PRESSURE AND LOAD PATTERNS ON SEAT INTERFACE: A COMPARISON BETWEEN HUMAN SUBJECTS AND CRASH TEST DUMMIES

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ABSTRACT

This study compares pressure and load patterns on the seat back generated by humans to those by Hybrid-III dummies in low severity rear impacts. 12 healthy human subjects, along with the fifth percentile female and 50^{th} percentile male Hybrid-III dummies, were used as test subjects. During the tests, the interface pressure distribution between seat and human or dummy was collected by means of a Tekscan system, at a rate of 50 frames/sec. The test seat was mounted to a mini-sled, which was powered by a bungy-cord. The bungy-cord accelerated the sled to a speed of about 1.3m/s (5 km/h) when the sled was brought to stop by means of a hydraulic damper. The stopping distance was approximately 30 mm which generated a deceleration pulse of about 3G. The results showed that at impact peaks, total dynamic loading due to human or dummy trunk weight on the seat back increased from static loading. Not only dummy loading increased more than human loading, but also for dummies, a larger portion of load transferred from lower back to upper back region. The dummies' load center in these tests migrated up on seat back more than 50 mm as compared to 20 mm for the humans during impacts. Furthermore, pressure distribution patterns differed significantly between the humans and the dummies. The results of this study will help improve the understanding of injury mechanism due to rear impact and provide fundamental data for dynamic human modeling.

SOFT TISSUE INJURIES have gained a lot of interest in recent years. Although rarely life-threatening, the injuries can have long-term implications. The injury can occur in rear impacts of low or moderate severity. In those situations, the seat, in particular the seat back, is a significant interface between the vehicle and the occupant.

The current methods to test the loading on seat-occupant interface typically utilize traditional crash-test dummies, such as the Hybrid-II and its successor the Hybrid-III, as human occupant substitutes. However, soft tissue neck injuries may occur in crash speeds much lower than those for which the dummies were developed, while the validity of the dummies as occupant substitutes in low-speed impacts is not fully evaluated. For instance, testing and field data indicates that the load-pattern generated by dummies may differ from that generated by humans.

STUDY OBJECTIVE

The objective of this study was to generate and compare load patterns on the seat and the seat back of humans and the Hybrid-III crash test dummies. The specific aims were: (1) to identify the overall load and pressure distribution patterns of humans and dummies in normal seated postures, and when pressed against the seat back; (2) to identify load transfer patterns between the lumbar and upper back regions under these conditions; (3) to quantify the difference in load patterns between humans and dummies; and (4) to identify the migration locus of the center of load on the seat back when transiting from normal seated postures to those that are likely to be assumed during rear impacts. The data may provide input for mathematical simulations of humans involved in rear impacts.

METHODS

SUBJECTS - The study was carried out at the Institute for Mechanics, University of Technology Graz (UTG), Austria. 12 paid human subjects were recruited in Graz. The selection criterion was standing height. To allow for valid comparison between human and dummies, the desired height was 1511 mm for small female at fifth percentile, and 1753 mm for medium male for 50th percentile of US population data (HANES, 1974). However, due to the difficulty in finding 5th %ile females, the recruited small female subjects were equivalent to medium female range according to the US HANES database. And one of the small subjects was a male. The mean standing height is 1605 mm for small subject group, and 1740 mm for medium subject group. Mean weight for two groups is 51 kg and 75 kg respectively. Before the test, each subject was briefed with the nature and procedure of the study which was reviewed and approved by the UTG Ethics Committee. An informed consent form was signed by each subject.

Two crash dummies were also used: Hybrid-III 5th %ile female and 50th %ile male.

MEASUREMENTS - Three categories of data were collected during the test. They are interface pressure distribution between seat and human or dummy, acceleration data on the head and chest, and high-speed video images. Acceleration and video image data were collected by UTG (Steffan, 1997) and are not covered in this paper.

Pressure distribution was measured using a Tekscan system (Teckscan Inc., MA, USA). The two pressure sensors are of 5315 type, one for seat cushion and the other for seat back. Each mat has 2,016 sensor units in 42 rows and 48 columns, running from R1 at the front to R42 at the rear for cushion, and from C1 at the bottom to C48 at the top for back. Each sensing unit on the mat is 10 mm apart from its immediately adjacent ones and 14 mm apart diagonally. Pressure mats were calibrated at Delphi Human Factors Lab before being used for the study. The newly calibrated mats possess a repeatability of 90%. The recording parameters of the pressure measurement were 50 frames per second with duration of 1.5 sec. For each record therefore, a total of 76 frames were captured to include the entire impact process.

