7

INJURY BIOMECHANICS RESEARCH
Proceedings of the Twenty-Ninth International Workshop.

Injuries and Mechanical Responses From Single Versus Dual Shoulder Impact Tests

J.H. Bolte IV, M.H. Hines, J.D. McFadden, R.G. Herriott, B. Donnelly

ABSTRACT

Normalized force-displacement responses and injury data based on dual shoulder impacts for a series of twelve subjects conducted at varying velocities were previously published by the authors. Understanding the effects of bilateral versus unilateral shoulder impacts on injury and force response is a necessary step before biomechanical response corridors can be developed from the data set. This paper assesses the effect that impacts to both shoulders of a subject had on the trauma injuries and the force-displacement responses. The basis for this paper is a new test series of lateral impacts to a single shoulder of four approximately fiftieth percentile subjects. The injury and force-displacement responses were compared with the bilateral shoulder impact test data from five of the previously impacted twelve subjects. All tests used for this comparison were conducted at approximately 4.4 m/sec. As in previous tests, the first thoracic vertebrae and both shoulders of the subject were instrumented with tri-axial linear accelerometers on the sternum, clavicle, acromion process, and inferior angle of the scapula. The impacting mass was instrumented with an accelerometer and displacement transducer. In addition to transducer data, the tests were documented by high-speed digital imagery. Injuries were documented by radiographs (x-rays), magnetic resonance images (MRIs), and autopsies. Several null hypothesis were tested to determine if the data set was confounded by multiple shoulder impacts including 1) there is no difference in the injuries produced by impacting a second shoulder, 2) there is no difference in the force-displacement responses produced by impacting a second shoulder.

INTRODUCTION

Injury and mechanical response of the shoulder due to lateral impact has yet to be studied in great depth. Thus far three separate studies have been completed that focused on trauma biomechanics of the shoulder. The first was an impactor study conducted on four cadavers by the Association Peugeot-Renault. The testing resulted in normalized force time histories and a suggested boundary of maximum shoulder deflection with respect to the thoracic spine of 34 to 41 mm (Road Vehicles, 1997). A second study conducted by Irwin et al. at Wayne State University was comprised of seven cadaver sled tests. This testing established normalized shoulder plus thorax force versus time histories and a proposed response corridor for an 8.9 m/sec padded wall impact (Irwin et al., 1994).

The third study, recently conducted by these authors at The Ohio State University, involved dual shoulder impacts for a series of twelve cadavers conducted at varying velocities. The results from this previous testing, presented at the 44^{th} Stapp Car Crash Conference, included injury findings and normalized force displacement responses. The authors found that the most common AIS level II injury sustained was a fracture of the distal end of the clavicle. Also documented was the discovery that displacement between the impacted acromion and the sternum was a good predictor of clavicular failure. Finally, it was determined that approximately 47 mm was the clavicle fracture threshold for a fiftieth percentile male (Bolte et al., 2000).

Two major issues surfaced during the presentation of this cadaver research. Did impacting both shoulders increase the number and severity of injuries? Was the mechanical response of the shoulder influenced by dual impacts? Recently completed single side impacts will be compared with the earlier dual impacts to answer these questions.

METHODS

In the trauma laboratory, four unembalmed fresh cadavers were subjected to a single impact to the left shoulder at a speed of approximately 4.4 m/sec.

Data Collection

Subject Selection and preparation. The research required the use of four unembalmed cadavers less than 24-36 hours post mortem so that all testing could be completed within 60 hours post mortem. All testing was conducted in compliance with NHTSA Order 700-4, and was approved by The Ohio State University Biomedical Sciences Human Subjects Review Committee. Subjects were required to be between 55-105 kg in weight and to be less than 75 years old or to be deemed fit by the research team. Cadavers meeting these criteria were then inspected for evidence of existing or old injuries to the shoulder girdles and sternum.

