Protection of Passengers Sitting Laterally in a Light Truck Box Undergoing Crash.

Z. Ashkenazi [1] M. Arcan [2]

TEL AVIV UNIVERSITY
FACULTY OF ENGINEERING
RAMAT AVIV , 69978 TEL AVIV, ISRAEL

Abstract

The purpose of this work was to investigate the biomechanical motion of the occupant who is sitting in a rear box of a light truck undergoing a standard crash test in order to suggest reasonable solutions; such solutions will confer the passenger the same protection level as available to the occupant sitting in the direction of travel and restrained by a three point seatbelt. Another objective was to expose to the relevant authorities, concerned with road safety, the danger of transporting unprotected human passengers in such boxes.

The research was conducted using the MADYMO 5.0 program. The model was a dummy sitting in a rear box which is undergoing deceleration of ECE-R 16 mid-severity crash (20 g , 50 $\frac{km}{h}$). Five main cases were examined: (1) no restraint system at all, (2) lap belt only, (3) padded wall only (4) combination of a lap belt and padded wall and (5) a protective net together with a lap belt.

Results show that in the case of no restraint systems the situation of the passenger can only be described as catastrophic and the use of a lap belt would cause even worse injury parameters. Two different solutions are suggested: (1) A padded wall, 100 mm thick with specific shock absorbing properties and a particular structure. (2) A new innovative approach of protective nets.

1 Introduction

In many countries it is common to transport people in a box which is built on top of a light duty truck (Fig 1). Most of the boxes are made by local manufacturers and are attached to the vehicle as an after market product. In the field of automotive safety research, the case of an occupant sitting laterally to the direction of travel does not attract any attention of investigators. The most similar application is occupant protection of car occupants against side impact [2, 3, 4, 5, 6, 8, 7, 12, 13, 14, 15]. Table 1 indicates the difference between these two cases.

The occupant who is sitting in such a box is exposed to more severe injuries during a crash, compared to the occupant sitting in the direction of travel, for the following reasons:(a) *Lack of restraint systems* —The occupant is not restraint and therefore is free to move in any direction within the space of the box, while the occupant, sitting in the direction of travel, is restraint by a shoulder-lap belt. (b)*Rigid environment* — The walls of the box are made of steel or fiberglass sheets both reinforced by metal columns, compared to a cabin interior which is softer due to the use of some padding materials. (c)*Local disturbances* — Window handles, metal reinforcing columns, bolts, nuts and any other rigid or sharp objects have major effect of stress-concentration. The front cabin is well designed to avoid contact of the occupant with any such objects.

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[1] Master degree student
[2] Professor of Applied Mechanics and Biomechanics

Objective The scope of this work is to analyze the risks upon passengers sitting in a rear box of a truck during a crash and to suggest restraint systems or structures to provide means of protection for those occupants. Another aim was to expose to the relevant authorities concerned with road safety the danger of transporting human passengers in such boxes.

Parameters	Rear Box Impact	Car Side impact
Impact velocities	High - Medium	Medium - Low
Penetration of the side wall	No penetration	Penetration relative to impact velocity
The head impacts against	A rigid wall	A side Pillar or a side window

Table 1: Comparison between a rear box impact and a car side impact

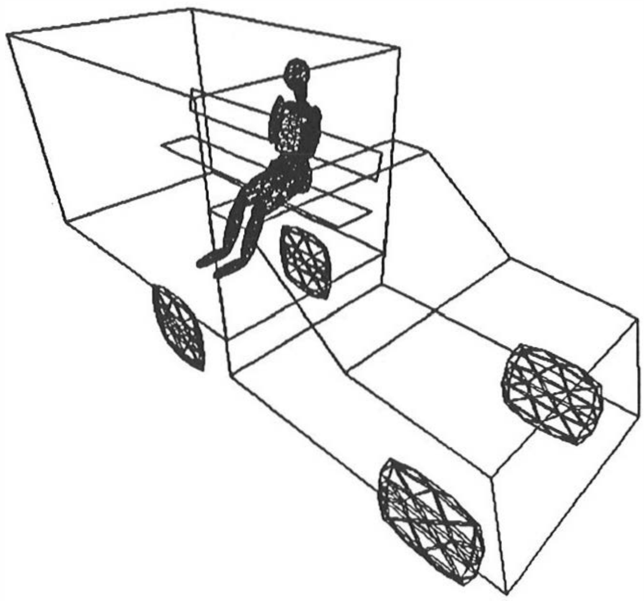

Figure 1: Light truck with a box for passengers transportation

2 Numerical Approach 3-D

A human body model The basic model of the human body was taken from MADYMO 3D databases [9]. The EUROSID represents a 50th percentile adult male, based on a first production dummy. It was designed to measure rib spinal and pelvis accelerations, as well as chest deflection time history [8]. Few modifications of the dummy were made to adjust it to the simulation of a side impact against a full height wall. *Head* — No original characteristics were included. Loading function was adopted from Bowman's head model [1]. *Hysteresis Functions* — were adopted for all the contact ellipsoids from the 2-D model of the 50th percentile Part 572 dummy for side impacts [9].