TEST SETUP - Seat and Sled - A modified driver seat was used for this test. For repeatability check, five seat backs and two seat cushions were provided as alternatives. The seat was mounted on a mini-sled at UTG. The sled was powered by a bungy cord which accelerated the sled to a speed of about 3 miles per hour. The deceleration device was adjusted so that the sled stops within 30 mm upon impact. This generated a deceleration pulse of about 3G (Figure 1). The impact velocity ranged between 4.8-5.5 km/h.

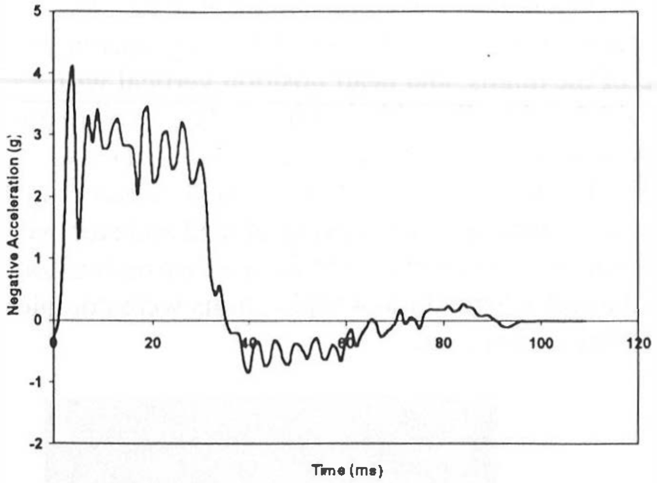


Figure 1. Sled acceleration pulse.

Accelerometers - For both humans and dummies, three-axis accelerometers were equipped on the head and in front of the chest. For dummy pelvis, an additional accelerometer was mounted. Triggering sled release activated the recording of acceleration. Coordinate systems for accelerometer measurement are shown in Figure 2.

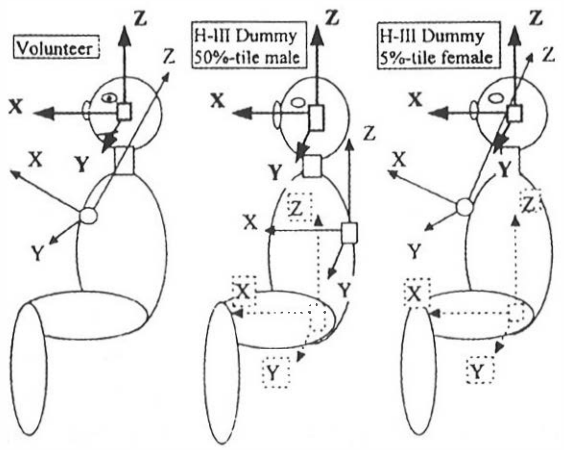


Figure 2. Coordinate systems of acceleration sensors.

High-speed Video Camera - The camera was mounted alongside the sled. Recording was initiated by a trigger which release activated high intensity lights and the camera. The camera took 1000 frames per second.

TEST PROCEDURE - The complete test included: (1) regular testing with 12 human subjects and two crash dummies, each with three replications using the same set of pressure mats; (2) reliability testing of pressure mats with crash dummies using two different sets of mats; (3) repeatability testing with one human subject at two different days; and (4) seat performance consistency testing with medium male dummy using two randomly picked seat backs.

For human testing, the procedure was explained and an informed consent form filled out. A medical doctor palpated the subject's back and to place three targets on the left side of the trunk which indicated the vertical levels of pelvic pivot center, L1, and T1. The investigator mounted chest and head accelerometer blocks on the subject before the subject sat into the seat. Sitting posture requirements were: cushion angle 12°, back angle 24°, knee angle, or the angle between lower leg and thigh, 110°, legs parting in parallel, hands naturally laying on top of the thighs, and head position vertical with minimum neck flexion or extension, with height adjustable headrest. The investigator put on seat belt for the subject and conducted final safety check. When all was set, the investigator pulled the trigger to release the bungy cord and thus the sled. Recording of all data, including seat interface pressure, started upon the release of sled and stopped when the sled went into full stop. The subject remained seated for another replication in five to ten minutes. And exited from the seat when all three replications were completed. Test setup for dummies was similar to that for humans.

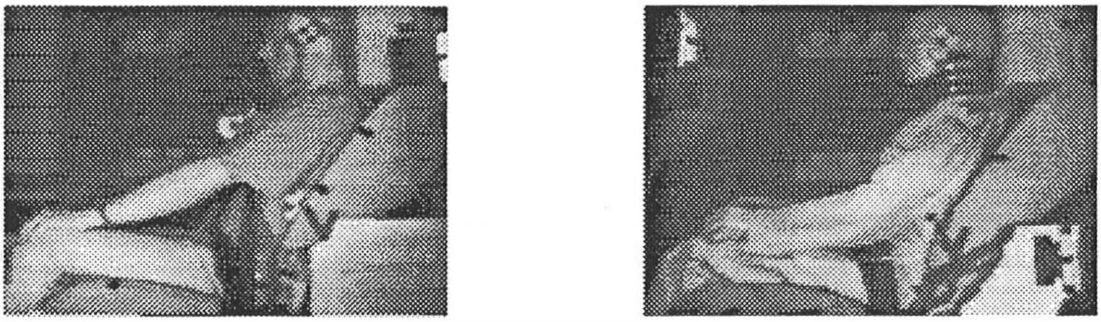


Figure 3. Test setup for medium male human subject and crash dummy.