Following the selection process, the cadavers were cleaned externally with a 10% bleach solution to guard against infection. Anthropomorphic measurements were then recorded before the subject was transported to the Magnetic Resonance (MR) facility where Magnetic Resonance Images (MRIs) and radiographs (X-Rays) were taken of the sternum, the first thoracic vertebrae, and both shoulder girdles. It is important to note that these images could not be used as subject selection tools because the film was not able to be analyzed prior to the impact testing. This was due to staffing and time constraints brought forth by the use of fresh cadavers for testing.

Instrumentation. Triaxial accelerometer mounts were positioned at eight locations throughout the upper thoracic region of the subject. The structures instrumented included the manubrium of the sternum, the first thoracic vertebrae (T-1), the right and left medial third of the clavicles, the lateral third of the left clavicle, both right and left acromion processes, and the inferior angle of the left scapula. Mounting techniques were designed to securely fasten the accelerometer mounts to the bony sites, while minimizing damage to the soft tissue of the cadaver, thus reducing the effect of the mounts on the motion of the shoulder girdles.

Other instrumentation used during the testing included an accelerometer on the backside of the impacting ram, a linear displacement potentiometer on the impactor, and a time-zero event channel. Output from the ram accelerometer was used to calculate the input force to the left shoulder for each impact. Output from the linear displacement potentiometer was differentiated to check the velocity of the ram calculated from the integrated accelerometer on the ram. Finally, a control switch was used to determine the time of the ram's initial contact with the subject's shoulder; the time-zero of the impact.

Positioning. Following instrumentation, the cadaver's upper limbs were passively exercised through their range of motion to eliminate rigor mortis. The subject was then positioned on the impactor seat with the center of the ram in line with the palpated center of the glenohumeral joint (Figure 1). The height of the subject in relation to the impactor face was adjusted vertically so that the center of the glenohumeral joint was 2.0 inches above the bottom of the ram. This height was determined to be the optimal height, based on prior testing, in order to keep the ram from interacting with the upper arm before impacting the shoulder. The cadaver was seated approximately 9.25 inches away from the ram to ensure that the ram reached a constant velocity before impacting the subject. The vertical distance between the acromion process of the impacted shoulder and the spinous process of T-1 was set at approximately one inch to control the shoulder "hunch" of the subject.

Figure 1: Typical Left Side Impact Test Set-up

Photographic Instrumentation. Photographic target pins were inserted into the triaxial accelerometer mounts after the subject was positioned. These pins enabled positioning measurements of the accelerometer mounts to be recorded for subsequent analysis. Measurements in the medial-lateral, anterior-posterior, and inferior-superior axes were taken from a common point, in order to determine the three-dimensional spacing between the mounts. Orientation of the pins prior to impact was also recorded to document the off axis angle of each accelerometer. Finally, the pins were used to support camera targets. Movements of these targets were recorded using a high-speed digital camera located in front of the subject. This view enabled motion of the targets to be tracked in the medial-lateral and inferior-superior axes.

Impact. After the pin measurements were completed, the left shoulder of each subject was impacted with a 23 kg pneumatic ram traveling at approximately 4.4 m/sec. The face of the ram, 8 in. horizontal by 6 in. high, was covered with a two inch thick piece of Arcel 310, 26.4 kg/m^3 density foam padding. The impact velocity of 4.4 m/sec was chosen based on prior testing results. It was determined that at this velocity, a subject of the approximate size of a 50^{th} percentile male, would almost reach an injury threshold level. Since a goal of these impacts was to document mechanical response, an input force below the level of injury threshold was desired. The velocity of the ram, tracked by an accelerometer mounted on the backside of the impacting surface, decreased during the loading phase of the impact.

Post-test. Following the impact, all of the instrumentation was removed from the subject. The cadaver was then transported to the MR facility where radiographs and MRIs were retaken so that any injuries that occurred during impact could be visualized, identified, and recorded. A pathologist performed a post-test dissection that focused primarily on the shoulder complex of both sides of the subject.

