SAE TECHNICAL PAPER SERIES

980362

Injury Causation in Rollover Accidents and the Biofidelity of Hybrid III Data in Rollover Tests

Robert Piziali, Robert Hopper,
Daniel Girvan and Raymond Merala
Piziali and Associates, Inc.

Reprinted From: Mechanics of Protection
(SP-1355)

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

International Congress and Exposition
Detroit, Michigan
February 23-26, 1998

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

980362

Injury Causation in Rollover Accidents and the Biofidelity of Hybrid III Data in Rollover Tests

Robert Piziali, Robert Hopper,
Daniel Girvan and Raymond Merala
Piziali and Associates, Inc.

ABSTRACT

There is a continuing debate in the scientific literature and among policy making bodies regarding the role of roof crush in the causation of rollover accident injuries. A question arising from field studies is whether the correlation between roof crush and injuries occurs because roof crush <u>causes</u> injuries or because roof crush is <u>associated</u> with accident severity, which is related to injury potential. Recent literature is reviewed to address this question. The Malibu rollover tests have been criticized for the level of "potentially injurious impacts" measured in the Hybrid III dummies used in these studies. Additionally, it has been asserted that the Hybrid III neck is excessively stiff in compression and that experimental testing with the Hybrid III produces results that are not representative of human occupant responses. A careful review of the literature reveals that the Hybrid III and cadavers have similar neck stiffnesses in some loading modes when subjected to the same boundary conditions. The time history of neck forces developed in a drop test using a Hybrid III dummy was compared to the time history of neck forces found in recently published cadaver drop tests and found to be similar. A published computational model proposing a causal relationship between roof stiffness and injury was found to be inaccurate and non-representative of human occupant kinematics. Research to date has found that roof crush is not causally related to injuries in typical rollover accidents.

INTRODUCTION

The question of whether roof crush increases injury risk during rollover accidents has been discussed regularly in the literature since 1970. A review of this literature was included in recent articles by Moffatt and Padmanaban (1) and James, et al. (2). Initially, researchers believed that the causal relationship between roof crush and injury risk was obvious. However, early field studies found little correlation between roof crush and injuries until the extent of roof crush became large. Some later studies found an increase in injuries with the degree of roof crush. By this time it was well understood that both the severity of the roof crush and the severity of the injury were related to the severity of the impact. Thus, it became important to determine if roof crush and injury were both associated with impact severity or if, for the same accident dynamics, roof crush caused injuries.

A series of dolly rollover tests with unrestrained and restrained dummies with production and reinforced roofs, often referred to as the Malibu studies (3,4), resulted in several important observations. First, the buttocks of the dummies left the seat at the time of vehicle trip and remained off the seat until the vehicle came to rest. This established that the potential injury mechanism where the occupant is squeezed between the seat and the roof was unlikely. Second, the forces on the dummies' necks were essentially the same for production and reinforced roofs when the impact to the roof was the same.

Moffatt and Padmanaban (1) found no differences in injury risk for normalized roof strengths that varied by a factor of over two (all of the roofs complied with FMVSS 216). They also found that convertibles had a higher risk of injury in rollovers than vehicles with roofs. These results demonstrated that a roof is beneficial, but little benefit is obtained by having roof stiffnesses greater than FMVSS 216.

In spite of this strong evidence establishing injury risk to be independent of roof strength and roof crush, recent articles have concluded that roof crush is causally related to injures (5,6,7,8). In addition, the Malibu series test methods have been criticized and the results contested based on the assertion that the Hybrid III neck is stiffer than the human neck (7,8).

This paper will review the literature and evaluate analytical and experimental results to address the following questions: 1) Do field studies demonstrate whether roof crush causes injury or whether roof crush is merely associated with injury; 2) are the conclusions of the Malibu studies concerning potentially injurious neck loads valid; 3) how do the neck stiffnesses of cadavers and Hybrid III dummies compare at injury producing load levels; and 4) what can be concluded from the model developed by Syson (8) with regards to roof stiffness and neck injury risk?

A REVIEW OF FIELD STUDIES

The basic vehicle and occupant kinematics in rollover accidents has been discussed by Moffatt (9). It is generally accepted that for a passenger side leading rollover there is little ground contact on the passenger side roof rail and that the most significant impact and roof crush occur on the driver's side roof rail as illustrated in Figure 1. It is also generally accepted that in this accident scenario the driver is at the highest risk of injury. Thus, both the driver's roof rail and the driver are exposed to a greater impact than the passenger's roof rail and the passenger. Therefore, observing that occupants in the vicinity of the greatest roof crush are the more severely injured does not establish a causal relationship. Roof crush and occupant injury can only be associated in this type of a study.

The "diving" analogy is a simplified means to explain the basic neck injury mechanisms in a rollover accident. This mechanism, illustrated in Figure 2, results in the neck transmitting an impulse to arrest the inertia of the torso after the head strikes the ground. First, the injury patterns observed in both diving and rollover accidents are similar. Second, a kinematics analysis of an offside occupant in a rollover shows that the body orientation relative to the ground and the velocity vector at impact can be similar to those for a diving impact.

While the previous concepts seem simple, they are often misunderstood by investigators. Figure 3 presents a simple example to explain the difference between association and causality. In Figure 3a, both the occupant and the vehicle are dropped from a low height and both suffer moderate damage/injury. In Figure 3b, both are dropped from a greater height and both suffer significant damage/injury. In this example it is clear that there is only association between roof crush and injury since the "occupant" is not in the vehicle Putting the occupant in the vehicle does not change association to causality. Thus, a field study must go beyond relating roof crush to injury risk in order to establish that roof crush causes injury or increases injury risk.

A recent article from Australia (5) that reviews previous literature and several case studies concludes that roof crush causes injuries in rollover accidents. The investigators' review of the literature shows an association between roof crush and injury which leads the authors to conclude that roof crush causes injury. Their case studies include 13 fatalities and 9 spinal injuries. A review of the 13 fatalities found only one belted, contained occupant whose injuries could be associated with roof crush. This occupant sustained a fatal neck injury, caused by loading similar to that observed in the Malibu tests with reinforced roofs. Of the 9 occupants with spinal injuries, 3 were restrained with roof crush in their area, 2 had unknown restraint use, and the remaining 4 had injuries unrelated to roof strength. Therefore, of the 22 occupants sustaining either fatal or spinal injuries, only 4 to 6 of the injuries could be readily associated with roof crush. No basis for a causal relationship was developed. Therefore this study does not present any data to support a causal relationship between roof crush and injury risk.

Rains and Kanianthra (6) attempted to establish causality for head injuries by relating injury risk to pre and post crash headroom. This new measure does not change the results of their study from association to causality. The authors admit to this problem at the beginning of the paper and in the conclusions, but refer to causality in the body of the paper. Since Abbreviated Injury Scale (AIS) levels are not presented, injury severity cannot be related to headroom reduction. The use of seated headroom also ignores variables such as restraint and seat characteristics, body compressibility, variations in seated height, and other factors. The study is also limited because the data base had only 35 head injuries to contained, restrained occupants.