A box model Out of many types of boxes available in the market the box that was chosen for the model was a universal rectangular box which was built out of the following parts: bench, front wall, roof, rear wall and floor. The stiffness properties of the box were assumed to be the same as an A-pillar of a typical car measured by Willke[16].

Crash parameters The crash simulated was a mid severity pulse, 20 g, 50 km/h. Typical acceleration profile of the ECE-R16 (*standard crash test for vehicle manufacturers*), was taken from [9] and is presented in Fig 2.

A Belt model Only lap belt configuration was simulated because a shoulder belt would load the neck, which is too fragile to tolerate those enormous forces. The following types of belt models were used: A simple belt with typical properties of a belt were taken from [10]. A FEM belt built out of a mesh of 59 nodes linked by 76 elements connected by two belt segments. The initial conditions of the nodes were acquired by a presimulation.

A pad model The pad system consists of three different pads, each pad was to cushion another part of the body: head, thorax and pelvis. A pad element was built out of a plate which was connected to front wall of the box by four equal Kelvin elements 100 mm long . The stiffness properties of the wall behind the pad were given to the plate.[3] The structure was held by a restraint point that prevented the model to collapse. By optimization, through a process of iteration and by controlling the values of the elastic and the damping forces of each Kelvin element, the preferable values were obtained. The following considerations were the guidelines of the step by step iteration process: (1) The resultant force function of each element was examined to get the desirable results of a typical energy absorbing materials. (2) The Kelvin elements were allowed to compress 80 mm approximately, leaving 20 mm to prevent bottoming. (3) The location of the pad was shifted alongside the wall to derive equal compression in each side. (4) The elastic and damping functions of each Kelvin element (Fig 3,5)were modified. (5) Simulating the revised model and back to step one.

The combined belt & pad model The combined model was built out of a lap belt and three pads. The pads and the belts were taken from previous models. The properties of the pad were optimized in the same manner as described above. The occupant was constrained to sit 0.4 m from the wall by the location of the lap belt. The elastic stress versus the relative elongation of each pad is presented in Fig 3. The damping coefficient versus relative velocity for each pad is presented in Fig 5.

The net models All net models were made out of a mesh of nodes which were linked by triangular membrane elements. The properties of the elements were similar to those of a safety belt.All net models were located 0.3 m from the front wall, the occupant was sitting 0.6 m from the wall.

Full size net models Three full size nets with different nodal densities were created to evaluate the effect of the net density on the results. (a) Normal density–the net was built out of 234 nodes linked by 400 elements. (b) Half density–the net was built out of 117 nodes linked by 192 elements. (c) Double density–the net was built out of 578 nodes linked by 1056 elements.
There are countless modes to support the net, the straightforward method is from the roof to the bench (*or floor*). In this configuration the nets could be easily removed or slid upwards into a retractor spool when the need to transport cargo instead of people arises. Number of removable nets can be placed along the same bench, consequently converting

[3] The order of the springs was changed but since the springs were arranged in series the result should not be affected.

the box into a modular means of transportation either for passengers or cargo without sacrificing the safety of human travelers. In order to evaluate the effect of type of the supports on the results another pattern of horizontally supported net was made, both are presented as follows: *Vertically* supported by five belt segments that were attached from the upper edge e to the roof of the box and five belts from the lower edge to the bench. *Horizontally* supported by five belt segments that were attached from the internal edge to the back wall of the box and five belts from the external edge to a virtual supporting column in the center of the box.

Split net models Two different nets were made, an upper one for the head and a lower one for the thorax and the pelvis.(Fig 6) *The upper net* was built of 81 nodes linked by 128 elements. *The Lower net* was built out of 153 nodes linked by 256 elements. Although the simulated nets were totally separated there are a few possible designs to integrate the split nets into one system without directly connecting them. An integrated system built out of separated nets can make full advantage of the modular box design, already mentioned, and to provide a higher protection level for the human passengers. The following methods were used to support the nets: *Vertically* supported, the upper net was supported by two belt segments that were attached from the upper edge to the roof of the box and two reinforced belt segments [4] were attached from the lower edge to the bench. The lower net was supported by four [5] belt segments that were attached from the upper edge to the roof of the box and the same number of belt segments from the lower edge to the bench (Fig 8). *Horizontally* supported, the upper net was supported by two belt segments that were attached from the internal edge to the back wall of the box and two belt segments from the external edge to a virtual supporting column in the center of the box. The lower net was supported by three belt segments that were attached from the internal edge to the back wall of the box and three belt segments from the external edge to a virtual supporting column in the center of the box.

3 Results

Various models were developed but only a few selected ones are presented.

3FRONT — The occupant was sitting in the direction of travel, restrained by a three point belt, and was undergoing the same deceleration field as the occupant in the box.