Data Analysis

Data was collected using a 48 channel data acquisition system. Signals from each transducer were transmitted to a central data acquisition system where analog to digital conversion was performed at a nominal sampling rate of 10,000 Hz. Output from all accelerometers was filtered at SAE class 180 after any bias was removed. For all results, time-zero was defined to be when initial contact was made between the ram and the subject. Impact force was calculated by multiplying the mass of the ram by the output of the accelerometer mounted on the head of the ram. High-speed digital motion analysis files were analyzed using a SAI Industries Image Express workstation. Shoulder girdle displacement was calculated by tracking the movement of the photographic targets with respect to each other.

All data was normalized to that of a fiftieth percentile male. First, the effective mass was estimated using the Impulse Momentum method (Road Vehicles, 1997). This method uses the change in velocity of the first thoracic vertebrae (Δ V), from the time of the initial ram contact until the time when the impacted acromion was maximally displaced with respect to the non-impacted acromion (Equation 1).

$$M_e = \frac{\int_0^T F dt}{\Delta V} \quad (1)$$

The data was normalized using a simple model analysis developed by Mertz (Mertz, 1994). The mass and stiffness ratios, R_m and R_k, were calculated for each impacted shoulder. The mass ratio was determined by taking the calculated effective mass of the fiftieth percentile male, 25 kg (based on testing), and dividing it by the calculated effective mass for each impacted shoulder (Equation 2). The stiffness ratio was calculated by taking the chest depth of the fiftieth percentile male, 236 mm (Mertz, 1994), and dividing it by the chest depth (L) of each subject (Equation 3).

$$R_m = 25kg / M_e \quad (2) \qquad R_k = 236mm / L \quad (3)$$

Finally, the factors used to normalize time (R_t), displacement (R_x), and force (R_f) were calculated using these mass and stiffness ratios (Equations 4 and 5).

$$R_t = R_x = \sqrt{R_m / R_k} \quad (4) \qquad\qquad R_f = \sqrt{R_m * R_k} \quad (5)$$

RESULTS

Injury findings and mechanical response output from the four unilateral shoulder impacts will be presented. These results will also be compared to the bilateral shoulder impact test data from five of the previously impacted twelve subjects.

Test Matrix

Essential cadaver characteristics, taken from anthropometric measurements are shown in Table 1. The table shows that the average age of the four male subjects was 72 years old. The average height of the subjects was 179 cm while the average mass was 74 kg. Two of the four cadavers were very comparable in size to the "standard" fiftieth percentile male with a height of 175 cm and a weight of 76 kg.

Table 1. SUBJECT CHARACTERISTICS

Subject Number	Gender	Age	Stature (cm)	Mass (kg)	Chest Depth (cm)
1301	M	64	185	103	31
1401	M	76	172	57	26
1501	M	84	175	64	23
1601	M	64	183	70	23
	Average:	72 ± 10	179 ± 6	74 ± 20	26 ± 4

Pre-existing conditions identified in the MRIs and X-Rays were important in determining if injuries detected in post-test imaging and autopsy were a result of the impact or were present prior to testing. Typical pre-existing conditions that were present included: degenerative joint disease in the glenohumeral, acromioclavicular, and sternoclavicular joints; tendonitis; rotator cuff tears and anterior and superior labral tears.

Injury Findings

The injuries sustained by the four subjects from these lateral impacts to the shoulder girdle are displayed in Table 2. Injury was documented using three different modalities for all of the test subjects: radiographs, magnetic resonance images, and autopsy. The table reveals that neither cadaver, 1301 nor 1601, sustained any type of injury due to the lateral impact. For the second subject, 1401, autopsy revealed that the left, impacted, sternoclavicular joint was loose. Looseness is defined as an increase in excursion of the end of one bone or the ends of both bones that comprise the joint when compared to a normal joint by the pathologist.