RESULTS

Pressure data was recorded on both cushion and back of the seat. As the major focus of this study was on back loading, only the back pressure data was analyzed. Data extracted for analysis include the recorded frames between 0.10 sec before the peak loading and 0.50 sec after the peak loading, a duration of 0.60 seconds.

Due to the acceleration, the total seat back load exerted by human or dummy trunk weight at sled release reduced by 27% from its static load. The load on the back was largely transferred to seat cushion as a result of friction between cushion surface and human/dummy thighs and the buttocks. When the sled approached the stopping device however, the total back load resumed to its static level.

Figure 4 depicts typical pressure distribution patterns by a medium male subject and the 50th %ile male dummy. Due to the difference in body build and sitting attitude, human subjects of the same standing height may produce different pressure distribution although general patterns are very similar. At the top of human back pressure chart, the two shoulder blades imprinted two regions of high pressure. Down to about 200 mm above seat biteline which is the line where seat cushion and back are first in touch, high pressure occurs around the lumbar area. The dummy pressure chart however does not show such anatomical definitions. Also noticeable is the contact area. Human backs exert more distributed pressure on seat back with smaller areas of high pressure concentration than the dummies. These aspects indicate different interaction of humans and of dummies with seat backs.

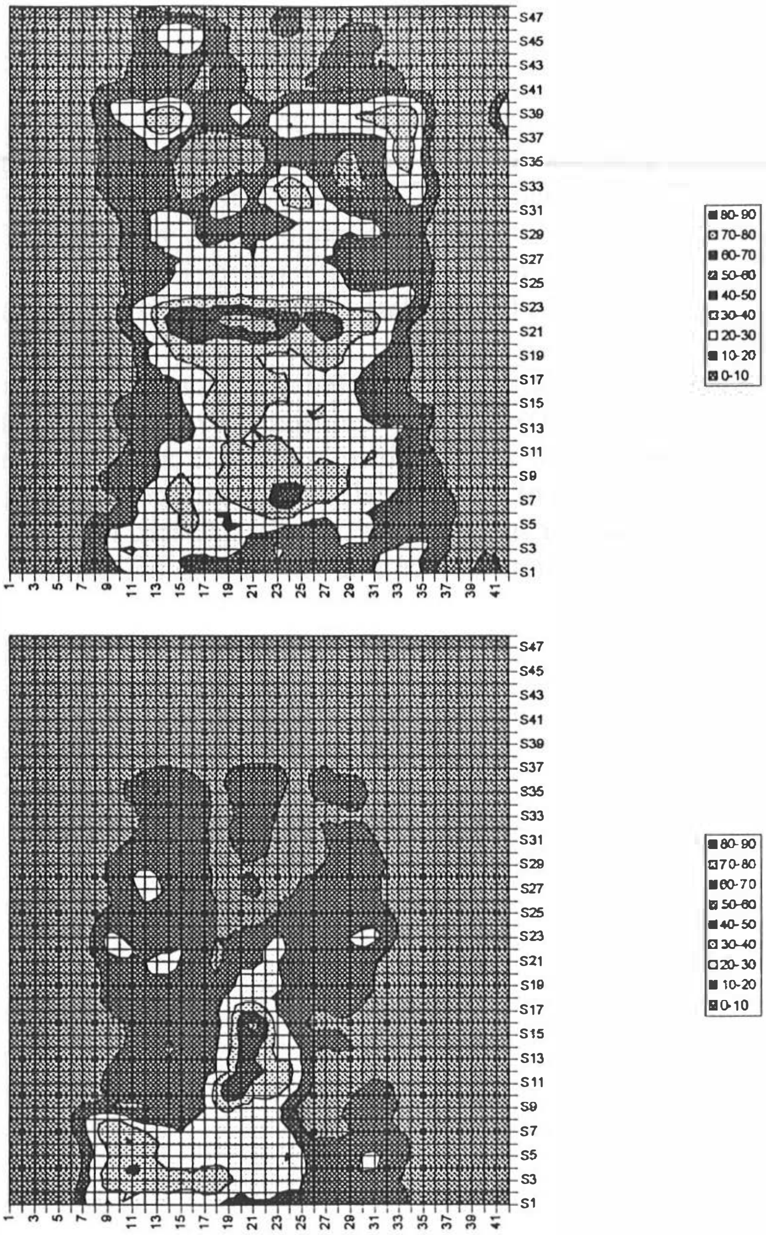


Figure 4. Pressure distribution pattern of a medium male subject (top) and the crash dummy.