In all the following models the distance was measured from the front wall to the occupant C.G while he was sitting laterally to the direction of travel.

3NNR — 0.7 m from a totally rigid wall, no belt and no pad. (*The wall was taken totally rigid so the worst case can be considered*).
3CNN — 0.4 m, no belt and no pad. (*The minimum distance from the wall*)
3NNN — 0.7 m, no belt and no pad. (*The normal distance from the wall*).
3NNA — 0.7 m, no belt and no pad but the left arm was raised.
3FNN — 2 m, no belt and no pad. (*The maximum distance from the wall*).
3CBN — 0.4 m, with a lap belt and no pad.

[4]Four times stiffer than normal belt
[5]Three when an additional lap belt was used

3NBN — 0.7 m, with a lap belt and no pad.
3CEN — 0.4 m, with a FEM lap belt and no pad.
3NEN — 0.7 m, with a FEM lap belt and no pad.
3CNP — 0.4 m, no belt and with a pad system.
3NNP — 0.7 m, no belt and with a pad system.
3CBP — 0.4 m, with a belt and with a pad system.
3CEP — 0.4 m, with a FEM belt and with a pad system.

In all the following models the occupant was sitting 0.6 m from the front wall of the box and was restrained by different net designs.

3V1B — Full-size net vertically supported with a FEM lap belt.
3V10.5 — Half density full-size net vertically supported with a FEM lap belt.
3V12.0 — Double density full-size net vertically supported with a FEM lap belt.
3V1N — Full-size net vertically supported without a lap belt.
3V2B — Two separated nets vertically supported with a simple lap belt.
3V2N — Two separated nets vertically supported without a lap belt.
3H1B — Full-size net horizontally supported with a FEM lap belt.
3H1N — Full-size net horizontally supported without a lap belt.
3H2B — Two separated nets horizontally supported with a FEM lap belt.
3H2N — Two separated nets horizontally supported without a lap belt.

Accelerations and Forces Figure 4 presents the accelerations of the head in the models 3NNN, 3FRONT, 3CBP, 3V2B and 3H2B.

Injury parameters The injury parameters HIC, GSI , 3MS , TTI and V*C as obtained from the simulations are presented in Table 2 and in Figures 7 and 8.

Graphical motion illustration Graphical motion of model 3NNN are presented in Fig 9, of model 3CEP in Fig 10 and of model 3V2N in Fig 11.

4 Conclusions

The case of no restraint systems The case of a passenger sitting in a rear box of a light duty truck undergoing crash ought to be described as catastrophic if injury parameters are considered. The severity of the injuries of the occupant in the box compared to the passenger sitting in the direction of travel, may be explained by a superior magnitude of deceleration involved. The skull is likely to be fractured and the brain would probably undergo irreversible damage. The internal organs of the chest would also undergo severe trauma. The worst case is to sit far from the front wall. In a frontal crash the box would lose its entire traveling velocity prior to the occupant–wall impact (*when traveling with 50* $\frac{km}{h}$ *is analogous to a free fall from 10 m on a rigid metal plate*).

Effect of the arm The main effect of the left/right arm, if located in the gap between the thorax and the front wall, is to reduce the TTI by 40 % while most of the other injury parameters are reduced slightly.

Belt-only system It appears that there is no significant difference between FEM and simple belt models. In both cases the use of a lap belt alone seems to make things even worse. The belt restrains the pelvis, causing the head to strike the front wall with all the upper body energy. This leads to the conclusion that **belts should not be used without complementary padding.**

Pad-only system When the occupant is sitting near a padded wall with energy absorbing cushions, 100 mm thick, the injury parameters are lowered almost to the same level of the passenger sitting in the direction of travel. The main drawback of the pad system is its dependence on the passenger position; if he is not sitting near the wall, the whole scenario changes for the worse.

Combined belt & pad system A better suggested solution looks to be the combined model. The great advantage of this combination is that the occupant is constrained to sit near the wall by the belt location. The belt would restrain the occupant to the nearby surroundings of the padded wall in the case of an oblique crash or a combination of a rollover ending in a frontal crash. A belt may also provide a good supplementary restraint system in the case of all other types of crashes[6], thus avoiding the occupant from striking the roof or the opposite wall. The drawback of this solution is its inability to provide protection for more than one passenger sitting on the bench.

The net system The injury parameters of the occupant restrained by a protective net are around the maximum allowed tolerance levels and are greater than that of the passenger sitting in the direction of travel. These results are a consequence of a limited net model with totally elastic properties and with no energy absorption. With consideration of visco-elasto-plastic properties and of friction induced between layers, net models[7] with more accurate and promising outcomes might be expected. An undesirable effect of a full net is the influence of forces exerted by the lower part of the body, the thorax and the pelvis, on the global net tension. In order to decrease the head injury parameters it is necessary to let the head impact a separate net which will be independent of the tension in the lower one. A reasonable solutions can be a split net system; the results obtained from the simulations indicate significant improvement of all injury parameters especially HIC[8] and GSI[9]. Although the simulated nets were totally separated, there are a few possible designs to integrate the split nets into one system without directly connecting them. Such removable net systems when placed along the same bench, can convert the box into a modular means of transportation, both for passengers and cargo without sacrificing neither safety of human travelers nor cargo space. This configuration is very promising for future research and might be very practical.