Table 2. INJURIES SUSTAINED DURING IMPACT

Subject Number	Side	Joints	Bones
1301	Left	None	none
	Right	None	none
1401	Left	Loose Sternoclavicular (751220.1)*	none
	Right	None	none
1501	Left	Loose Sternoclavicular (751220.1)* Loose Acromioclavicular (750220.1)*	Distal Clavicle Fracture (752200.2)*
	Right	Loose Sternoclavicular (751220.1)* Loose Acromioclavicular (750220.1)*	none
1801	Left	None	none
	Right	None	none

* Abbreviated Injury Scale rating

The only impacted subject to receive greater than an AIS level 1 injury was subject 1501. The impact to the shoulder girdle resulted in a fractured left distal clavicle: an AIS level 2 injury. Autopsy also revealed looseness in both the left and right sternoclavicular and acromioclavicular joints. The finding of joint looseness on the right, non-struck, side of the cadaver reveals that during an injury producing impact, injuries may be sustained on the non-struck side of the subject.

In order to determine if impacting both sides of a single cadaver confounds the injury results, an injury comparison was made between these four single impact subjects and five previous subjects whom were impacted on both sides at similar impact speeds, see Figure 2. Due to testing time constraints in the previous study, the injuries could only be documented once both impacts had occurred. Therefore, it was difficult to determine which injuries occurred from each of the two impacts. Figure 2 reveals that a higher percentage of subjects impacted on both sides sustained at least one injury compared to subjects impacted on only the left side: 80% rate of injury versus 50% rate of injury. It was also documented that subjects in this single impact study averaged only one injury per side, while subjects impacted on both sides averaged more than double that at 2.6 injuries per side.

