the strokes and accelerations of intruding vehicle components. Analogous to the crash pulse used to characterize vehicle and sled tests, a "toe pan pulse" can be defined to characterize the intrusion. Little research has been done to describe the displacement and the collapse of the toe pan's thin metal structure. In addition to the longitudinal translations, large toe pan and floorpan rotations occur during the intrusion event. For offset vehicle tests, the available intrusion data have been obtained from a single uniaxial accelerometer mounted to the toe pan. As the crash progresses, the toe pan rotates and the actual orientation of the axis of the accelerometer becomes poorly defined.

Kuppa and Morgan (9) have addressed this problem by making several simplifying assumptions based on a 58 km/h offset frontal collision between a Ford Taurus 1991 4-door sedan and a 1991 Honda Accord DX-4 4-door sedan. They have produced an equivalent toe pan pulse and brake pedal pulse designed to preserve the gross characteristics of the original data and to be readily reproducible in a laboratory.

At the present time it is not known which intrusion parameters (e.g., intrusion displacements and accelerations) are significant in the study of ankle trauma. A major goal of this research

program is to evaluate the correlation of these parameters with observed trauma and to recommend which parameters should be used to define the standard toepan pulse.

OCCUPANT SIMULATION

Advanced ATB Foot model

To study the effects of muscle tensing, toepan intrusion and initial occupant positioning on lower extremity injuries, an advanced foot model has been developed for the Articulate Total Body (ATB) occupant simulator. This model consists of five segments comprising the ankle, heel, tarsal, metatarsal and phalange regions that have been oriented relative to each other to approximate the arch of the foot. The heel attachment is currently represented by a stiff ball joint; the other joints each contain two orthogonal axes which represent inversion/eversion and plantarflexion/dorsiflexion. Figure 6 shows two views of the undisturbed foot and also its response to induced loads. In Fig. 6c, the floor has risen and rotated counter-clockwise in a corkscrew motion. This has caused the foot to invert since the heel load, both normal and frictional, exceeds that in the more flexible forefoot. Figure 6d shows the effect of a dorsiflexion-inducing load. Note how the arch has compressed so that the mid-foot contacts the floor. At present, the joint flexion and stop data are approximate. Obtaining better joint data for the model is one goal of this lower extremity research effort. With such data the forces and torques about these general regions of the foot can be estimated both for different crash conditions and toepan/brake pedal geometries. Future work will involve adding some additional "shoe" elements to the simulated occupant.

Comparison of tensed and tethered legs

A major goal of lower extremity research is to understand the effect that muscle tension and occupant "bracing" can have on kinematics and loading during the height of the crash event. Volunteer sled tests (10) and postulated injury mechanisms from NASS studies (5) suggest that muscle tensing of the lower extremities significantly influences occupant kinetics and kinematics. As part of the design phase of the lower extremity study, computer models have been created to study the feasibility of simulating muscle tension in the legs and back with a tether attached to the leg. The goal is to keep the tether system as simple as possible while still duplicating the critical loadings. Figure 2 shows the front and side views of the "tethered" model at T=0. Two tethers have been attached to the end of the upper legs near the knee. They wrap around each thigh and attach to the floor on either side of the leg. The offset anchor points prevent the legs from twisting sideways as the loads on the feet increase. In addition, two tethers have been attached to the upper legs near the hips with anchor points near the top of the seat back (this is feasible for the reinforced seat that will be used in the sled bed tests). The purpose of these latter tethers is to represent, in part, the upward force that tensed legs exert on the upper body through the hip joint. The braced occupant tends to push the torso back and up. As a result of this force the pelvis does not "plow" into the seat as much as when the occupant is relaxed. In addition, the hip tethers compensate for the substantial downward force, generated by the knee tethers on the occupant as a whole. The "tensed" muscle model is the same as the tethered model except that the tethers are replaced by a stiffened joint torque functions in the waist hips and knees.

The vehicle and toepan pulses for the following simulations taken from Kuppa and Morgan (9) and represent a 58 km/h initial velocity, a peak vehicle acceleration of about 25 G, and a toepan intrusion of 21.5cm. The chosen foot/toepan pre-load value of approximately 1800 N

on each foot was based on an estimate of Armstrong and Waters (10). The plots begin at -20msec, indicating that the onset of the crash was delayed by 20msec to allow the occupant system to equilibrate before the beginning of the crash event.