Friedman and Friedman (7) include a National Accident Sampling System (NASS) analysis and case studies to support their contention that roof crush causes injuries. The NASS analysis finds that the occupant closest to the most significant roof crush is at the highest risk of injury. Again, this merely establishes association, not causality. The authors also run computer models of injury producing accidents with increased roof stiffness and added padding and claim to observe a reduction of cervical injury risk. No details of the modeling were presented. One indication of errors in their analysis is the claim that padding would reduce neck injuries. While neck injury criteria are still in the early stages, it has been noted that an impulse criteria at the head is better correlated with cervical spine injury than peak force (10,11). The addition of a reasonable thickness of padding will have no significant effect on the resulting impulse. Syson (8), a critic of the Malibu tests, found no reduction in neck loads with the addition of reasonable padding in his modeling of drop tests (although his model is questionable, as discussed in the next section).

It should also be noted that the Mertz injury criterion for the neck (12) is approximately an impulse function. The allowable force decreases with increased duration (constant impulse) until quasi-static criteria apply. Finally, the lead author has reviewed several computer models developed by Friedman in the past and found each of them to contain significant errors. Therefore, in the absence of specific, detailed case study examples, their proposed results cannot be verified.

Moffatt and Padmanaban (1) conducted a study which related the risk of injury in a rollover accident to a normalized roof strength (the ratio of the roof strength to vehicle weight). The vehicles in the study had normalized roof strengths ranging from 1.7 to 3.7. If the hypothesis that roof strength reduces the risk of injury was valid, one would expect a decrease in injury rates with an increase in roof strength. This study found no such relationship. The risk of injury in rollovers was essentially constant over the entire range of roof strengths.

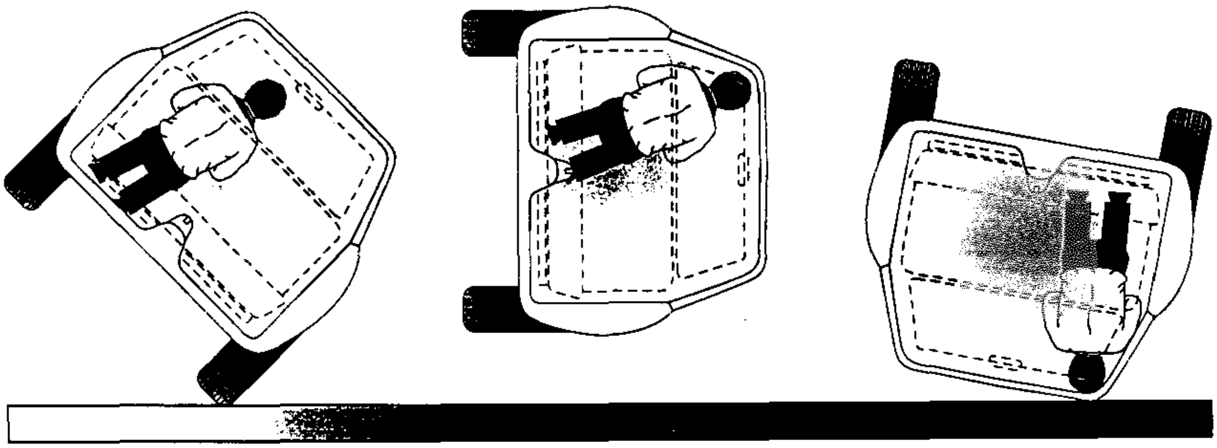

Figure 1. Passenger side leading rollover illustrating trip and initial ground contact with the driver's side roof rail.

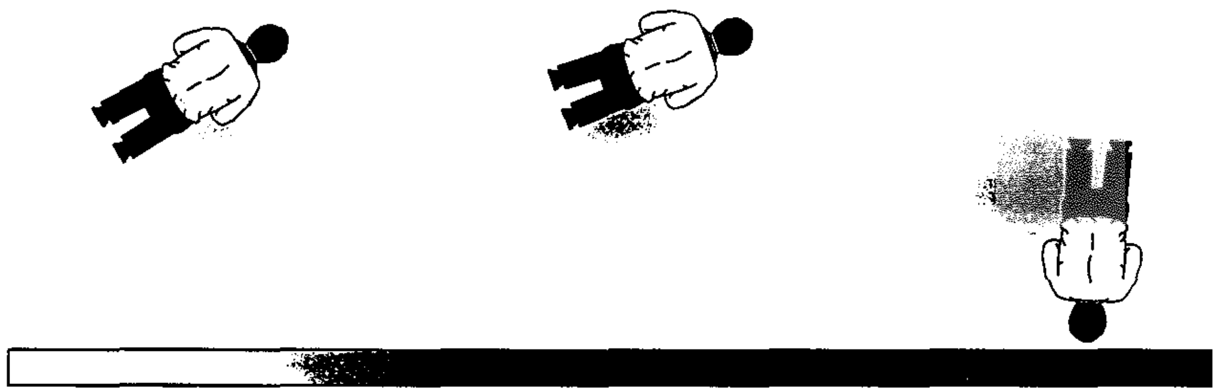

Figure 2. Occupant kinematics associated with the initial roll sequence of a passenger side leading rollover.

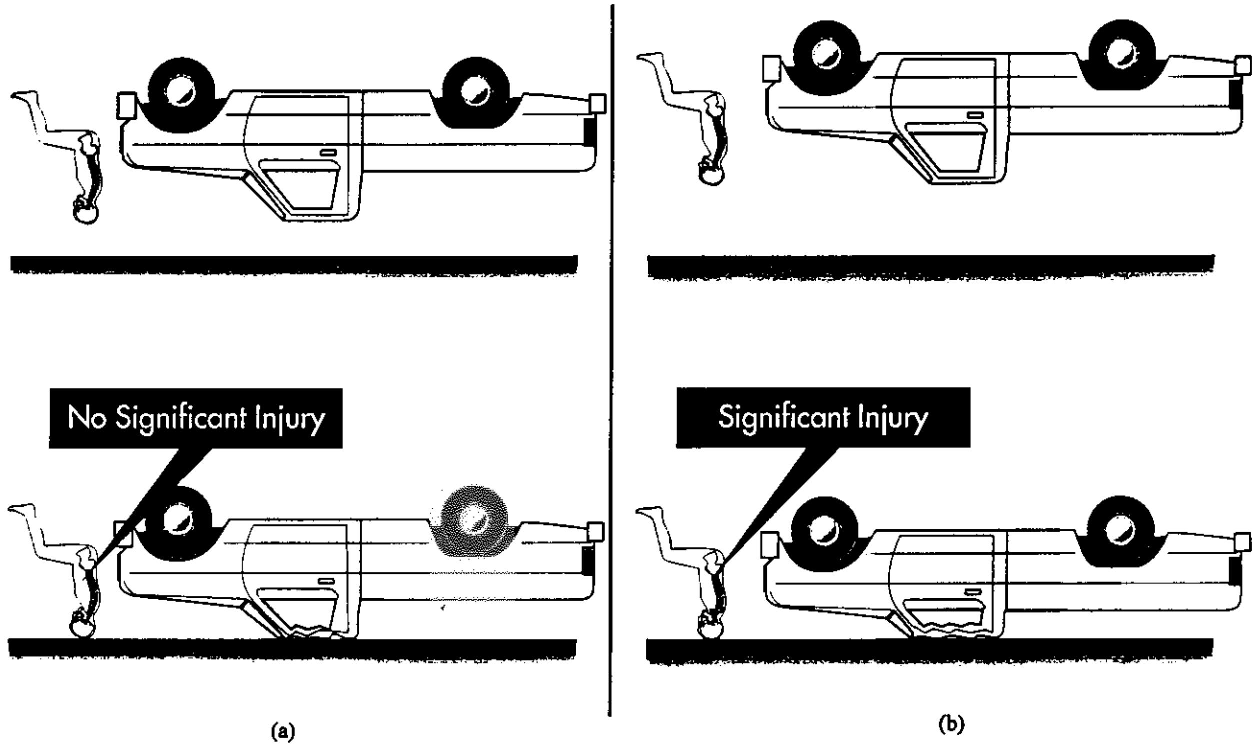

Figure 3. Association between injury and roof crush. In Figure 3a, the occupant and vehicle are independently dropped from a low height, resulting in little roof crush and no significant injury. In Figure 3b, the occupant and vehicle are independently dropped from a greater height, resulting in more significant roof crush and significant injury. Both injury potential and roof crush are dependent on drop height.