TOTAL LOAD ON THE BACK AND SHOULDER-LUMBAR LOAD RATIO - Two critical parameters are derived from pressure distribution data, and they are total load and shoulder-lumbar load ratio.

Total Load - At any recorded time frame, this is calculated on the entire back of the seat, thus on human or dummy back, by multiplying average pressure with active contact area. Naturally this parameter changes during the impact. Within the time duration that was analyzed, total load was at its peak at 0.10 sec. Figure 5 describes the magnitude of back load among male vs. female, and humans vs. dummies. Apparently, males experienced higher back load than females during the process. The difference is significant between male and female dummies. Between humans and dummies, female dummy had less back load than female subjects at peak load, while male dummy had more back load than male subjects.

Table 1 provides a summary of mean load at two time frames: 0.00 sec and 0.10 sec. At 0.00 sec, average static load on small female subjects was significantly higher than that for 5%ile female dummy, 22 kg vs. 10 kg. But the back load for male subjects was comparable to that for male dummy, 26 kg vs. 24 kg. At 0.10 sec however, two aspects are noteworthy. First, the females' back load had a higher percentage increase than males, 91% vs. 69% for humans, and 180% vs. 129% for dummies. Secondly, dummies had much higher load increase than humans, 180% vs. 91% for females, and 129% vs. 69% for males. Results from analysis of variance indicated that both the *Class* factor (dummy vs. human) and the *Gender* factor are significant in affecting dynamic loading pattern.

Shoulder-Lumbar Load Ratio - is calculated as the load ratio between upper back and lower back regions. The two regions were separated by the location of L1 on the human back. Calculation for each human subject was based on his/her actual L1 location. For dummies locations of L1 were calculated from the means for human subject L1. Mean L1 location for small subject group is 232 mm from the biteline (min. 210, and max. 270), and for medium subject group 267 mm (min. 230 mm, and max. 300).

Figure 6 shows that shoulder-lumbar load ratios for females are higher than for males, indicating that a larger portion of total back load is on upper back for females. Especially noticeable is the huge difference between female and male dummies.

Table 2 summarizes the mean load ratios at two time frames: 0.00 sec and 0.10 sec. For humans, the load ratios between shoulder and lumbar increased by about 30% under peak load for both females and males. For dummies, the change in load ratios is even greater. For 5th %ile female dummy, the load in upper back at peak load was twice as much as that in the lower back, an increase of 145% from the ratio before the impact. For 50th %ile male dummy, the static load ratio between shoulder and lumbar regions was much less than that for male human, indicating that the dummy's back load was concentrated on lower back due to its lack of flexibility under static conditions.

Although shoulder-lumbar load ratio seems to follow the same temporal trend as the total back load during the impact, their implications are different. Total load only tells about the change in dynamic load during the impact, but load ratio reveals how the load is re-distributed on the back at the moment of impact. The later has important applications in identifying load transfer pattern during the impact and therefore in designing an effective protective mechanism for occupants.

Tables 1 and 2 provide the average values of load ratios only. There are large variations between, and even within, human subjects. Average coefficients of variation (CV), which is the standard deviation divided by the mean, was calculated to indicate the extent of variation of the parameter in concern. The larger the CV value, the more scattered the parameter. For the total load on the back, average CV is 16% for the female and 11% for the male subjects. For load ratios between shoulder and lumbar however, the average CV is 33% for the female and 27% for the male subjects.

Table 1. Summary of mean total load: human vs. dummy, and at normal vs. peak load. SF stands for small female, and MM for medium male.

	Load (kg)		Load increase from normal to peak (%)	Difference in peak load between dummy & human (%)
	at 0.0 sec	at 0.1 sec		
Human Small Female	22	42	91	
Human Medium Male	26	44	69	
Dummy Small Female	10	28	180	-33 (vs. SF Human)
Dummy Medium Male	24	55	129	25 (vs. MM Human)

Table 2. Summary of shoulder-lumbar load ratio: human vs. dummy, and before vs. at peak load.

