Behavior of ATD, PMHS and Human Volunteer in Frontal Crash Test

Kazuo Higuchi 1)  Kristy B. Arbogast 2)  Richard W. Kent 3)

1) Retired (Honda R&D/TAKATA), 2-10-14Mita, Meguro, Tokyo, 153-0062, Japan (E-mail: kazuo.higuchi6294@gmail.com)
2) Center for Injury Research and Prevention, The Children’s Hospital of Philadelphia, 2716 South St., Philadelphia, PA, USA 19146
3) University of Virginia, Center for Applied Biomechanics, 4040 Lewis and Clark Dr, Charlottesville, VA, 22911 USA

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ABSTRACT: There are many studies comparing the behavior of ATD (anthropomorphic testing device) and PMHS (Post Mortality Human Subject = Cadaver) to improve the bio-fidelity of ATD. The best method to get bio-fidelity data for the development of ATD is human volunteer tests. But the human volunteer tests can be conducted only at low speeds. Previously we conducted low speed human volunteer tests, and high speed and low speed tests with ATD and PMHS. We compared the result of those tests at low speed and concluded the excursion of the human volunteer is less than the excursion of PMHS and the ATD’s excursion is the least. But we could not make any conclusions about human volunteer response at high speed due to lack of data. We accessed high speed human volunteer test data which had completed in the 1970’s in United States sponsored by National Highway Traffic Safety Administration (NHTSA) from NHTSA’s archives. In this report we compared these high speed human volunteer test results with our previous work and concluded the excursion of human volunteer is less than the excursion of PMHS at higher speeds, mimicking the findings at lower speeds.

KEY WORDS: Safety, Occupant protection, Anthropomorphic Dummy, Crash Test, Safety Belt, Human Volunteer

1. Introduction

The bio-fidelity of anthropomorphic testing devices (ATD) is very important. Early ATDs only simulated the size and weight of human. Later in 1970’s new ATDs which were targeted to evaluate the performance of airbags, were developed. They considered impact response of body segments such as the head, neck, thorax, abdomen and knee. This first dummy with bio-fidelity was called Hybrid III. Those body segment responses were defined from impact tests of PMHS (Post Mortality Human Subject = Cadaver), but there were no requirements for whole body response. Hybrid III was developed for air bag test in which the occupant behavior was free flight. In the 1980’s, use of seat belt increased and the whole body response of belted occupant becomes more important.

The team of CHOP (Children Hospital of Philadelphia), UVA (University of Virginia) and the current lead author conducted research using ATD, PMHS and human volunteers [1], to study the relationship between these three, and found the ATD’s forward displacements were consistently less than those exhibited by the PMHS in frontal crash [2]. Also we concluded PMHS over-predicted the forward excursion of the volunteers at low speed (9 km/h) [3]. But we could not evaluate response difference between PMHS and volunteers in the high speed loading condition because of the lack of data for volunteers at high speed. The National Highway Traffic Safety Administration (NHTSA) of the United States conducted high speed human volunteer tests to find if advanced protection systems can protect occupants in high speed frontal crashes in the 1970’s [4][5]. For this analysis, we accessed the report and video of NHTSA’s high speed human volunteer frontal crash tests, which were conducted at Naval Air Development Center (NADC), Philadelphia. The objective of NHTSA’s high speed human volunteer tests was to explore occupant protection, and in that project an ATD was used just for the prediction of the severity of impact condition in the subsequent human volunteer test. So the difference of behavior between them was not analyzed. In this report we compared these human volunteer data to our test data with ATD and PMHS for making the difference clear between them.

2. Method

Method of NADC test is discussed in 2.1 and our method is discussed in 2.2

2.1. High Speed Human Volunteer Test

NHTSA’s high speed human volunteer test was conducted at the NADC, Philadelphia, using their Horizontal Accelerator facility during 1971 to 1974 with human volunteers from U.S. Navy.
System Description. Several advanced occupant restraint systems at that day were included in this program. We used the data from the tests using the 3-point harness system with energy absorbing webbing, integrated into the vehicle seat (Fig. 1). The performance of the energy absorbing webbing was very similar to current seat belt force-limiter systems and its shoulder belt webbing was designed to yield around 3000N ~ 5000N (Static Load).

