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## METHODS FOR THE INVESTIGATION OF AIRBAG-INDUCED UPPER-EXTREMITY INJURIES

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### INTRODUCTION AND BACKGROUND

A variety of injuries to the upper extremities have been reported as a result of airbag deployments. The most prevalent type is superficial skin trauma such as erythema, contusion, abrasion, or burn caused by contact with the airbag fabric, module cover, or exhaust gasses. Reed et al. (1992) characterized abrasion injury resulting from contact with a deploying airbag. Reed et al. (1994) characterized the potential for burn from airbag exhaust gases. Huelke et al. (1995) describe fifteen anecdotal cases of field accident data in which more serious injuries to the forearm, including fractures to the radius and ulna bones, resulted from steering-wheel airbag deployments. Most of these fractures seem to have resulted from direct contact with the airbag and module door, entrapment between the airbag and steering rim, or flailing of the forearm and hand into other parts of the automotive interior.

A number of different types and locations of radius and ulna fractures can result from these different airbag-induced injury scenarios. Preliminary unpublished data indicate that small females, especially older individuals, may be most vulnerable to forearm injury as a result of contact with a deploying airbag. However, a more recent unpublished study of accident data indicate that airbag-induced forearm fractures are experienced by both males and females across a range of age and stature.

Little fracture-tolerance data for the human forearm are available. The most prevalent data focus on static three-point bending tests of isolated bones. Weber (1856) determined loads and moments required to produce failure in ulnae obtained from 4 males and 5 females. Messerer (1880) determined load and moment to produce failure in 12 human radii and ulnae using a 3 point bending approach. Motoshima (1960) conducted 3-point bending

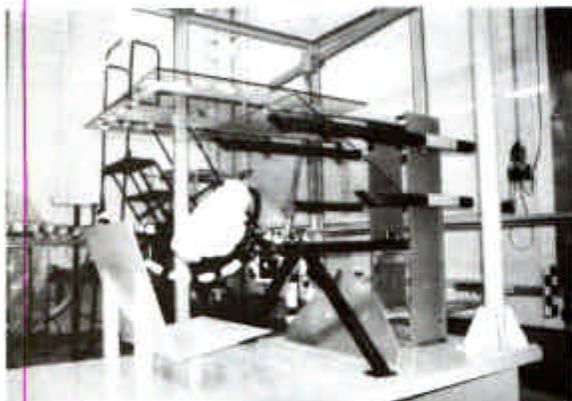
tests in the anteroposterior direction on isolated wet bones of the forearms of 35 human cadavers. Jurist (1977) examined the stiffness of 45 embalmed human ulnae in bending created by anteroposterior loading. Mennen (1989) performed quasi-static three-point bending tests on the forearms of 32 anesthetized baboons. Although these different studies report a range of tolerance values, a number of relevant observations can be made that can help in the design of laboratory investigations of airbag-induced forearm fractures. These include:

- forearm bone strength is related to age, sex and body weight
- large variations in tolerance exist between similar sized individuals
- there can be a significant difference in tolerance between the two forearms of an individual
- bones of young people are capable of extreme bending without fracture
- soft tissue is not an important factor at low loading rates
- in adults, the diaphysis of the radius is 10% stronger than that of the ulna in adults
- the direction in which the load is applied relative to the cross-sectional shape has a significant effect on failure load
- bone strength is most highly correlated with mineral content, followed by stiffness and cross-sectional area

In order to better understand the driver, airbag, and driver/airbag factors and conditions under which the airbag-induced fractures occur, it is useful to conduct static airbag deployment tests using unembalmed human cadavers. This paper describes preliminary methods and procedures for setting up and conducting these tests.

## METHODS

The test apparatus developed for conducting whole-body static airbag-deployment tests using unembalmed cadavers is shown in Figure #1. It consists of a steering wheel and airbag assembly mounted to a static test platform. The platform is equipped with a rigid-back seat inclined at 22 degrees to the vertical, an adjustable windshield-header-roof assembly, and variable-position instrument panel parts. The steering wheel is oriented at 30 degrees to the horizontal, which is more inclined than in a typical personal-licensed vehicle during normal driving conditions. The test facility allows for conducting tests to simulate injuries that may result from direct airbag loading, as well as injuries caused by the airbag flinging the arm and hand into the windshield.