	Load ratio		Load ratio increase from normal to peak (%)	Difference in peak load ratio between dummy & human (%)
	at 0.0 sec	at 0.1 sec		
Human Small Female	0.88	1.14	30	
Human Medium Male	0.70	0.93	33	
Dummy Small Female	0.83	2.03	145	78 (vs. SF Human)
Dummy Medium Male	0.39	0.76	95	-18 (vs. MM Human)

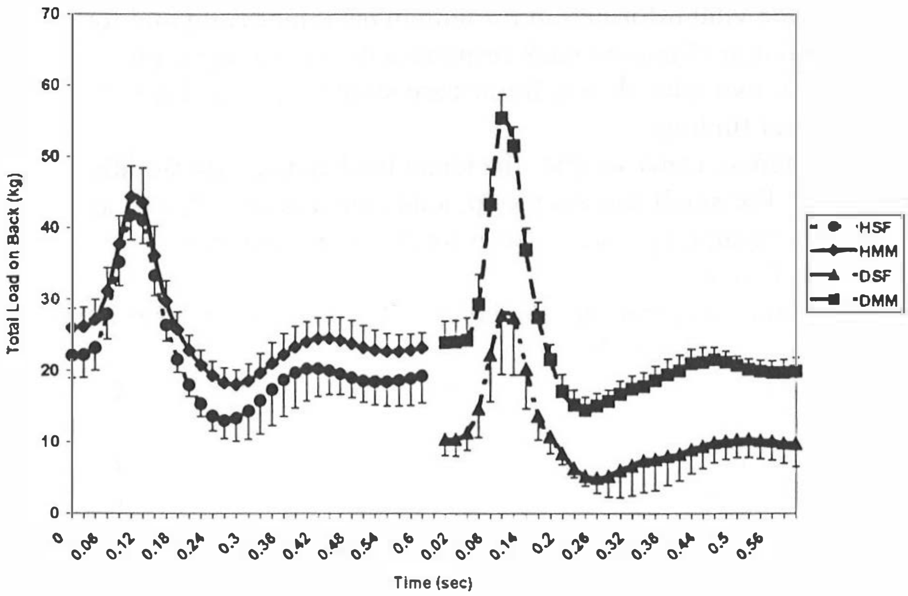


Figure 5. Total load on the back of humans and dummies: M +/- 1SD. HSF stands for human small female, HMM for human medium male, DSF for small female dummy and DMM for medium male dummy.

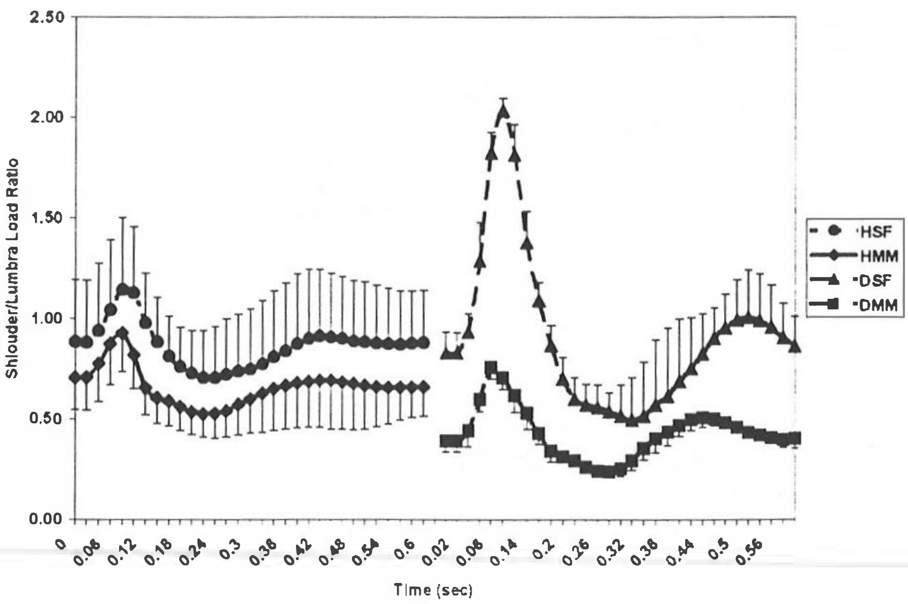


Figure 6. Load ratio between shoulder and lumbar region: M +/- 1 SD. Legends are the same as in Figure 5.

CENTER OF LOAD MIGRATION DURING PEAK LOADING - The dynamic interaction between seat back and the back of occupant's body, as shown with temporal trends in total load and shoulder-lumbar load ratio, also causes migration of load center on seat back. Due to differences in displacement among spinal segments during the impact, total pressure on seat back is not only increased but also re-distributed during peak loading.

The Entire Back - Figure 7 describes the migration pattern of load center as calculated from the pressure distribution data. The location of load center is defined as the longitudinal distance from the load center on the seat back to seat biteline. Again, the biteline on seat back is the bottom line where the back first contact the cushion. The load center migration data may provide vital information for human back modeling and for evaluating the dummy representation of human back responses in normal and high loading. Load center locations at two critical time frames are summarized in Table 3.