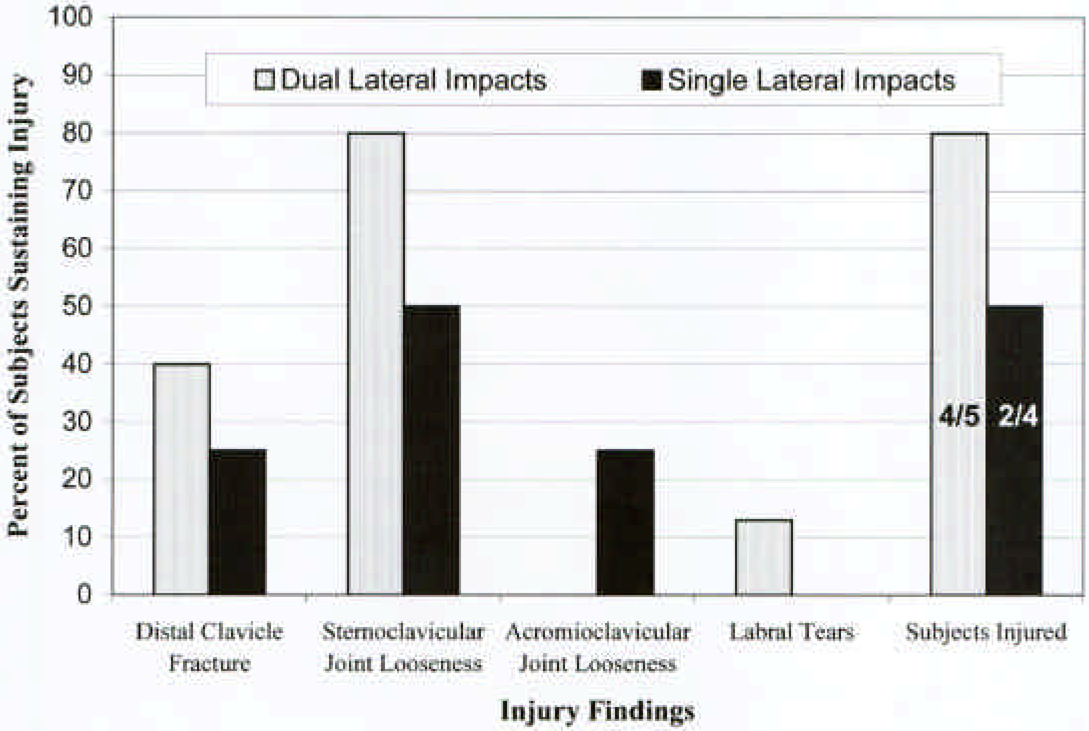

Figure. 2: Injury Comparison Between Dual and Single Impacts per Subject

Mechanical Response Findings

The average curve representing the normalized force displacement responses from a set of first impacts and the average curve for a set of second impacts is shown in Figure 3. The displacement shown in the figure is the amount of movement recorded between the impacted acromion and the sternum. This displacement has been shown to be a good predictor of clavicular failure (Bolte et al., 2000). The average curve for first impacts was calculated from the mechanical response of cadavers 1301, 1401, and 1601. Subject 1501 was not included because of the failure of the distal clavicle, resulting in a possible abnormal response. Also included in this average were two subjects from the previous dual impact shoulder study. These two tests, conducted at similar speeds, were the first impacts to subjects that were impacted bilaterally. Thus, the average mechanical response results from first side impacts to five separate subjects. Also plotted in Figure 3 is the average curve representing the normalized force displacement response from the second impact to subjects impacted on both sides. This average mechanical response curve is comprised of second side impacts to three separate subjects. Figure 4 shows the same data but with the displacement occurring between the impacted and the non-impacted acromion processes.

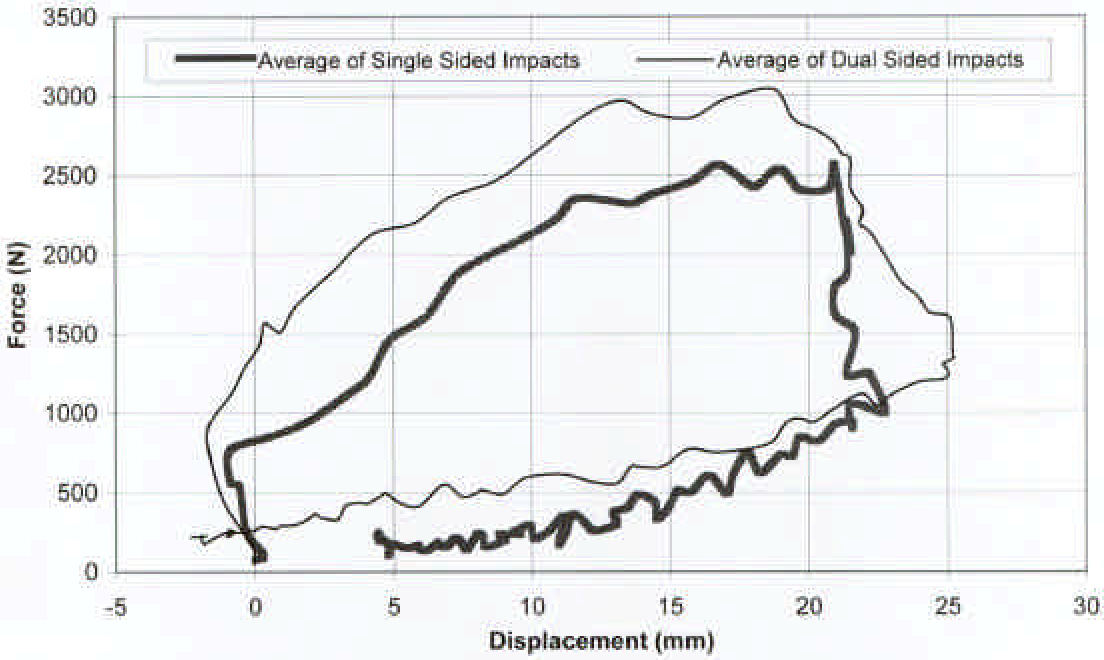

Figure. 3: Force Versus Displacement Between the Impacted Acromion and the Sternum