Test Subjects. Five human volunteer subjects participated the tests. They were all adult males. They started from low speed, and then increased the speed step by step. Finally two volunteers reached a sled change in velocity (ΔV) more than 30 mile/hour. Final report of this project examines data from these two volunteers. Table 1 shows anthropometric data of these two volunteers.

Test Methods. Each volunteer was tested several times, in increasing severity up to 48.9 km/h. Table 2 shows test number, speed, and subjects. Instrumentation included a tri-axial accelerometer mounted on the hockey helmet which used by

| Test No. | Speed     | subject |
|----------|-----------|---------|
| 2739     |           | ATD     |
| 2743     | 28k/h(17.5mph) | V4      |
| 2744     |           | V7      |
| 2682     |           | ATD(Hy2) |
| 2683     | 44k/h(27.5mph) | V7      |
| 2699     |           | V4      |
| 2742     |           | ATD(Hy2) |
| 2745     | 48k/h(30mph) | V4      |
| 2746     |           | V7      |

subject. Also the acceleration was measured with a miniaturized accelerometer cluster mounted on a bite plate. Shoulder belt load and lap belt loads were measured. Sled acceleration and toe pan loads were also measured. High-speed cameras recorded occupant kinematics through the use of photo targets mounted on the subject’s body. The belt system was donned tightly, such that two fingers would fit snugly between the band and the clavicle and hip. The initial position was with the volunteer facing forward, centered in the seat, with his hands placed on his thighs just proximal to the knees with his thumbs facing medially and they were instructed to place their chins on their chest prior to the onset of acceleration to avoid head-neck involvement recommended by Dr. John P. Stapp from his experience in his work.

They were also instructed to use all available muscular restraint to resist acceleration. Following the test, the volunteer was interviewed and examined.

Table 1 Subject Anthropometric Data

| Subject | Age | height | weight | sitting height | head-neck length | buttock-knee length |
|---------|-----|--------|--------|----------------|------------------|--------------------|
| V4      | 34  | 166cm  | 63.5kg | 90cm           | 30cm             | 56cm               |
| V7      | 19  | 184cm  | 72.6kg | 95cm           | 25cm             | 62cm               |

Fig. 2 Sled Acceleration Pulse (from [4])
Fig. 2 shows the acceleration pulse experienced by Volunteer 7 through this test project.

2.2. Low Speed Volunteer and ATD, PMHS Test

This non-injurious low-speed tests with human volunteers as well as low-speed and high-speed tests with PMHS was conducted by CHOP and UVA. The test matrix is shown in Table 3. Although the original study included pediatric subjects a sample of ten adult volunteers was selected to be used in this study. The group of PMHS consisted of three cadavers nominally of the size of a 50th male percentile. The main anthropometric characteristics of each of the subjects are shown in Table 4.

The protocol of the study was reviewed and approved by the Institutional Review Boards at The Children’s Hospital of Philadelphia and the Oversight Committee of the Center for Applied Biomechanics – University of Virginia.

Volunteer study

The Children’s Hospital of Philadelphia conducted non-injurious low speed frontal sled tests on pediatric and adult human volunteers. The safety envelope of deceleration pulse was defined from an amusement park bumper-car impact. [1]

A total of 30 male subjects enrolled in the study (20 children and 10 adults). Each subject had six trials on a custom designed sled. The crash pulse for the adult group was 3.82 G over 119.2 ms. Volunteers were asked to remain relaxed during the tests. Forward motion of occupants was restrained by a three-point conventional seatbelt equipped with a retractor. The initial torso and knee angles were set to 110 degrees as natural sitting position by adjusting the foot and back rest position. To minimize the effect of initial head angle, the subjects were asked to initially position their head by focusing on a point placed directly in front of them at the level of their nasion. The seatbelt D-ring height was adapted to each occupant so as to maintain homologous loading conditions among subjects. Reflective markers were placed on the head, neck, torso, and upper and lower extremities. These markers were tracked using a 3D motion analysis system. On the spine, markers were located on the spinal process of C4, T1, T4, T8 and T12. The anterior superior iliac spines of the subjects were also tracked during the duration of the test.