There are a few significant findings:-

1. Under static loading of human trunk weight, the mean load centers are slightly lower than L1 locations. For small subject group, load center is at 222,mm, as compared to 232 mm for mean L1 position. And for medium male group, it is 241 mm as opposed to 267 mm.
2. For human subjects, mean load center on the seat back for medium males is about 20 mm higher than that for small females;
3. At peak loading, mean human load centers migrated up by an amount slightly over 20 mm;
4. For dummies, load centers on seat back for both male and female are lower than those for respective human subject groups. The load center for 50[th] %ile male dummy is 58 mm lower than that for medium male human subjects;
5. At peak load, dummy load centers on seat back migrated up 50 mm or more.

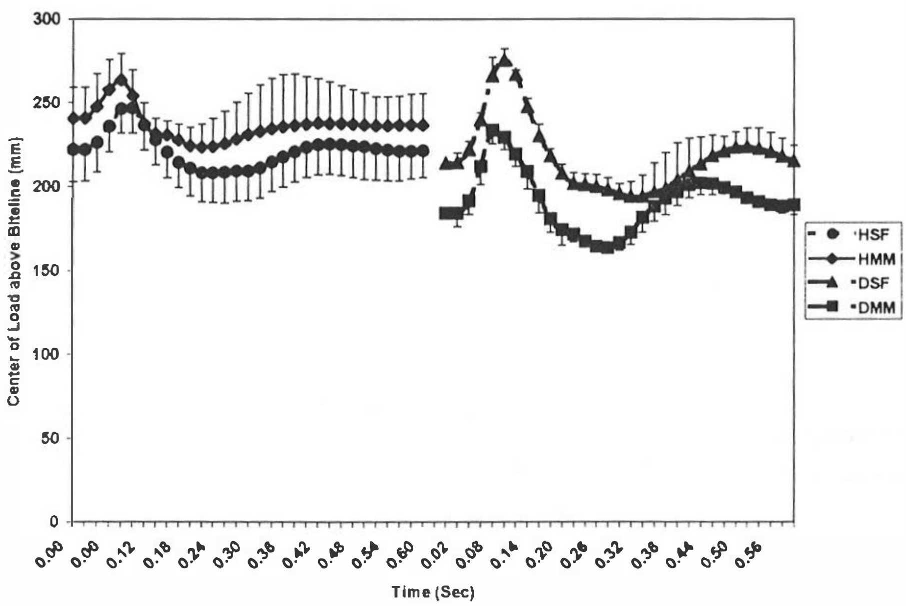


Figure 7. Center of load migration above seat biteline on the back. Legends are the same as in Figure 5.

Table 3. Summary of load center from biteline on seat back at two time frames, in mm.

	At normal load	Difference from human	At peak load	Difference from human	difference at normal/peak load
Human SF	222		247		25
Human MM	241		263		22
Dummy 5th %ile F	214	-8	275	28	61
Dummy 50th %ile M	184	-57	234	-29	50

Upper Back and Lower Back - To provide detailed information for potentially positioning an occupant protection device, load center locations are calculated for the lower back and upper back separately. As mentioned earlier, the separation of upper back from lower back is at L1 location for each subject, and for dummies it is at the mean L1 location of corresponding human subject group. All data shown in Table 4 and Figure 6 represent location of load centers from seat biteline. For clarity, only the first 0.12 seconds, from Frame 1 to Frame 7, are accounted in the analysis.

Table 4. Load center locations on upper back and lower back as measured from biteline, in mm.

Time	Small Female				Medium Male			
	Human		Dummy		Human		Dummy	
(sec)	Lower back	Upper back	Lower back	Upper back	Lower back	Upper back	Lower back	Upper back
0.00	150	320	169	303	158	340	129	319
0.02	150	320	169	303	157	340	129	319
0.04	150	325	169	311	157	348	129	321
0.06	145	338	160	324	155	361	128	337
0.08	143	352	164	341	151	370	136	375
0.10	140	357	165	353	145	370	134	367
0.12	139	353	166	351	140	366	133	364

The data shows that:-

- On upper back, mean load centers for human subjects at peak load moved up from its static location, by 37 mm for females and 30 mm for males , to 357 mm and 370 mm respectively. Dummies' load centers also migrated up to levels comparable to humans;
- On lower back, load centers for humans slightly migrated down, while dummy load centers did not;
- Under non-dynamic conditions, the load centers on seat upper back by dummies were slightly lower than those by respective humans. On lower back, male dummy load center was consistently lower than humans, while female dummy load center was higher than humans.

By comparing the load center migration patterns of the upper back region with those of the entire seat back, one may conclude that load center migration on seat back is primarily due to the much increased load on the upper back.