MALIBU STUDIES

The Malibu I tests (3) were conducted with unrestrained Hybrid III dummies in 1983 Chevrolet Malibus with production and reinforced roofs. Each vehicle was "launched" into a rollover at 30 mph using a dolly fixture in accordance with FMVSS 208. The study concluded that, "Upon ground impact, the chance of neck injury was primarily dependent upon two factors: (1) The orientation of the dummy and (2) the change in velocity of that portion of the vehicle against which the head of the dummy was touching. Roof deformation relative to the seat had no effect on the injury mechanics in these tests. The theory that head and neck injuries in rollover accidents are from the roof 'coming down' and pinning the occupant into his seat is not supported. That sequence of injury did not occur. The rollcaged vehicles did not have any increased level of protection over the standard roof vehicles in these tests"

The Malibu II tests (4) were conducted in a similar manner except that the dummies were restrained and drop tests were included. Conclusions were similar to those of Malibu I with the addition that: with the vehicle upside down, the Hybrid III dummy's head was in contact with the roof; neck loads were the result of diving type impacts; seat belts prevented ejection and projection impacts but did not result in a reduction in head and neck loads; the rollcaged vehicle had fewer potentially injurious impacts; and under similar impact dynamics in the rollover and drop tests there was no increase in the level of protection in the rollcaged vehicles.

Since the publication of the Malibu studies other authors have reviewed this work and have drawn new conclusions. Friedman and Friedman (7) note that the Malibu II studies found fewer potentially injurious neck loads in the reinforced roof vehicles than in the production roofed vehicles. They claim that this is a benefit of reinforced roofs. The reason for the reduction, as explained by Bahling, et al., (4) was that the reinforced roof was more elastic and rebounded higher at passenger side roof rail impact such that the driver's side roof rail rolled further before contact, resulting in a less severe impact. The reduction in potentially injurious neck loads among vehicles with reinforced roofs was due to a reduced number of severe roof contacts. This reduction in the number of severe roof contacts was attributed to the changes in the vehicle kinematics, not the strength of the roof. In an actual rollover accident, with the variety of trip mechanisms, terrain, and vehicle characteristics, structural roof stiffening may lead to fewer, more, or a similar number of roof impacts. It is not reasonable, based on the dolly rollover tests, to assume that all vehicles with reinforced roofs will have fewer potentially injurious impacts in actual rollover accidents.

The actual test for the crashworthiness of a vehicle's design is, given the same impact, what is the risk of injury? To analyze this question Bahling, et al., (4) compared neck loads in dummies positioned over roofs that had the same change in velocity at impact for production and reinforced roofs. The resulting neck forces were essentially the same. They further compared production and reinforced roofs in one foot drop tests to ensure the impacts were similar. The results were again comparable, with the dummies in the reinforced vehicles usually recording a larger neck force than the dummies in the production vehicles.

The Malibu studies demonstrated that when the impact is similar, the neck loading on the dummy is comparable for production and reinforced roofs. Thus, production and reinforced roofs have equivalent risk for neck injuries in rollover impacts.

Both Friedman and Friedman (7) and Syson (8) criticize the Malibu authors for using 2000 N of axial neck force as the “potentially injurious impact force” when comparing neck forces for production and reinforced roofs. They claim that this level is too low and they have reanalyzed the data using different neck load thresholds. They find that the production roof has an increased frequency of high neck loads and claim that reinforced roofs result in lower neck injury risk. However, while both Friedman and Friedman (7) and Syson (8) use the Mertz (12) neck injury criterion, which is illustrated in Figure 4, they do not consider the impact duration part of the criterion. Since the production roof has more potentially injurious impacts due to the nature of the test method, an increased occurrence of high neck forces would be expected to some extent. Again, these criticisms confuse the severity of the impact with the crashworthiness of the vehicle.

Friedman and Friedman (7) claim that the Malibu tests are invalid because the Hybrid III neck is not representative of the human neck and the dummies “can neither, hold on, brace themselves, protect their head and neck with the arms, nor keep their chin on their chest”. However, the authors do not offer any evidence that occupants in rollover accidents attempt such maneuvers, can perform these maneuvers, or that attempting such maneuvers alters forces in a significant way.

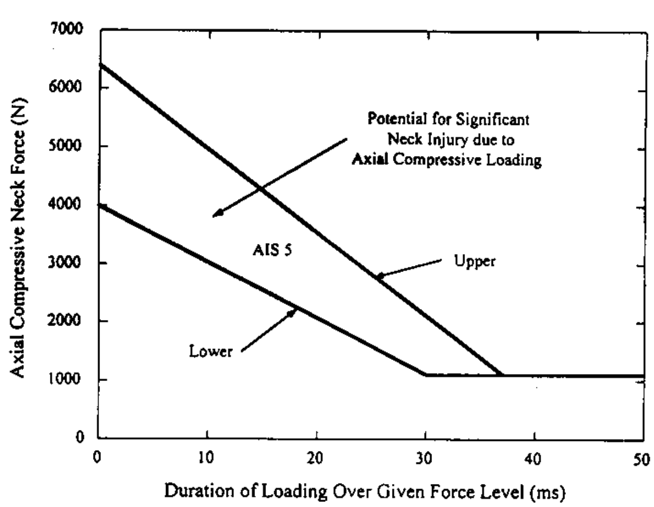

Figure 4. Neck axial compressive tolerance derived from Mertz, et al., (11).

Friedman and Friedman (7) and Syson (8) also claim that the Hybrid III neck stiffness is too great to simulate human neck injuries. At the same time, they both use the Mertz neck compression injury criterion (13) in their analysis of the Malibu studies. This injury criterion is based on studies in which the Hybrid III dummies were exposed to impacts which caused cervical fractures in humans (12). The resulting Hybrid III neck forces were used to establish the injury tolerance curve. Thus, using the Hybrid III dummy in conjunction with the Mertz neck compression injury criterion is appropriate to evaluate the potential for human neck injury.