Summarizing Conclusion It is evident that the case of no restraint system is catastrophic. The use of a padded wall together with a lap belt gives good results but is useful only for one passenger on the bench. The approach of a protective net could be the solution for safe transportation of passengers or when needed a full cargo space.

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[6] Such as rollovers or side impacts of the truck which are beyond the scope of this work.
[7] These features are not available in MADYMO 5.0
[8] Head Injury Criterion
[9] Gadd Severity Index

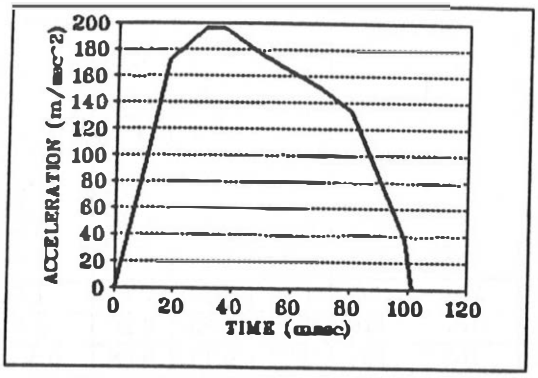


Figure 2: Vehicle deceleration-time histories

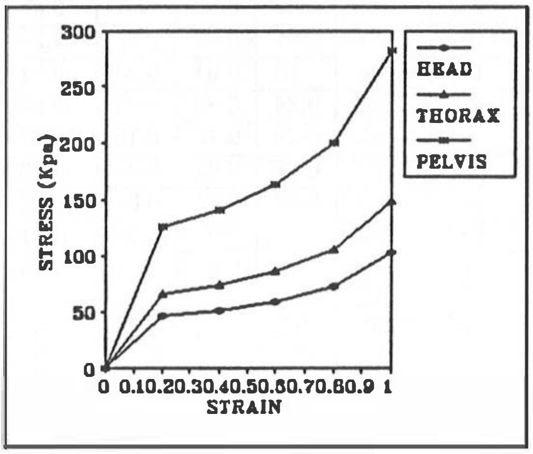


Figure 3: Elastic stress versus strain of pads

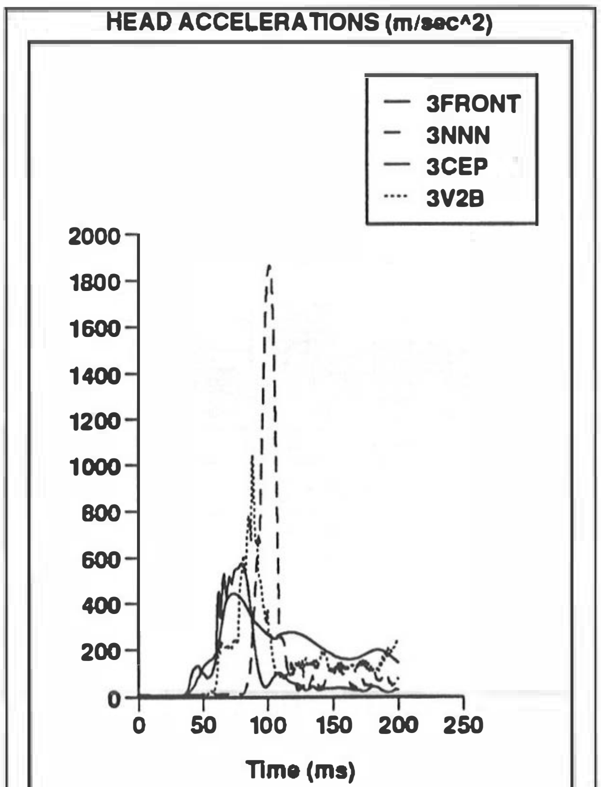


Figure 4: Accelerations of the head

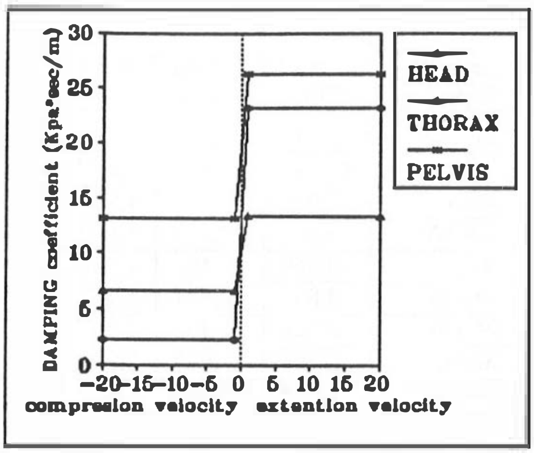
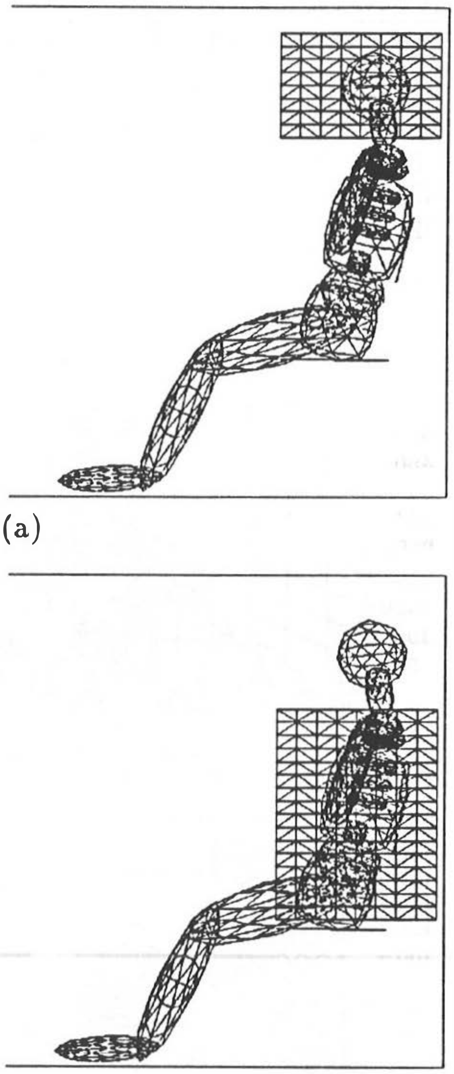


Figure 5: Damping coefficient versus velocity of 3-D combined models



(a)

(b)

Figure 6: Split net (a) upper part, (b) lower part

MODEL	HIC	GSI	3MS	TTI up rib	TTI mid rib	TTI low rib	TTI mean	V*C upp rib	V*C mid rib	V*C low rib	V*C mean
Allowed	**1,000**	**1,000**	**600**	**90**	**90**	**90**	**90**	**1.3**	**1.3**	**1.3**	**1.3**