PMHS study

The University of Virginia Center for Applied Biomechanics performed sled tests on PMHS. PMHS were screened before testing to confirm the absence of any infectious blood disease (HIV, Hepatitis B, Hepatitis C) and of any other pathology that could affect the impact response and injury occurrence of the subjects.

Kinematic data were obtained using camera Vicon MX™ motion capture system. The cameras tracked the motion of spherical retroreflective targets within the camera’s collective viewing volume. Other details of instrumentation and data treatment is in reference [2]

Each PMHS was first subjected to a low speed (approximately 9 km/h) frontal impact comparable to that of the volunteers. Then, a high speed test (approximately 40 km/h) was performed on the same subject. Figure 3 shows the 9km/h and 40 km/h deceleration pulses used in the PMHS study [2] [3]. The PMHS was restrained by a three-point seatbelt of similar characteristics to the one used in the volunteer study. Belt position on the torso of the PMHS as

| Test Speed Hybrid III 50th (test No.) | 9km/h | 40km/h |
|-------------------------------------|-------|--------|
| PMHS (test No.)                     | 1397, 1401, 1404 | 1398, 1402, 1405 |
| Human Volunteer                     | 6 runs for each 10 subject | NA |
well as the position of the seatbelt anchor points with respect the seat matched the conditions used in the volunteer tests [1]. Initial position of the PMHS was set to replicate the volunteer initial position. PMHS head initial angle was set to zero degrees. A comparison between the initial position of one of the PMHS and one pediatric volunteer is shown in Fig. 4.

Normalization of results and corridor creation
Before undertaking any scaling effort, the responses from each of the subjects were combined into corridors representing each of the four datasets considered in the analysis: pediatric volunteers at 9 km/h, adult volunteers at 9 km/h, adult PMHS at 9 km/h and adult PMHS at 40 km/h. The method described in [8] was used here to preserve the characteristic shape of individual trajectories in the sagittal plane. Each group of subjects was normalized to the 50th percentile within their age group. The anthropometric characteristics of the 50th percentile adult male are included in Table 4. The method provides the average response of the subject and a corridor that includes the standard deviation of the response in both the X and Z axes.

UVA also conducted PMHS and ATD tests with a normal belt and with a pre-tensioner and force-limiter in 48km/h. Table 5 is the test matrix and subject characteristics.

### Table 5 Test Matrix and Subject Characteristics

| Test # | Restraint | Age / Gender | Stature (cm) | Mass (kg) | BMI* (kg/m²) | ΔV (km/h) | λw ** | λz ** |
|--------|-----------|--------------|--------------|-----------|--------------|-----------|-------|-------|
| 1262   | Standard  | 51/M         | 175          | 55        | 18           | 48.9      | 1.11  | 1.00  |
| 1263   | Standard  | 57/F        | 165          | 109       | 40           | 47.1      | 0.88  | 1.06  |
| 1264   | Standard  | 57/M         | 179          | 59        | 18           | 48.5      | 1.08  | 0.98  |
| 1386   | FL+PT     | 67/M         | 175          | 69        | 23           | 48.2      | 1.03  | 1.00  |
| 1387   | FL+PT     | 69/M         | 171          | 67        | 20           | 49.6      | 1.04  | 1.02  |
| 1389   | FL+PT     | 72/M         | 183          | 72        | 22           | 49.4      | 1.01  | 0.96  |

*BMI: Body Mass Index = Mass / Stature²
** Scale Factors: λw = (77 kg / Mass)², λz = (175 cm / Stature)