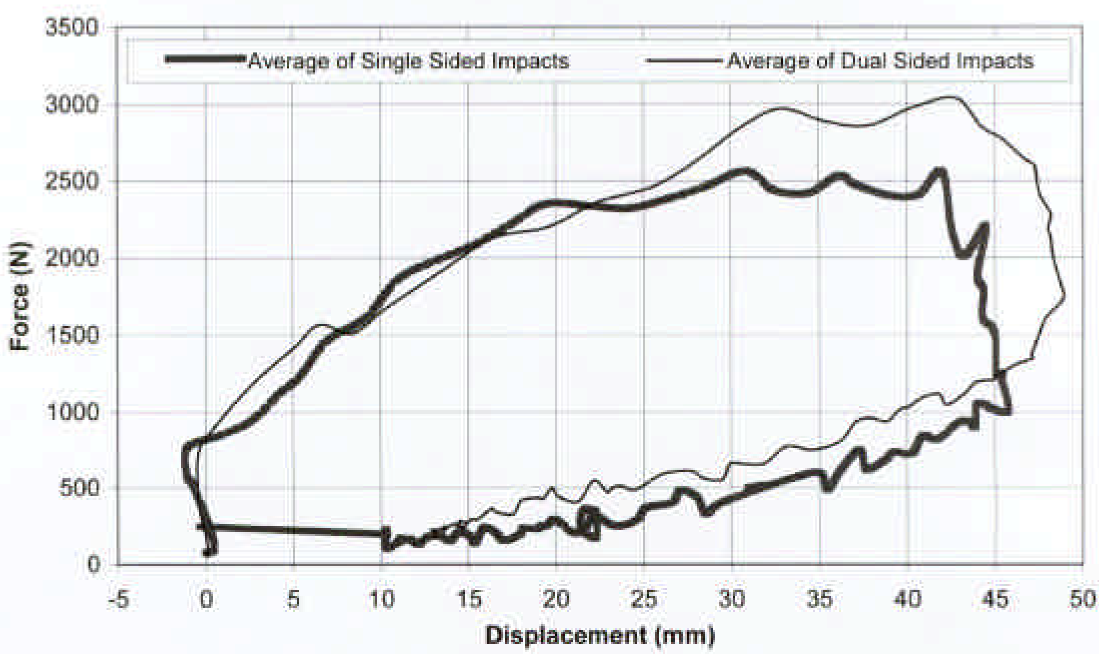

Figure 4: Force Versus Displacement Between the Left and Right Acromions

Both figures reveal similar traits between the response of the subjects to the initial impacts and the response of the subjects to the second impacts. The stiffness for both sets of data is very similar. The only difference between the single and dual impacts is that the dual impacts resulted in slightly higher displacements and forces for both figures. However, this small difference could be due to variability between the impacted cadavers.

CONCLUSIONS

To determine if conducting bilateral shoulder impacts to a subject confounds the results of a test, one must look at the testing from both an injury and a mechanical response standpoint. If the goal of the study is to examine low severity injuries due to lateral impacts to the shoulder girdle, the results show that one would only want to conduct a single impact per cadaver.

- Contra-lateral injuries were documented in 1 of 4 single sided impacts
- Dual sided impacts increased the number of injuries per subject
- Dual sided impacts did NOT increase the severity of the injuries

From a mechanical response standpoint, impacting both sides of a single subject did not seem to affect the mechanical response of the shoulder to a lateral impact. Therefore, if the goal of the testing is solely to look at response, both shoulders could be impacted and studied.

- Loading stiffness was similar for both dual and single sided impacts
- Cadaver variability was the likely cause for slight difference in the displacements and forces recorded in the dual impacts.