3FRONT	312	510	336								
3NNR	14,715	17,694	2,952	616	954	1,040	870	1.04	1.68	2.42	1.7
3CNN	1,650	1,974	1,097	136	151	161	150	0.62	0.89	1.19	0.9
3NNN	3,625	4,265	1,602	186	177	164	175	1.37	1.78	2.18	1.7
3NNA	3,860	4,498	1,696	294	303	291	295	1.25	1.63	2.11	1.6
3FNN	3,884	4,437	1,713	182	169	167	170	1.48	1.88	2.26	1.8
3CBN	2,020	2,499	1,307	109	110	103	105	0.23	0.14	0.08	0.13
3NBN	5,709	7,972	2,208	49	47	48	48	0.03	0.02	0.03	0.03
3CEN	1,714	2,073	1,163	139	151	157	149	0.49	0.59	0.7	0.58
3NEN	5,188	7,200	2,099	66	66	67	66	0.07	0.07	0.06	0.07
3CNP	360	464	620	97	108	116	107	0.28	0.31	0.33	0.31
3NNP	1,150	1,341	859	149	158	158	155	0.84	0.84	0.84	0.84
3CBP	217	306	551	79	88	88	85	0.23	0.16	0.13	0.17
3CEP	217	299	507	75	89	96	87	0.28	0.22	0.20	0.23
3V1B	758	1,347	603	170	160	145	158	0.82	0.01	0.05	0.3
3V10.5	917	1,779	716	139	132	131	134	1.7	0.07	0.06	0.61
3V12.0	871	1,585	805	112	69	75	85	0.03	0.06	0.07	0.05
3V1N	1,178	1,981	748	101	88	102	97	0.01	0.03	0.03	0.02
3V2B	432	714	551	103	110	132	115	0.04	0.06	0.04	0.05
3V2N	687	1320	440	119	125	81	108	0.04	0.01	0.05	0.03
3H1B	945	1385	747	73	89	78	80	0.1	0.14	0.07	0.10
3H1N	841	1264	721	59	58	70	62	0.16	0.31	0.47	0.31
3H2B	532	787	545	73	120	143	112	0.04	0.09	0.07	0.06
3H2N	1,036	1,444	689	104	74	103	93	0.07	0.17	0.3	0.18