### 3. Result

#### 3.1. High Speed Human Volunteer Tests

Initial position and general behavior can be taken from video and measured acceleration and loads are obtained from the original reports [4] [5]. Fig. 5 shows the initial position and maximum excursion of subject V4 in the 44km/h high speed impact test (Run No. 2699). As instructed the volunteer placed their chin on their chest to avoid the damage to neck. After this test the subject reported high lap belt pressure and momentary breath loss, but no pain and no bruise or abrasion on the body. The flexion moment of head-neck complex appears very
small. The oscillography data from test 2699 from original report is shown in Fig. 6. Run number 2745 and 2746 is the highest speed run in this project (48km/h). Fig.7 and 8 show the initial position and maximum excursion of subjects V4 (Run No. 2745) and V7 (Run No. 2746) in the 48km/h impact test. The subject report after these run is not found. Again the subject placed his chin on chest prior to test start and the head-neck flexion moment appears small. The shoulder maximum forward excursion of subjects V4 and V7 in crash tests speeds from 10km/h to 50km/h.
Fig. 9 Shoulder Displacement High Speed
is shown with the data of PMHS and ATD in Fig. 9, and it ranged from 80mm to 380mm. The shoulder displacement at 40km/h is estimated between 200mm and 340mm.

3.2. Low Speed Volunteer and ATD, PMHS Tests
Table 6 and Table 7 show the values and timing of the maximum forward excursion of the head, spine and pelvis in the ATD and PMHS tests in low speed.

Low speed human volunteer test
Table 8 shows the maximum excursion of 10 human volunteers in low speed (9km/h) test. This indicate that Human volunteer has a smaller forward excursion for the head and upper torso and a larger pelvis excursion compared to the PMHS. The ATD has the smallest head and upper torso forward excursion. Fig. 10 shows the initial position and time of maximum excursion of high speed (40km/h) PMHS test of 1405. Table 9 and Table 10 show the values and timing of the maximum forward excursion of the head, spine and pelvis obtained in the ATD and PMHS tests at high speed, respectively. Apparently the excursion of PMHS is larger than ATD. The trajectories of head, torso and pelvis of PMHS and ATD under similar

| Subject (No. / age) | Head | T1 | T4 | Pelvis (ILC) |
|---------------------|------|----|----|-------------|
| 37-18               | 206  | 163| 150| 120         |
| 36-22               | 165  | 153| 137|  no data    |
| 35-24               | 190  | 146| 128|  89         |
| 34-20               | 193  | 163| 146|  114        |
| 33-19               | 194  | 137| 123|  117        |
| 27-30               | 192  | 136| 125|  131        |
| 24-22               | 202  | 157| 147|  136        |
| 23-22               | 219  | 168| 150|  124        |
| 22-24               | 203  | 156| 140|  112        |
| 21-22               | 209  | 169| 141|  103        |

Average 197.3 154.8 138.7 116.2222

Table 6 Mean excursion of ATD, Low speed

|          | X    | t    |
|----------|------|------|
| Head     | 178.3(±2)| 159(±0) |
| Spine    | 102(±1.8)| 138.5(±6.4) |
| Pelvis   | 87.0(±0.5)| 140.0(±9.9) |

Table 7 Excursion of PMHS, Low speed

|        | X(mm)  | t (ms) | X(mm)  | t (ms) | X(mm)  | t (ms) |
|--------|--------|--------|--------|--------|--------|--------|
| Head   | 283.8  | 233    | 291.6  | 239    | 319.74 | 291    |
| T1     | 211.0  | 223    | 203.7  | 200    | 217.3  | 207    |
| T2     | 161.4  | 196    | 129.7  | 280    | 157.7  | 167    |
| T4     | 95.72  | 162    | 80.40  | 154    | 108.4  | 148    |
| L4     | 70.38  | 157    | 64.1   | 149    | NA     | NA     |
| Pelvis | 51.96  | 149    | 58.5   | 141    | 67.5   | 131    |

Fig. 10 PMHS 1405
The excursion of PMHS is far larger than that of the ATD, and the torso of PMHS leaning more forward than ATD. PMHS used in tests 1404 and 1405 exhibited a fracture of the anterior body of C4 (AIS 650230.2) involving disruption of the Anterior Longitudinal Ligament (ALL) (AIS 640284.1), avulsion fracture of the T1 left transverse process (AIS 650420.2) and fractures of the anterior vertebral body of T12 (AIS 650430.2) and spinous processes of T12 (AIS 650418.2) and L1 (AIS 650618.2), involving tearing of the ALL (AIS 650484.1). The other two PMHS did not have apparent injury.