NECK STIFFNESS

In addition to the previously noted qualitative criticisms of Hybrid III neck stiffness, Syson (8) developed a lumped mass, linear spring model of an occupant (torso, neck, and head) and vehicle (body, seat, lap belt, roof stiffness, roof padding, and roof) to simulate neck loads in drop tests. His study concludes that a lower neck stiffness decreases neck injury risk in vehicles with stiffer roofs. His neck stiffnesses range from 0.53 KN/cm (claimed to be human neck stiffness) to 10.51 KN/cm, a ratio of about 20 to 1. Syson bases his evaluation of neck stiffness on articles by Yoganandan, et al., (14), Pintar, et al.,(15), and Myers, et al.(16). In the Pintar study (15), heads of cadavers were impacted with an electro-hydraulic actuator while muscle tension was simulated with a spring and pulley system attached to the head. The study reported peak forces at the head and at the base of the cervical spine. These forces differed more for the cadaver than for the dummy. Peak actuator displacements averaged 3.4 cm for the cadavers and 2.4 cm for the dummies. No stiffness data was available.

Yoganandan (14) applied loads to the heads of intact cadaver torsos and the heads of isolated cervical spines (without musculature), and to C2-T2 specimens using an electro-hydraulic actuator. Again, the boundary conditions at the head were not carefully controlled, making a direct comparison of the data somewhat questionable. However, it can be seen from Table 1 that the head/neck stiffness of the Hybrid III is similar to the cadaver head/neck stiffness in this test series.

Table 1. Comparison of neck stiffnesses at 2.54 mm/sec. from Yoganandan (14)

Specimen	Stiffness (KN/cm)	Hybrid III/ Cadaver Stiffness Ratio
Hybrid III head and neck	5.56	
Cadaver Head-cervical spine	1.49-3.94*	1.4-3.7
Hybrid III neck	7.14	
Cadaver Isolated cervical spine	1.52-3.15	2.3-4.7

* The upper value for cadaver head-cervical spine stiffness is based on the value reported in the text.

The study by Myers et al., (16) carefully controlled the boundary conditions of the cervical spine for three different test conditions. T1 was held fixed at a 25 degree angle such that the C7-T1 motion segment was free to move. For the fixed boundary condition the base of the skull was constrained for both linear and rotational motion. For the rotationally constrained boundary condition the base of the skull was unconstrained for linear motion but rotation was constrained. For the unconstrained boundary condition both linear motion and rotation of the base of the skull were unconstrained. The applied load was vertical compression. Stiffness comparisons between the Hybrid III and the cadavers must be made for the same boundary conditions. When reviewing Table I in the article by Myers, et al., (16) it should be noted that the neck stiffness comparisons are made at low loads. This table reports ratios of Hybrid III stiffness to cadaver stiffness of 10.2 for a fully constrained boundary condition, 11.8 for a rotationally constrained boundary condition, and 50.3 for an unconstrained boundary condition. While these observations are valid at low loads, neck stiffness at potentially injurious loads is important in the rollover tests.

The stiffness data at higher forces can be derived from Myers' work (16). Figure 5 illustrates the Hybrid III and cadaver force-deflection data for fully constrained and rotationally constrained boundary conditions derived from Myers' Figures 6 and 10. The unconstrained data is not included as this boundary condition did not result in any injury at maximum test displacement. Note that for both boundary conditions there is finite displacement prior to the load increasing. The stiffness at higher loads can be estimated by assuming approximately 50 N of compressive preload in the neck (due to contractile muscle forces) and fitting the portion of the force-deflection curve above 50 N with a straight line. This technique results in a fully constrained boundary condition stiffness of 9.6 KN/cm and a rotationally constrained boundary condition stiffness of 0.73 KN/cm. The fully constrained boundary condition is consistent with burst fractures often seen in rollover accidents. The stiffness value of 9.6 KN/cm is actually larger than that reported for the Hybrid III. Table 2 in the Myers paper summarizes data for several tests. Table 2 of this paper presents the average stiffness values calculated from the peak force and displacement data based on Myers' reported displacement. Adjusted stiffness data is also included in Table 2 which reflects the reported displacements minus 3 mm corresponding to the 50 N preload previously discussed. Adjusted stiffness data derived from Myers' Figure 10 is also included.

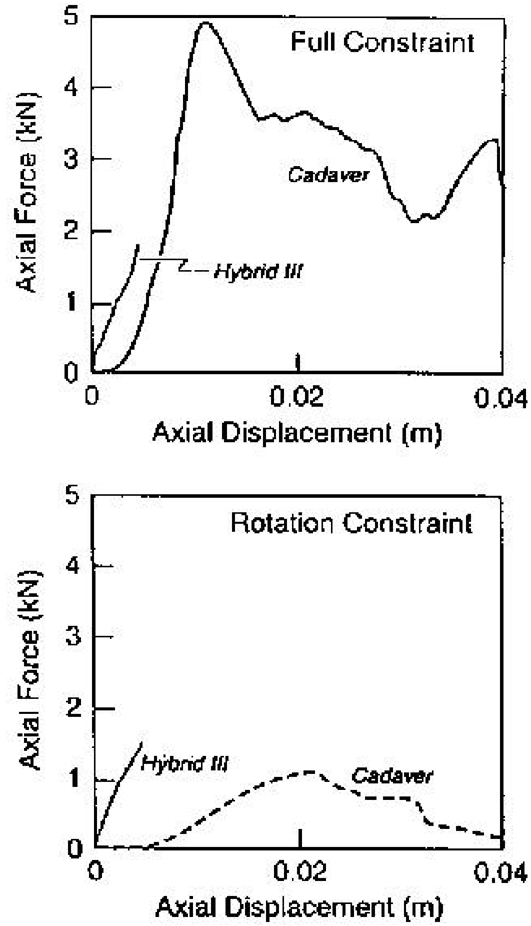

Figure 5. Hybrid III and cadaver force-displacement data corresponding to fully constrained boundary conditions, derived from Myers, et al., (15).

Table 2. Cadaver axial test results from Myers' (16) Table 2 and Figure 10

End condition	**Range of stiffnesses from Table 2 (KN/cm)**				**Average stiffness from Table 2 (KN/cm)**		**Adjusted stiffness from Figure 10 (KN/cm)**
	reported		adjusted		reported	adjusted	linear fit
	min	max	min	max			
Full constraint	1.8	5.7	2.1	7.5	3.6	4.6	9.6
Rotational constraint	0.24	1.0	0.24	1.1	0.57	0.61	0.73

Table 3. Hybrid III data derived from Myers' (16) Figure 6

End condition	Peak force (N)	Axial deflection (cm)	Stiffness (KN/cm)	Hybrid III/adjusted cadaver stiffness
Full constraint	1850	0.44	4.2	0.89* : 0.39**
Rotational constraint	1580	0.46	3.4	5.3* : 3.1**

*based on average adjusted cadaver stiffness data from Table 2
**based on cadaver data derived from a linear curve fit to Figure 4 data corresponding to loads above approximately 50 N

Myers provides data for the Hybrid III up to about 4.5 mm. A linear fit from the origin to the end of the data was used to generate the stiffness data in Table 3. The curve for the Hybrid III's rotationally constrained stiffness was starting to soften after about 2.5-3.0 mm and may be more similar to the cadaver data at larger displacements. The results in Table 3 clearly demonstrate that the ratio of Hybrid III to cadaver neck stiffness ranges from 0.39 to 0.89 for the fully constrained case and from 3.1 to 5.3 for the rotationally constrained case. These results demonstrate that the neck stiffness of the Hybrid III is approximately the same as the cadaver stiffness for compressive loading with a fully constrained end condition and is not unreasonably stiff for the rotationally constrained loading condition. It should be noted that in the Myers' study the average failure load for the fully constrained tests was 4810 N and for the rotationally constrained tests the average failure load was 1720 N.