Table 2: Comparison of injury parameters

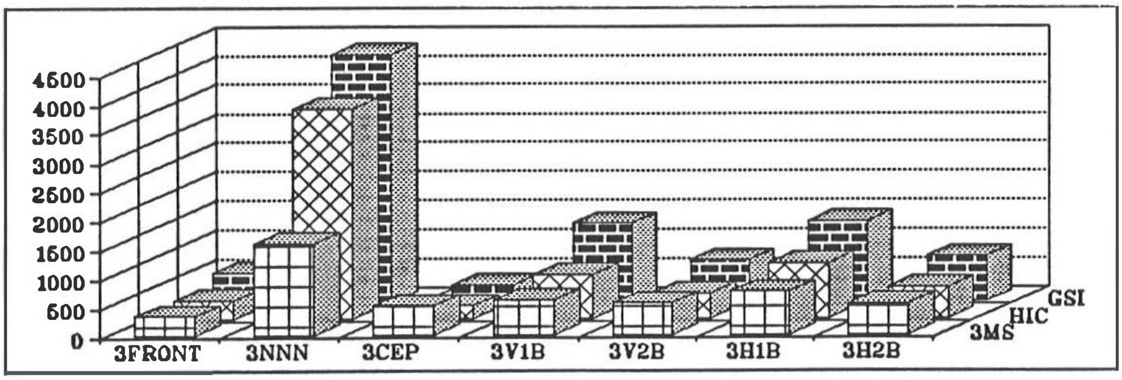


Figure 7: Comparison of HIC, GSI and 3MS (3-D)

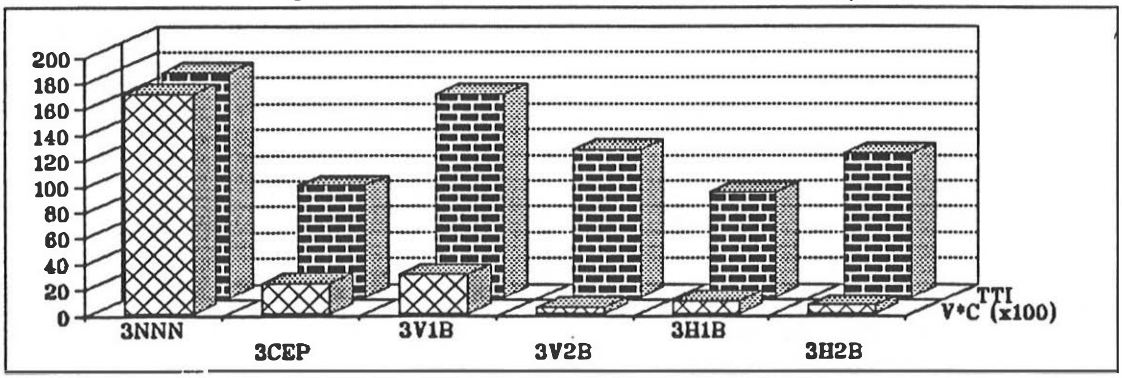


Figure 8: Comparison of TTI and V*C (x100)