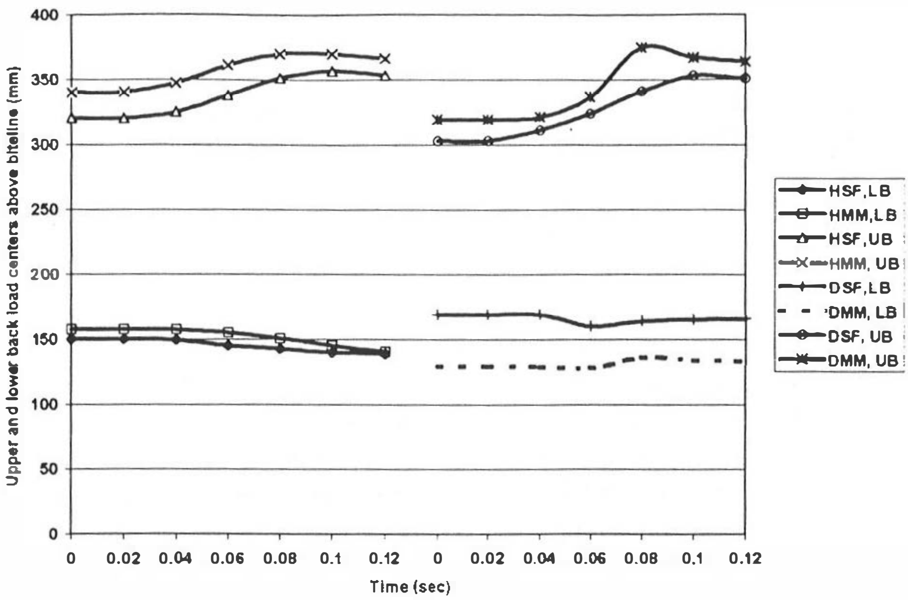
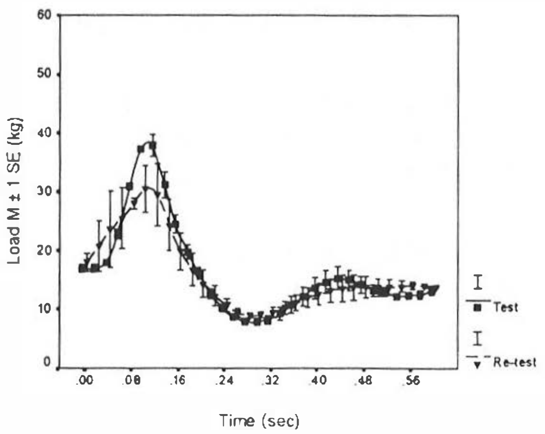


Figure 8. Load center locations of human subjects and two dummies. LB stands for lower back and UB for upper back.

DISCUSSION

TEST RELIABILITY - Reliability can be affected by three major sources of errors: (1) physical degradation of seat performance due to impact test, (2) loss of sampling sensitivity in pressure mats and (3) variation in seat manufacturing consistency.

The first and second errors were assessed by test-retest repeatability check using a small female subject. The subject attended the first test the first day and the last test the second day. The same seat and same pressure mats were used. From Figure 9, test-retest difference in mean load is distinguishable. However, no statistically significant difference was found, either in total load, or in load ratio. The difference may be attributed to the difference in sitting posture. Variation in measurement accuracy of different pressure sensors was also examined by repeated tests with dummies. Both dummies were tested three times using the first pair of pressure mats, and re-tested using a different set of mats. The results were very comparable without systematic difference.



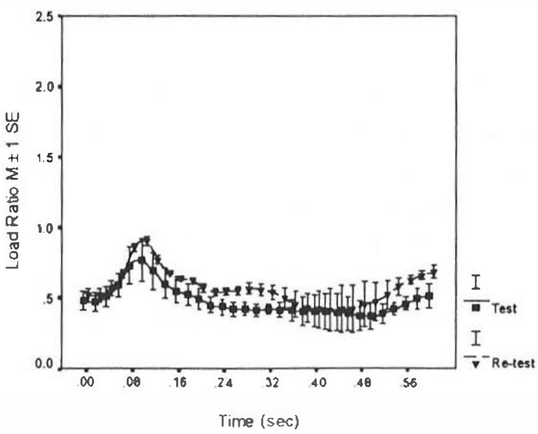


Figure 9. Test-retest repeatability check with a small female subject.

While the pressure mats performed well in test-retest assessment, the sensors have intrinsic problems in measurement accuracy. Previous test and calibration studies indicated that measurements using Tekscan system have an error range of ±10%. Therefore, caution has to be taken in interpreting the results of this study.

Comparison of back difference was possible through testing three seat backs, using 50th %ile male dummy. Again, no significant difference existed. See Figure 10.