Yoganandan, et al., (14) also measured the Hybrid III neck stiffness at various loading rates and found the stiffness increased with loading rate. Yoganandan's data is reproduced here as Table 4. Syson arbitrarily selected 5.25 KN/cm for the stiffness of the Hybrid III neck but uses neck stiffness data up to 10.5 KN/cm in his simulations. Based on Yoganandan's data, the latter value may be appropriate for the Hybrid III under dynamic loading conditions. Since the spine is a viscoelastic structure, the stiffness of a cadaver neck will also increase with loading rate. Consequently, any comparison of dummy neck stiffness data with cadaver data must be at similar loading rates. In view of these considerations, the cadaver compression stiffness data from Table 2, obtained for the fully constrained boundary condition at a displacement rate of 1.0 cm/sec, ranges from 2.1-9.6 KN/cm, which is comparable to the Hybrid III data in Table 4 at similar rates.

From the above review of neck stiffness data it is clear that a neck stiffness of 0.53 KN/cm is much too low for the neck in axial compression at failure loads with a fully constrained boundary condition. Despite this observation, Syson uses the Mertz failure criterion developed for burst compression fractures. These fractures are associated with the fully constrained boundary condition. A stiffness of 0.53 KN/cm is more consistent with the rotationally constrained boundary condition which has a failure load of 1.7 KN, not the 4.0 KN level used in Syson's paper. Additionally, it is important to note that with a neck stiffness of 0.53 KN/cm, there would have to be 7.5 cm of deflection in the neck prior to reaching Syson's proposed failure force of 4.0 KN, or 11.3 cm for the 6.0 KN maximum failure load on the Mertz curve. This is significantly more deflection at failure than Myers (1.1-3.9 cm) or Pintar (2.5-4.3 cm.) found for boundary conditions consistent with observed injuries.

Table 4. Hybrid III neck test data derived from Yoganandan's (14) Table 6

Rate of loading (mm/sec)	Stiffness (KN/cm)
254.0	11.24
25.4	8.4
2.54	7.14

Comparing the dynamic response of the Hybrid III and cadaver to a simple drop test also provides insight regarding the comparative system stiffnesses. Figure 6 depicts the force time history of the neck load cell of a Hybrid III dummy in a drop test. The dummy was in a compact pickup truck with a reinforced roof. Also illustrated in Figure 6 is the force-time history of a load cell at the base of a cadaver neck/head specimen as reported by Nightingale, et al., (17) for an impact with a flat rigid surface (Test C). The similarity of the pulse widths indicates that the dynamic response of the two systems is comparable. Although the drop tests did not afford the ability to carefully control boundary conditions and the testing environments are not identical, significant errors stemming from substantially different system stiffnesses are not apparent based on this drop test data. Although further developmental work may result in even more biofidelic dummy necks, the available data indicates that the Hybrid III can produce meaningful results for some modes of compressive neck loading.

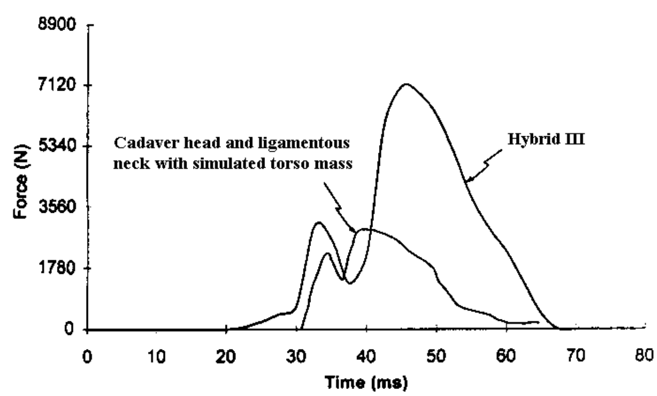

Figure 6. Neck compressive force histories corresponding to inverted drop tests with the Hybrid III and human cadaver. Hybrid III data is based on an impact with a vehicle roof surface. Cadaver data is derived from Test C of Nightingale, et al., (16) using a rigid, flat impact surface.

THE SYSON MODEL AND INPUT DATA

The validity of any analytical model is a function of the model's ability to simulate the physical system it represents and the accuracy of the input data. Syson (8) developed a discrete parameter model to simulate restrained and unrestrained occupants in a drop test comparable to those conducted by Bahling, et al. (4). The models, illustrated in Figure 7, are one dimensional and feature lumped masses, linear springs, and no damping. Syson's modeling assumes that an effective torso mass is perfectly aligned with the neck and that there is no separation between the seat and the occupant's torso at the time of initial roof contact. It is well known that the human body and the automotive structures modeled are nonlinear damped structures. In addition, modeling the multi-degree of freedom human body with two masses and one spring, even if nonlinear and damped, is very approximate and must be based on experimental data using similar loading conditions to have any potential for producing reasonable results. These fundamental characteristics of Syson's model can lead to misleading results.

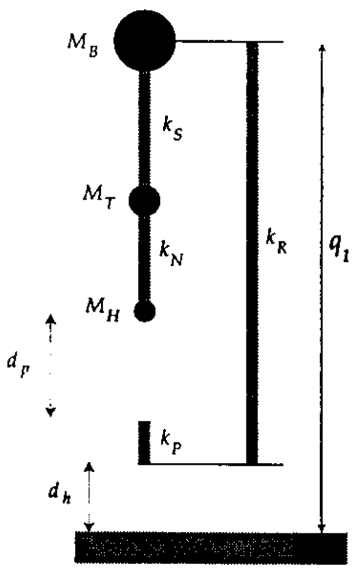

Figure 7a. Discrete parameter drop model for an unrestrained occupant based on the work by Syson (7).

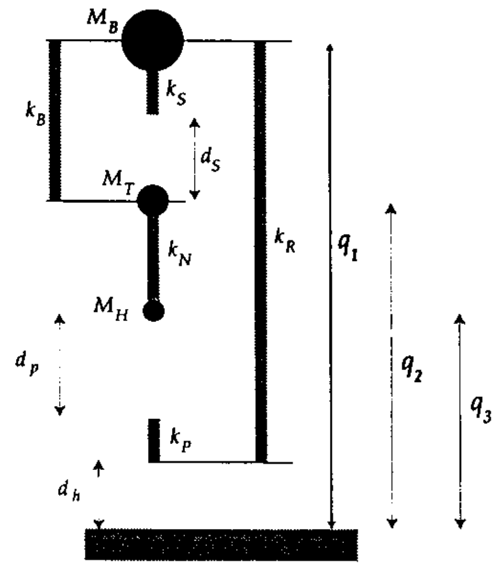

Figure 7b. Discrete parameter drop model for a restrained occupant derived from the work by Syson (7). The model includes the attributes of Syson's restrained occupant model but also incorporates the ability to introduce spacing. designated by d_S, between the occupant's torso and the seat.