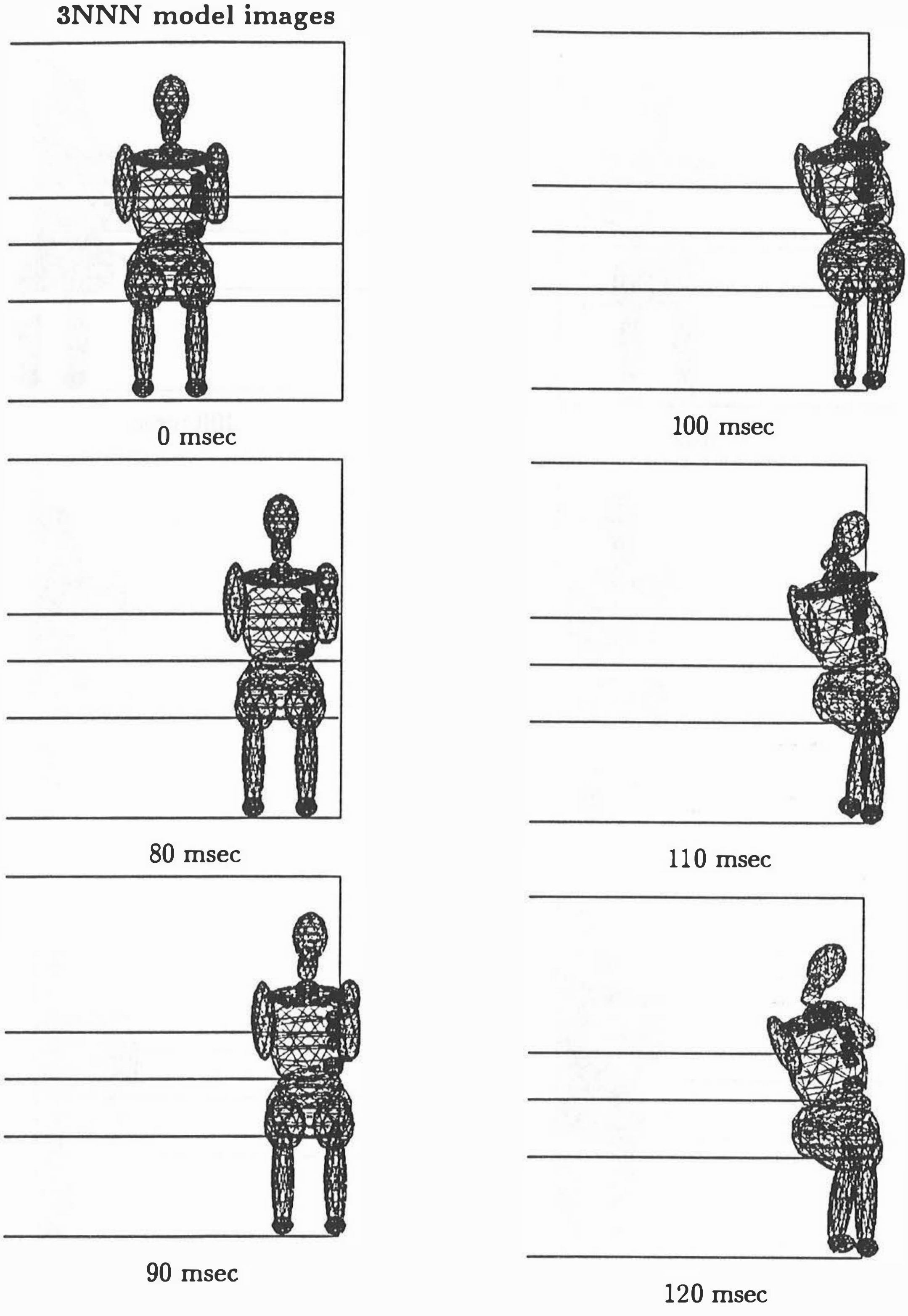


Figure 9: 3NNN — The occupant was sitting 0.7 m from the wall, no belt and no pad.