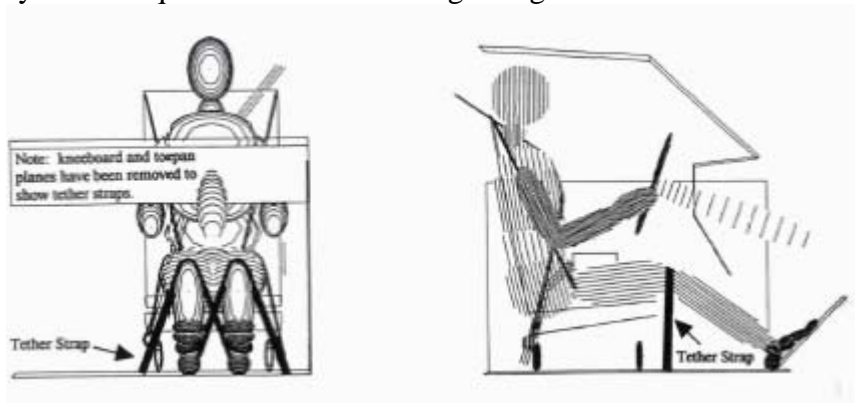


Figure 2 (11)

Figure 3b, c and d show the toepan/right foot load histories during a simulated frontal crash with toepan intrusion for three different muscle tensing/tethering conditions. For comparison Fig 3a shows the load history for a “relaxed” occupant model without tethering. There was little difference in the results for the left and right feet since no pedal effects were simulated at this time. This is a preliminary study, but as Fig 3 demonstrates it appears that this simple tether system has a great potential for creating lower limb impact conditions which mimic a tensed occupant. At present it is uncertain how tensed muscles respond to additional loading, therefore three different cases were compared to show that the tether system is sufficiently versatile to handle whatever behaviour is deemed to be correct. The first case, Fig 3b simulates muscles that produce linearly increasing resistance as the leg is loaded, and which unload nearly elastically. The case in Fig 8c is the same as 8b except that unloading is very inelastic. Finally, Fig 8d shows the results when the muscle resistance remains constant throughout the crash event, which is the behaviour suggested by the work of Armstrong and Waters (10). The qualitative agreement is very good in that the tethered legs show the same relative changes between stiffness models as do the tensed legs. Peak magnitudes are also very close.

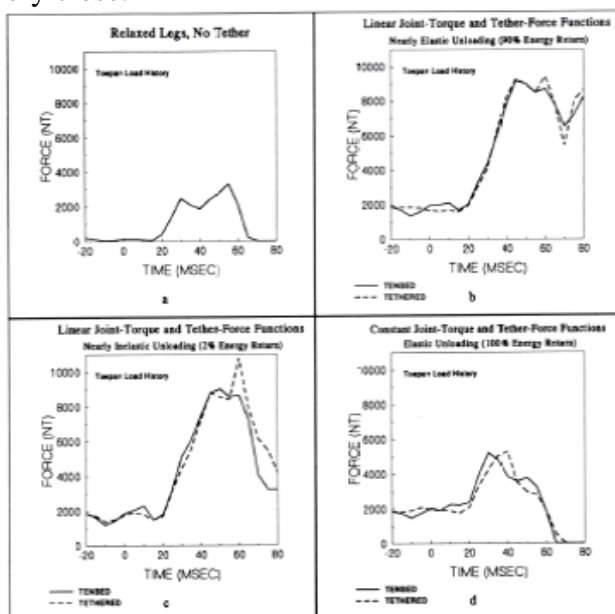


Figure 8 Resultant loads on the right foot/toepan for differing load conditions (11)

There is still work to be done to fine tune the initial conditions of the tether system, such as the correct stiffness and pretension to assign to the knee tethers in proportion to the hip tethers. Also, the tensed knee tends to push the foot up along the toepan while the tether pulls it down. Because the toepan is very stiff, small shifts in foot position can produce large changes in contact force. Maintaining the proper orientation of the foot may require a heel stop such as that used in the test by Armstrong and Waters (10). Once these issues are addressed the simulations will be used to investigate the tether system's behaviour when an asymmetry such as a break pedal is introduced.

Determination of initial conditions

In order to simulate a tensed occupant bracing with both its legs and its back, it was necessary to determine initial conditions for the simulation which involved a pre-load on the feet, on the back and in the joints of the leg and back. A systematic procedure was utilized to remain in a near equilibrium state during the entire simulation. Afterwards, the results were examined to determine at what time the load on each foot was approximately 1800 N. the toepan position and body positions corresponding to this condition were then used as initial conditions for the crash simulations. Since these initial positions were really taken from a quasi-static simulation, they could not be expected to represent perfect equilibrium. For this reason, an extra 20msec was provided at the beginning of the crash simulations to allow the system to settle down before the onset of the crash.

INJURY MEASUREMENT

Ankle injuries include fractures, avulsions (a type of fracture where the insertion site of a tendon or ligament is pulled away from the rest of the bone), and damage to the articular surfaces of joints. Initially, all cadaver specimens will receive set of radiographs to provide reference data and to evaluate bone quality. Following an impact test, the specimen will receive a second, identical set of radiographs which will be read by a radiologist of the University Radiology Department. The radiologist's assessment of the specimen will be used to guide an autopsy of the specimen where particular attention will be given to the condition of the articular surfaces

CONCLUSIONS

The data collected through this study should help to develop novel instrumentation packages for use with cadavers and a deceleration sled with programmable toepan intrusion, as also to improve modelling and simulation tools for assisting of tests and for interpreting the obtained data. These data should be used in improving the biofidelity of anthropomorphic test devices, to develop injury risk functions for the human ankle, and to improve the clinical understanding of the mechanisms involved in this significant public health problem.

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