The vehicle and occupant input data are also critical if meaningful results are to be obtained. In this regard, several questionable values are used in Syson's model. The neck stiffness values cover a range of 20 to 1 and the higher values of 5.25 KN/cm and 10.5 KN/cm are consistent with published neck stiffness values as previously noted. A seat stiffness of 0.35 KN/cm was used in Syson's model, which is based on values used in Calspan's Crash Victim Simulation (CVS) program. This value may be appropriate for situations in which the seat is severely compressed. In a drop test the seat is initially unweighted and subsequently compressed over only a few centimeters. MacLaughlin (18) measured the load-displacement data for 10 automotive seats in the center of the seats. The stiffness of these seats over the first 5 to 7.5 centimeters ranged from 0.037-0.096 KN/cm. The maximum stiffness at large displacements did range to higher numbers (0.12-0.53 KN/cm). However, for the drop tests being simulated, the stiffness used by Syson is too large and leads to inappropriate seat forces.

The seat belt stiffnesses used in Syson's models ranged from 0.88-1.75 KN/cm. The actual stiffness is a complex, non-linear function based on the characteristics of the retractor, belt, seatback and occupant. One approximation to the stiffness of these systems can be taken from a study by Arndt, et al. (19). Using human volunteers, Arndt measured the displacement from a normal seated position to an inverted position in an experimental seat/ restraint fixture. Using the overall displacement and correcting for body rotation, these data establish approximate stiffness values for a 45 degree lap belt angle of 0.061 KN/cm with 2.5 cm of slack and 0.080 KN/cm with 222 N of pretension. It is important to note that Arndt did not use a shoulder belt in his experiments. Research has demonstrated that the shoulder belt will keep the occupant's back against the seatback but will not exert large restraining forces along the vertical axis of the occupant's torso for relatively small displacements. The displacement for Arndt's 1.0 g loading was 13.0 cm for 2.5 cm of initial belt slack and 10.0 cm for 222 N of belt pretension. Both of these displacements are greater than the 7.62 cm clearance between the head and the roof used in Syson's model. In fact, Syson predicts less than 1 cm of displacement for 1 g loading. Therefore, his belt model is inappropriate for drop tests.

The roof stiffnesses used in Syson's simulations ranged from 1.75 KN/cm to 7.0 KN/cm. (It should be noted that this stiffness is referred to as strength in Syson's paper.) It is not clear if Syson is using a stiffness range representative of current vehicle models, or if he is using a range that he believes is stiffer than current models. Since roofs have a nonlinear load-displacement characteristic, the best linear stiffness fit to the data depends on the magnitude of the displacement. For example, Diagram 2 in Moffatt and Padmanaban (1) is a typical result from a FMVSS 216 roof test. If a straight line is drawn from the origin to point A (the approximate linear limit) the stiffness is 10.9 KN/cm. If a line is drawn to point B (the maximum load) the stiffness is 4.4 KN/cm. Kahane (20) published roof loading data on 108 vehicles manufactured from 1974 to 1985. The data included the load and displacement at the FMVSS 216 limit and at the maximum force. The linear stiffness values based on the slope of a line from the origin to the FMVSS 216 limit ranged from 1.51 KN/cm to 7.98 KN/cm with an average of 4.47 KN/cm. The linear stiffness based on the slope of a line from the origin to the point of maximum force ranged from 1.22 KN/cm to 7.83 KN/cm with an average of 4.18 KN/cm for the peak force. Given the typical nature of these load displacement tests, it is clear that the roof is even stiffer in load ranges below the FMVSS 216 limit. Using the lower Syson stiffness of 1.75 KN/cm and his vehicle weight of 12 KN results in a displacement of 10.3 cm at 1.5 times vehicle weight. The resulting force to weight ratio at the FMVSS 216 displacement limit of 12.7 cm is 1.85. The range of peak force to weight reported by Moffatt and Padmanaban was 1.7 to 3.6. Given the nonlinear nature of the data it appears that the stiffness range used by Syson is consistent with the stiffness range of the vehicles in the fleet and with those studied by Moffatt and Padmanaban (1). Since no correlation was found between roof strength and injury risk in the Moffatt and Padmanaban field study, any conclusions to the contrary from an approximate simulation study must be attributed to inaccuracies in the model.

It is also informative to examine representative output data from Syson's analysis. To do this we used the computer source code published in the paper to recreate the governing equations and characteristics which were evaluated with Mathematica. The only difference in the model implementation is that Syson used a first order integrator while we used a fourth order integrator. Syson's time step was not provided. We used a time step of 0.001 sec and verified convergence. We then ran the program to recreate the output of Figure 5 in the Syson paper and found close agreement.

Figure 8 presents output data for an unrestrained occupant with drop height of 305 mm, a neck stiffness of 0.53 KN/cm, and a roof stiffnesses of 1.75 KN/cm. Figure 9 uses the same data except that the roof stiffness was increased to 3.5 KN/cm. The peak force in the neck is approximately the same for both runs, but the softer roof has a dual peak. This second peak extends the time the load is on the neck. The second peak occurs due to the timing of the load from the seat bottom. With the stiffer roof the seat bottom loading occurs later and is more out of phase with the rebound phase of the loading in the neck. Therefore, the supposed benefit of a shorter pulse in the neck with the stiffer roof is due to the timing of the seat load. This is inaccurate for multiple reasons. First, the seat would not be in contact with the occupant at roof contact as noted in both Malibu studies. Second, the seat stiffness used by Syson is considerably higher than that of production seats and consequently produces artificially high loads that are transferred to the neck. In addition, since Syson's model is undamped, results in the rebound stage will be subject to considerable error. It is during the rebound of the torso that the extended pulse is observed. Therefore, the claimed pulse extension takes place well after an undamped model has any potential for validity. Moreover, this pulse extension is only observed for the lowest roof stiffness of 1.75 KN/cm. The other three roof stiffnesses used by Syson resulted in pulse durations comparable to the simulation with a roof stiffness of 3.5 KN/cm as depicted in Figure 9. Therefore, no trend is established for relating increases in stiffness to reduced loading pulse duration.

Syson's model was modified to have an initial condition corresponding to a 5.08 cm spacing between the seat and the torso and a 2.54 cm space between the head and the roof padding as illustrated in Figure 5b. The simulation used a neck stiffness of 10.51 KN/cm. The results of this analysis are shown in Figure 10 for a roof stiffness of 1.75 KN/cm. The neck pulse durations and maximum forces were unchanged with increases in roof stiffness.

Finally, the only significant benefit that Syson (8) attributed to stiffer roofs was a decreased neck load pulse duration. As noted previously, the failure criterion used by Syson and illustrated in Figure 4 was based on tests with the Hybrid III. There is no indication that this failure criterion is applicable to double pulse load histories as found in Figure 8. In addition, if the force time histories in Figures 8 and 9 are compared to the failure criterion of Figure 4, both would predict serious neck injury. The pulse in Figure 8 is above 2000 N for about 0.2 seconds and is clearly in the static tolerance part of the compressive neck injury tolerance curve and well above the static tolerance of 1100 N. The pulse in Figure 9 is above 2000 N for about 0.075 seconds and is also in the static tolerance part of the curve and well above the 1100 N level. As a consequence, it is difficult to expect a different outcome for the two neck load histories based on the compressive neck injury criteria illustrated in Figure 4.