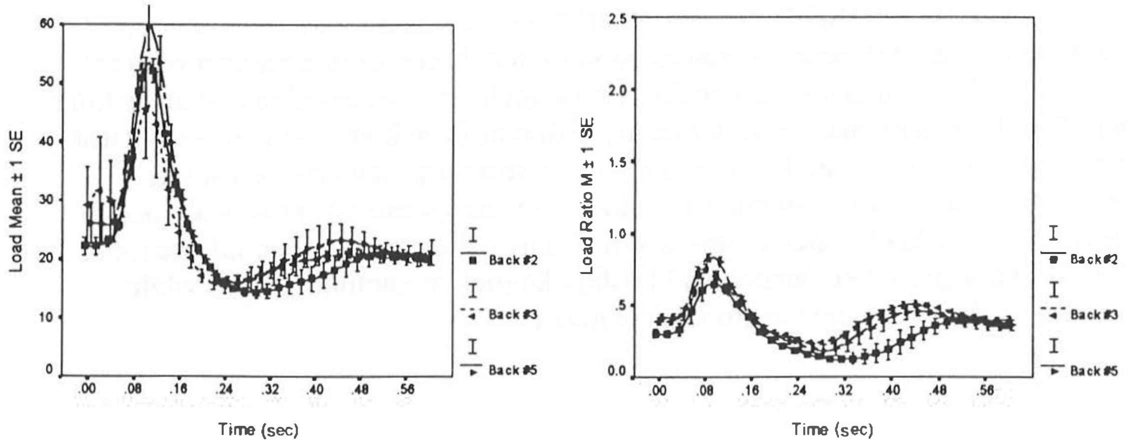


Figure 10. Seat back consistency check.

TEST RESULTS GENERALIZATION - Limitation Due to Subject Groups - The small subject group used for this study was at about 50th %ile of the female population height according to the US anthropometric database (HANES 1974), while the small female dummy is 5th %ile. There is no official data regarding dummy standing height, and only erect sitting height is specified. For the 5th %ile female dummy it is 790 mm, while for the female subject group with a median standing height of 1605 mm, the erect sitting height is 850 mm, which is at 53th %ile. For medium male subject group, the standing height data matches very well, at a median of 1740 mm, with a nominal erect sitting height of 907 mm.

The HANES database was published more than 20 years ago and humans become increasingly taller due to genetic and environmental factors. In the US however, populational development may have been hindered by two major aspects[1]. One is the immigrants from global regions where the stature of general population is lower than that in western countries, and the other the aging populations. It may therefore be reasonable to state that neither the current Hybrid-III 5th %ile dummy nor the subject group truly represents populational 5th %ile female height.

Limitations Due to Specific Seat Design - Although the reliability examination did not reveal significant problems with the reliability of the test results, other limitations in interpreting this data and utilizing it have to be fully acknowledged. Cushion length of the seat used in this study may not permit small female subjects and 5%ile female dummy to reach the lower back support. Load ratio between shoulder and lumbar at 0.00 sec is higher for females than for males, due to the fact that female human subjects and dummy had short thighs and they were not able to reach the lumbar support, thus exerting more trunk weight on upper seat back.

In addition to seat length, other features of the seat such as seat contour and stiffness of supporting assembly (trim cover, foam, and suspension) are unique for this study, and may not represent general seat features in seat dynamic response at impact.

[1] Cited from a committee discussion of GM Seating Comfort Task Force, 1996.

The level of difference between seat designs or vehicle platforms cannot be assessed unless another comparative study is carried out using a number of seats with varied design and engineering features.

Speed and Deceleration Rate - The values of response parameters examined in this study are dependent upon and specific to the test conditions, e.g. the sled speed, track travel distance, and deceleration rate.

DUMMY RESPONSES VS. HUMAN RESPONSES - The result section showed that there are differences between humans and dummies in a number of areas. First, there is anthropometric or dimensional mismatch. As discussed in earlier sections, the small female dummy may be significantly different from humans in body dimensions. Secondly, compared to human body, dummy trunk structure lacks viscoelasticity. Figures 2 and 3 indicate that dummies are much less energy-absorbent at peak load. A third difference is in load center as revealed in Figures 5 and 6. Another difference is that human backs have prominent anatomical landmarks such as shoulder blades while dummies do not have the same anatomical features.

CONCLUSIONS

This study was aimed to compares pressure and load patterns on the seat back generated by humans to those by Hybrid-III dummies in low severity rear impacts (3G, 4.8-5.5 kph). The results would lead to the following conclusions:

1. Static pressure distribution patterns on seat back differed significantly between the humans and the dummies, especially in anatomical landmark identification and in contact areas.
2. At impact peaks, total dynamic loading due to human or dummy trunk weight on the seat back increased significantly as compared to static loading, by 69-91% for humans and 129-180% for dummies. A large portion of the increased load was exerted on upper back region, especially for dummies.
3. At impact peaks, dummies' load centers on the seat back migrated up more than 50 mm as compared to 20 mm for the humans during impacts. This is primarily due to dynamic loading increase in the upper back region.

The results of this study will help improve the understanding of injury mechanism due to rear impact, and provide fundamental data for dynamic human modeling and validation of models.

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