ACKNOWLEDGEMENTS

This research was made possible by support from the National Highway Traffic Safety Administration, Department of Transportation, and The Ohio State University College of Medicine and Public Health. The research would also not have been possible without the help of an extraordinarily diverse and talented team: Matthew Hostetler from the Transportation Research Center Inc., Don Kincaid, Bill Stranges, Drs. Petra Schmalbrock, Peter Baker, Joseph Yu and Alan Litsky from The Ohio State University.

REFERENCES

BOLTE, J.H., HINES, M.H., McFADDEN, J.D., SAUL, R.A. (2000). Shoulder Response Characteristics and Injury Due to Lateral Glenohumeral Joint Impacts. Proc. 44th Stapp Car Crash Conference, Paper No. 00S-11, 261-280.

IRWIN, A.L., WALIKO, T.J., CAVANAUGH, J.M., ZHU, Y., KING, A.I. (1994). Displacement Responses of the Shoulder and Thorax in Lateral Sled Impacts. SAE Paper No. 933124, 1271-1279.

MERTZ, H.A. (1994). A Procedure for Normalizing Impact Response Data. SAE Paper No. 840884, 1159-1166.

Road Vehicles – Anthropometric Side Impact Dummy – Lateral Impact Response Requirements to Assess the Biofidelity of the Dummy, ISO/TC22/SC12/WG5 Document N455-Revision 4, (1997)

DISCUSSION

PAPER: **Injuries and Mechanical Responses from Single Versus Dual Shoulder Impact Tests**

PRESENTER: ***John Bolte, VRTC***

QUESTION: *Richard Kent, University of Virginia*

This is very interesting research. I think it's bad news for those of us who might want to do matched impacts in this way. I was interested in the forced deflection curves comparing the single impacts versus the dual impacts. I myself have also tried to do scaling with cadavers of different sizes and I suspect that it is not perfect and you probably still have some specimen to specimen variability here. And I wondered if it was not possible to look at the first impact versus the second impact on matched, on the same cadaver, and perhaps get forced deflection curves for the first impact and the second impact, and then that way remove that cadaver variability or if that was not possible?

A: In the STAPP paper of last year we did plot the first impact versus the second impact and there was quite a bit of variability. This, obviously, I don't know if I stated this, is the average of those trying to come out. And the problem with the three that we use for the dual, we had a case where we had weeble wobble and a large person that took it. And I think it added a lot of the variation that you're seeing. So I don't remember off the top of my head exactly what the STAPP showed from last year, but we did look at it.

Q: *Guy Nusholtz, Daimler Chrysler*

Without looking at the variability, I don't know that you can declare these things similar or different because there might be enough variability that they are in fact the same or they could in fact be different. Have you tried to do any sorting, either a statistical process or using correlations or anything to try and find out whether there's a significance there?

A: I am going to be completely honest with you that this was done two nights ago at 3:00 in the morning. So that stage will be there. That is somewhere we could look down the line.

Q: Because if you are able to get away with dual impacts you got twice as much data for extracting the information.

A: I agree. I mean a lot of people said why even bring this subject back up because if you prove that they are totally different then it blows some people say, what we presented last year at Stapp.

Q: That doesn't look totally ---.

A: We wanted to answer the question to see if it is the case. Last year's work was to find injury threshold whereas this is trying to find mechanical response.

Q: *Erik Takhounts, NHTSA*

Could you explain to me what is that negative displacement there?

A: I was waiting for this question. The negative displacement and the force without displacement is due -- I think Guy last year asked me in STAPP about anticipatory cadavers and them jumping away from the impact. And what it is, depending on the subject and how well we can get their arms down at their sides with the ram. Sometimes the ram connects a little bit lower before it hits the shoulder causing the acromion to slight go out. I mean you're only talking one millimeter.

Q: You measured deflection how?

A: Deflection was measured using the photo target system. So it's the force from the ram.

Q: Your previous slide has more negative deflection.

A: Yes. That one. Thank you, very much