It is clear that the model and data used in the Syson paper are not capable of providing any insights into understanding neck injury risk and the effects of roof stiffness.

CONCLUSION

In field studies of rollover accidents it is difficult to determine if neck injury risk is associated with roof crush or caused by roof crush. Studies which quantitatively assessed roof strength did not find any reduction of injury risk with increased roof strength. These studies conclude that roof strength is not causally related to injury risk. Critics of the Malibu studies have noted fewer potentially injurious neck loads among vehicles with reinforced roofs. These observations confuse impact severity with vehicle performance. The Malibu studies noted that, for similar impacts, neck loads were similar for both production and reinforced roofs. It has also been shown that the neck stiffness of the Hybrid III dummy and the human cadaver is reasonably similar for both fully constrained and rotationally constrained compressive loading. Both of these boundary conditions have been experimentally associated with neck injury. Consequently, the conclusions of the Malibu papers concerning neck loads are appropriate. Finally, the computer model and analysis developed by Syson are not representative of drop tests with Hybrid III dummies or cadavers. No meaningful conclusions can be based on Syson's analysis.

ACKNOWLEDGMENTS

We would like to thank Matthew Kaplan for his contributions to this work. The authors also appreciate the invaluable assistance of Amy Rickerson in the preparation of this document.

REFERENCES

1. Moffatt, Edward A. and Padmanaban, Jeya, "The Relationship Between Vehicle Roof Strength and Occupant Injury in Rollover Crash Data," 39th Annual Proceedings; AAAM, Oct 1995.
2. James, Michael B.; Allsop, Douglas L.; Nordhagen, Ronald P., and Decker, Robin L., "Injury Mechanisms and Field Accident Data Analysis in Rollover Accidents," SAE Paper No. 970396, 1997.
3. Orlowski, Kenneth F.; Bundorf, R. Thomas, and Moffatt, Edward A., "Rollover Crash Tests - The Influence of Roof Strength on Injury Mechanics," SAE Paper No. 851734, 1985.
4. Bahling, G. S.; Bundorf, R. T., and Kaspzyk, G. S.; Moffatt, E. A.; Orlowski, K. F., and Stocke, J. E., "Rollovers and Drop Tests- The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," SAE Paper No. 902314, 34th Stapp Car Crash Conference Proceedings, pp. 101-112, 1990.
5. Rechnitzer, George and Lane, John, "Rollover Crash Study - Vehicle Design and Occupant Injuries," Monash University Accident Research Centre, Report No. 65, Victoria, Australia, Dec 1994.
6. Rains, Glen C. and Kanianthra, Joseph N., "Determination of the Significance of Roof Crush on Head and Neck Injury to Passenger Vehicle Occupants in Rollover Crashes," SAE Paper No. 950655, 1995.
7. Friedman, Donald and Friedman, Keith D., "Roof Collapse and the Risk of Severe Head and Neck Injury," Proceedings of the 13th ESV Conference, pp. 753-765, Nov 1991.
8. Syson, Stephen R., "Occupant to Roof Contact: Rollovers and Drop Tests," SAE Paper No. 950654, 1995.
9. Moffatt, Edward A., "Occupant Motion in Rollover Collisions," 19th Annual Proceedings, AAAM, pp. 49-59, Nov 1975.
10. Piziali, R. L., "Cervical Spine Injuries in Sports," Biomechanics in Sport - A 1987 Update, Bioengineering Division, ASME, Vol. 6, pp. 123-127, Dec 1987.
11. Alem, Nabih M.; Nusholtz, Guy S., and Melvin, John W., "Head and Neck Response to Axial Impacts" SAE Paper No. 841667, 1984.
12. Mertz, H. J.; Hodgson, V. R.; Thomas, L. Murray, and Nyquist, G. W., "An Assessment of Compressive Neck Loads Under Injury-Producing Conditions," The Physician and Sportsmedicine, pp. 95-106, Nov 1978.
13. Mertz, Harold J., "Injury Assessment Values Used to Evaluate Hybrid III Response Measurements," Safety and Crashworthiness Systems, General Motors, Feb 1984.
14. Yoganandan, N.; Sances, A., and Pintar F., "Biomechanical Evaluation of the Axial Compressive Responses of the Human Cadaveric and Manikin Necks," Journal of Biomechanical Engineering, Vol 111:250-255, Aug 1989.
15. Pintar, Frank A.; Sances, Jr., Anthony; Yoganandan, Narayan; Reinartz, John; Maiman, Dennis, J.; Suh, Jung Keun, et al., "Biodynamics of the Total Human Cadaveric Cervical Spine," SAE Paper No. 902309, 1990.
16. Myers, Barry S.; McElhaney, James H., Nightingale, Roger W.; Doherty, Brian J.; and Richardson, William J., "The Influence of End Condition on Human Cervical Spine Injury Mechanisms," 35th Stapp Car Crash Conference Proceedings, SAE Paper No. 912915, 1991.
17. Nightingale, Roger W.; McElhaney, James H.; Richardson, William J., and Myers, Barry S., "Dynamic Responses of the Head and Cervical Spine to Axial Impact Loading," Journal of Biomechanics, 29(3):307-318, 1996.
18. MacLaughlin, Thomas F.; Sullivan, Lisa K., and O'Connor, Christopher S., "Experimental Investigation of Rear Seat Submarining," Proceedings of the 12th ESV Conference, pp. 261-271, 1989.
19. Arndt, Mark W.; Mowry, Gregory A.; Dickerson, Charles P., and Arndt, Stephen M., "Evaluation of Experimental Restraints in Rollover Conditions," SAE Paper No. 952712, 1995.
20. Kahane, Charles J., "An Evaluation of Door Locks and Roof Crush Resistance of Passenger Cars," Accident Reconstruction Journal, pp. 24-47, Mar/Apr 1995.