4. Discussion
In order to compare differences between high speed volunteer tests conducted by the NADC and the volunteer, PMHS and ATD tests conducted by CHOP and UVA, specific aspects of the test conditions and set up are noted.
1) The difference of test speed and sled deceleration pulse.
2) NADC test used the seatbelt with energy absorbing shoulder webbing, but the test by CHOP and UVA used conventional seatbelt system.
3) Initial position and muscle tension.
The deceleration pulse of NADC is more severe than the pulse of CHOP and UVA, because absolute velocity change (44 km/h vs 40 km/h) and shape of deceleration (Initial part low G and higher G later, means less ride down energy). This factor increase the excursion in NADC tests compared to the tests at UVA and CHOP.
Regarding the difference of seat belt system, UVA also conducted the test used the normal seat belt and a seat belt with force limiter and pre-tensioner at 48 km/h. [9] Table 11 compares the result of both conditions. The force limiter increased the excursion about 160 mm even the presence of a pre-tensioner. Thus the energy absorbing webbing without pre-tensioner would increase the displacement more than 160 mm at 48 km/h. Considering those factors contributing to increased excursion (deceleration pulse and seat belt system difference), the human volunteer’s excursion (around 280 mm) was still smaller than PMHS (417 mm~457 mm at T1).
One possible reason for this reduction is the difference of subject’s state or condition. Volunteers in the NADC study is prepared for the impact, tensed their muscles and put their chins on their chest to reduce the flexion moment. This muscle tension greatly affected the kinematics, but the amount of it is not...
clear at this point. Another point to highlight is injury status of subject. In NADC project no injury was reported for the two volunteers, on the other hand one of three PMHS recorded many injuries. Table 12 shows the information about PMHS and the injured PMHS is not in an abnormal condition prior to the test. Thus we may conclude that the PMHS appears to have more injury than the Human Volunteer.

### Table 12 PMHS information

| Test # | Head X | Shoulder X | Hoc X | Knee | Torso Angle | Submaximal Observed |
|--------|--------|------------|-------|-------|-------------|---------------------|
| 1263   | 1262   | 1264       | 1565  | 1397  | -19         | Yes Yes Yes         |
| 1251   | 1285   | 1246       | 1367  | 1401  | -18         | Yes Yes Yes         |
| 1248   | 1248   | 1293       | 1363  | 1402  | -21         | Yes Yes Yes         |
| 1251   | 1258   | 1285       | 1367  | 1401  | -20         | Yes Yes Yes         |
| 1248   | 1248   | 1293       | 1363  | 1402  | -21         | Yes Yes Yes         |

*All displacements are relative to the initial positions. The torso angles are the maximum absolute torso angles. All displacements are scaled, and are in cm.

5. Conclusion

Forward excursion of human volunteers in high speed frontal impact tests at NADC, were compared with the excursion of ATD and PMHS tests at CHOP/UA.

In the context of differences in the test conditions between these tests, we conclude that the forward excursion of a human volunteer with tensed muscles in high speed frontal crash loading condition is less than the forward excursion of PMHS. Previously we reached same conclusion for relaxed human volunteer in low speed test conditions. More study is needed to examine the response of the relaxed human volunteer in high speed impacts. Same as our previous conclusion, the excursion of ATD is far less than PMHS and human volunteer.

In addition, we observed that the human volunteer has less injury than PMHS. This difference may due to the response of living human body include muscle tension, but we should examine effect of subject age.

Lastly the position of placing the chin on chest combined with muscle tension appears to have substantial effect in reducing flexion moment of neck to avoid injury.

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