3CEP model images

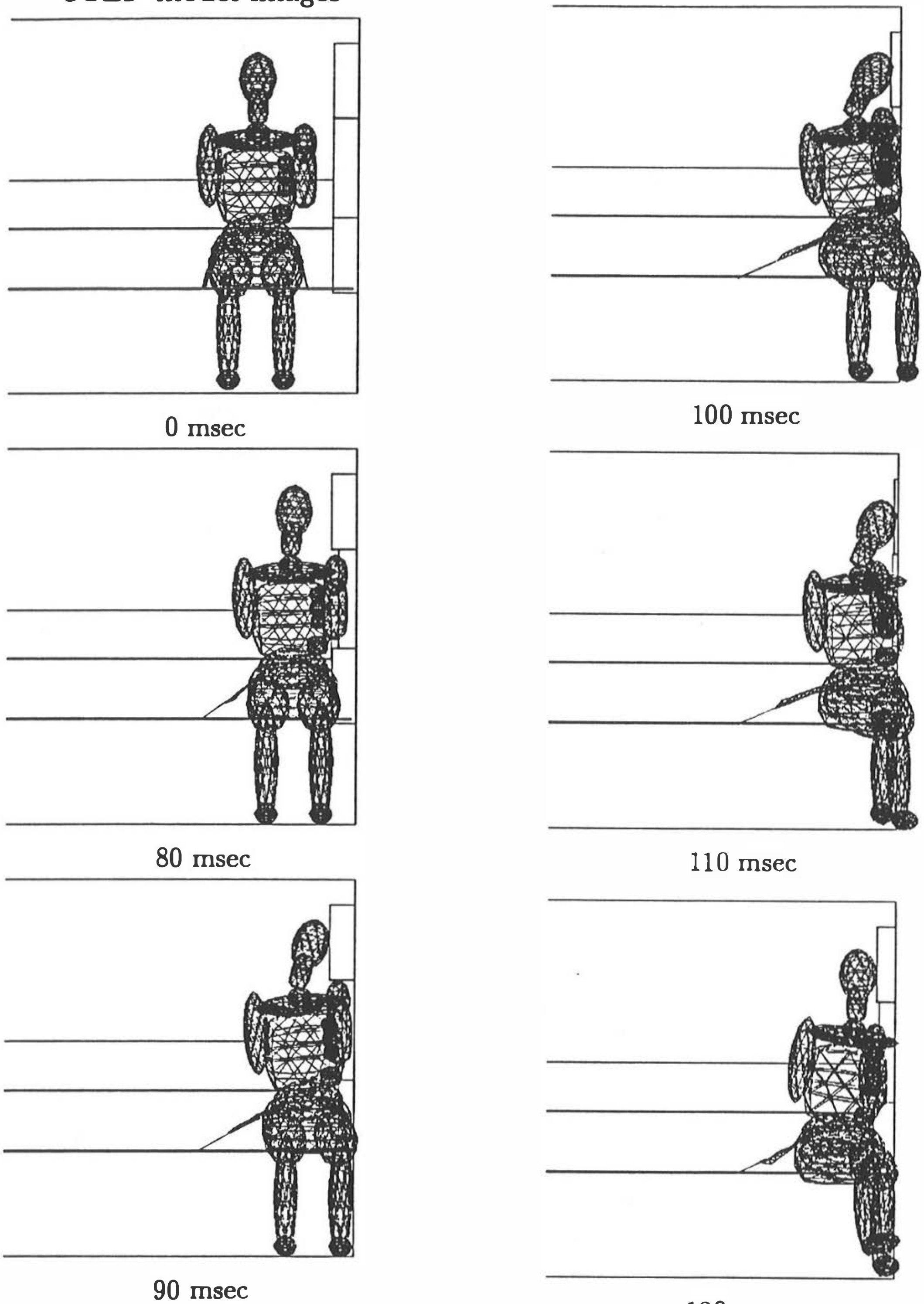


Figure 10: 3CEP — The occupant was sitting 0.4 m from the wall, with a belt and a pad system.

3V2N model images

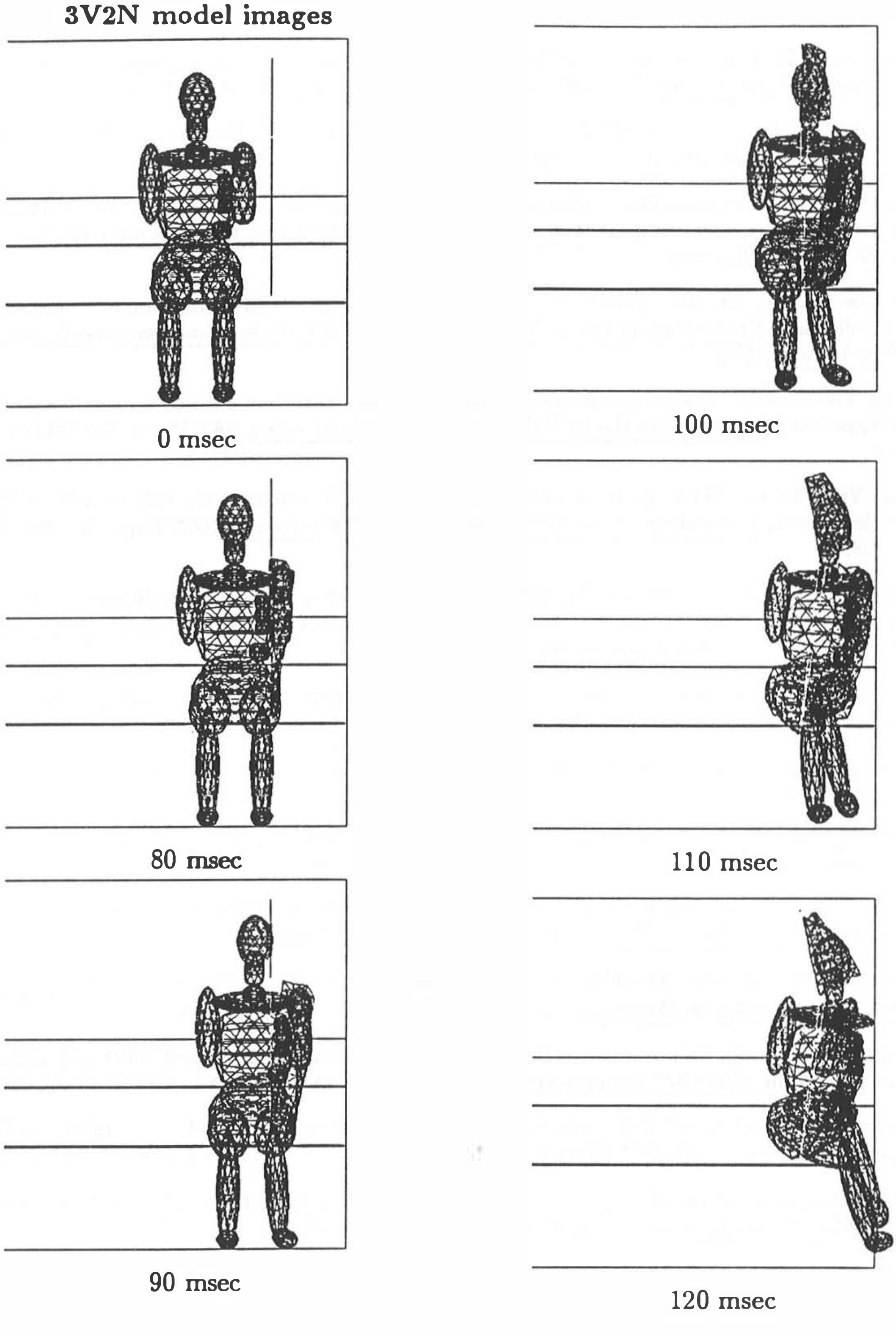


Figure 11: 3V2N — Two separated nets vertically supported without a lap belt.

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