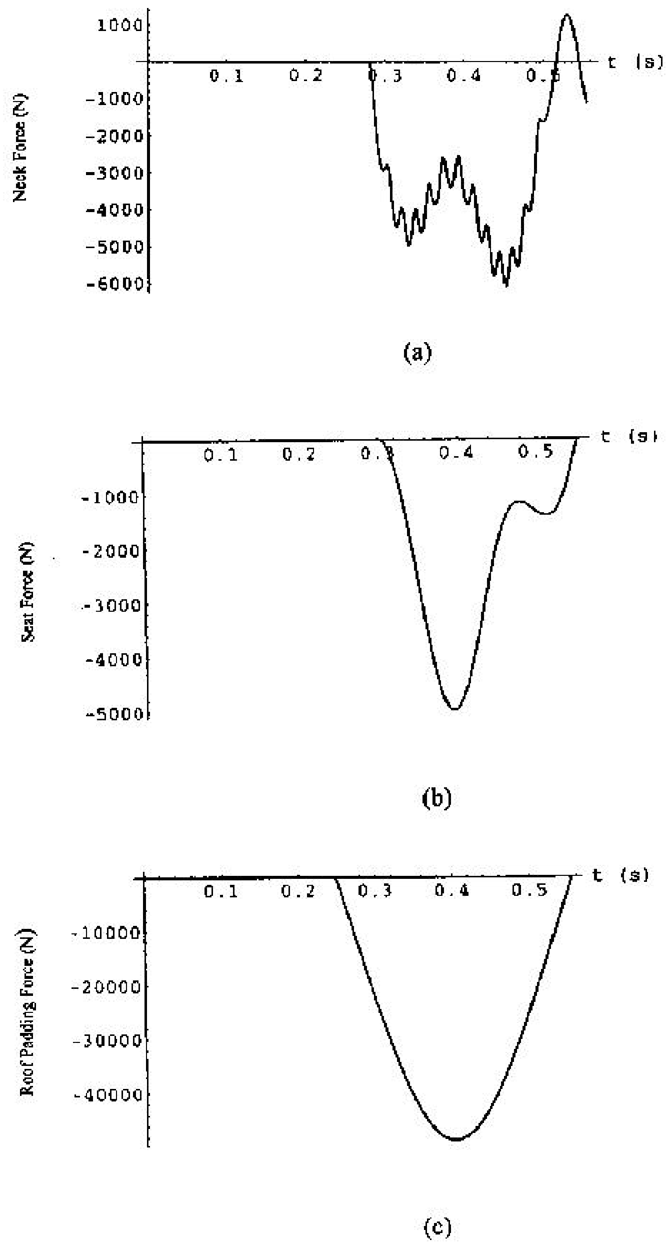

Figure 8. Force histories derived from Syson's unrestrained occupant model using a drop height of 305 mm, a neck stiffness of 0.53 KN/cm, and a roof stiffness of 1.75 KN/cm.

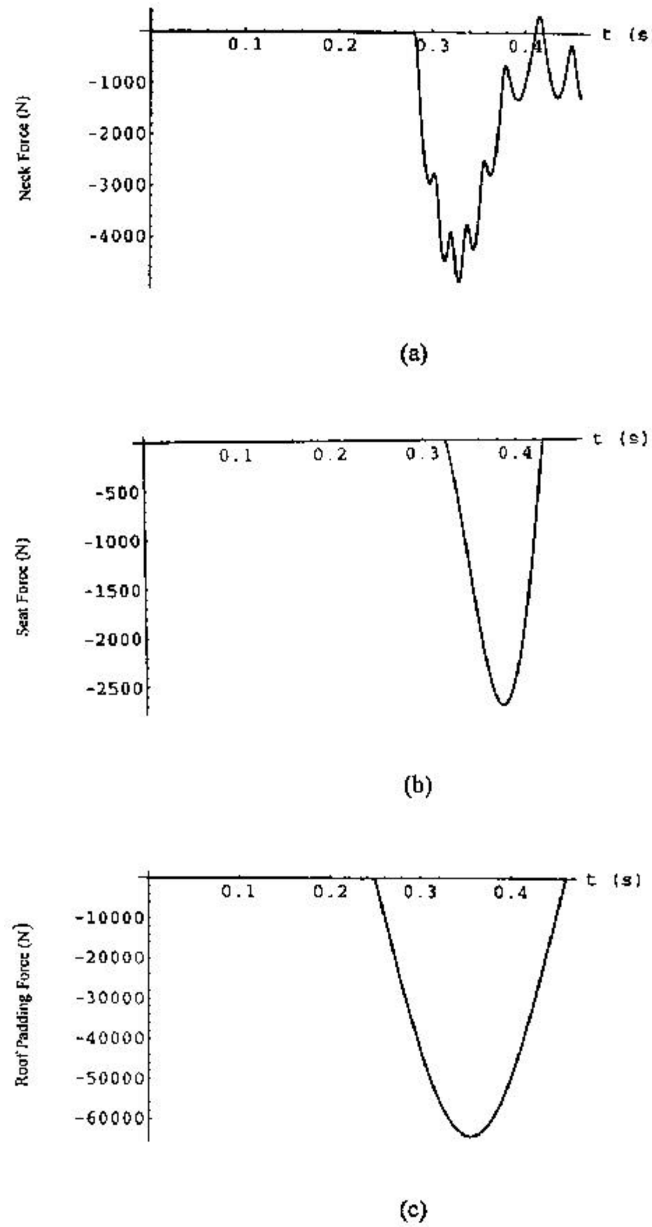

Figure 9. Force histories derived from Syson's unrestrained occupant model using a drop height of 305 mm, a neck stiffness of 0.53 KN/cm, and a roof stiffness of 3.5 KN/cm.

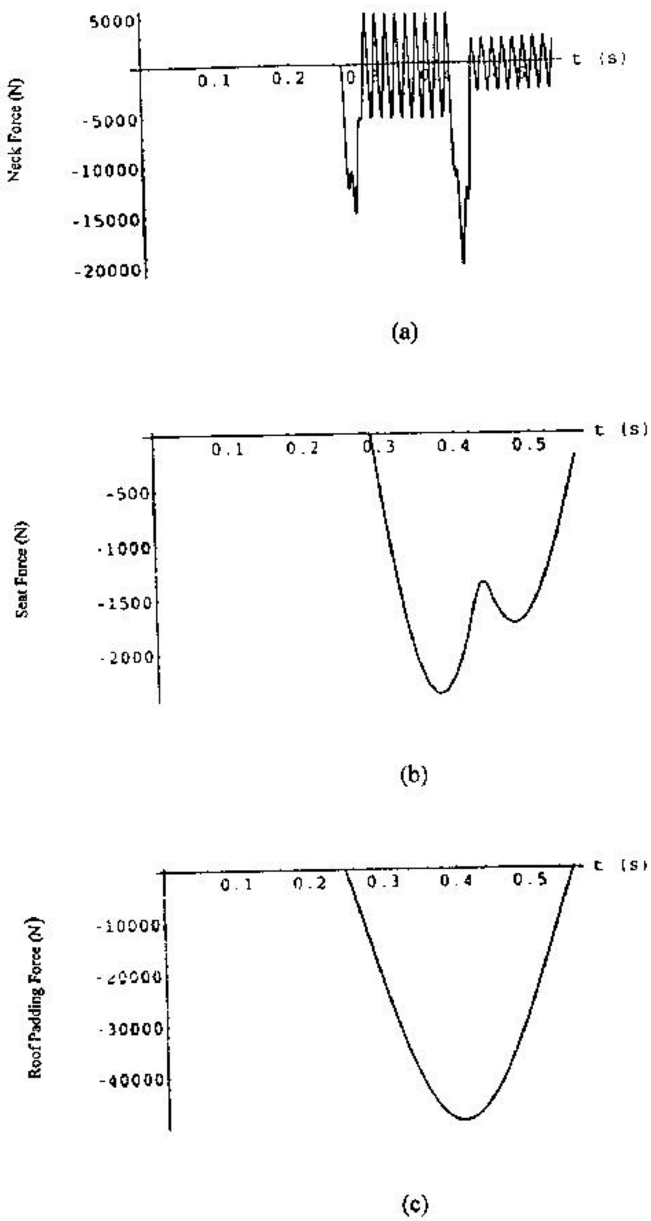

Figure 10. Force histories derived from Syson's unrestrained occupant model using a drop height of 305 mm, a neck stiffness of 10.51 KN/cm, and a roof stiffness of 1.75 KN/cm, and incorporating an initial seat to torso spacing of 5.08 cm.