**Figure#1:** Test facility for conducting static deployments of steering-wheel airbags into cadaver forearms.

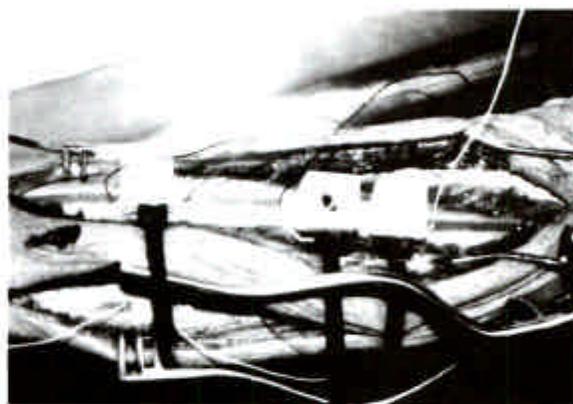
### Specimen Screening

Each cadaver specimen is screened for signs of infection diseases and other abnormalities. Serologic screening is performed for hepatitis B and C and HIV. Evidence or knowledge of degenerative bone changes due to osteoarthritis, rheumatoid arthritis, osteoporosis, metastatic carcinoma in the hand, wrist forearm, arm and shoulder regions preclude the use of a specimen. Healed fractures or orthopedic implants in the hand, wrist or forearm, and any unhealed fracture or surgery of the upper extremities are also cause to reject a specimen.

### Specimen Preparation and Instrumentation

Two incisions are made on the posterior aspect of the forearms, following the radius and ulna, beginning 2.5 cm from the elbow and ending 2.5 cm from the wrist. The interosseous ligament is preserved as much as is possible.

The full width of the posterior aspect of the forearm bones is exposed, and the surfaces are carefully cleaned using acetone. A thin layer of cyanoacrylate is applied to these surfaces and allowed to dry. Accelerometer-mounting blocks are attached to the proximal and distal portions of the radius. These blocks are made of Delrin, have four rounded feet and two slots through which plastic wire ties are passed. A tensioning tool is used to tighten the wire ties after the blocks are positioned. Similarly, a Delrin target-mast block is attached to the mid-diaphysis of the radius. The target mast, which is a 15.2 cm brass tube with plastic spheres attached at the end and 5 cm from the end, is positioned in this mounting block via a set screw. A representative forearm preparation is shown in Figure #2.



**Figure #2:** Cadaver forearm prepared for testing with Delrin mounts and crack detection gauges.

To determine the exact time of bone fracture during airbag loading, three crack detection gages are fixed (glued) to proximal, mid-diaphysis and distal regions of each radius and two crack detection gages are attached to each ulna. Crack detection gages are available in a variety of configurations. The devices used in this study are essentially long (2.5 cm), single-element strain gages with large bonding pads. A gage is wired in series with one arm of a full Wheatstone bridge. The bridge elements are fixed resistors. High-gain signal conditioning is used so that when a crack detection gage breaks a distinct level shift is observed. The gages are pre-wired using accelerometer wire and miniature connectors. The solder connections are insulated with conformal coating, and tested in saline prior to use. Cyanoacrylate adhesive and a Teflon application tool are used to install three gages on the radius in proximal, mid-diaphysis and distal locations. Two gages, mid-diaphysis and distal, are installed on the ulna. Finally, the wounds are sutured using umbilical tape, leaving the accelerometer blocks exposed.

After instrumenting the cadaver's forearms, the head and face of the specimen are protected with a heavy cotton wrap and the hands and head are covered with a double-over knotted stockinette material. The cadaver is then dressed in footed tights and leotards. Small holes are cut in the fabric on each forearm for instrumentation access. A webbing harness is attached to the cadaver and post-instrumentation, pre-test x-rays are taken. The forearms are imaged in both pronation and supination.

### Testing

The instrumented cadaver is seated in the rigid test seat and offset from the center of the steering wheel to allow free motion of the entire extremity. The feet are placed at the toe board, and there is a moderate bend at the knees. The thorax of the cadaver is secured to the seat using additional webbing material. Thick padding is placed over the exposed seatback edges to prevent injury to the flailing arm from interaction with the rigid seatback. Accelerometer blocks with three linear accelerometers are installed on each accelerometer-mounting block, and the target masts are also installed. After the connections to the crack detection gages have been made, the cables are bundled and sutured to the shoulders. Some areas of the forearms are wrapped lightly with utility tape to further constrain the cables.

The forearm to be tested is positioned such that the middle of the pronated forearm is perpendicular to the module tear seam at its center. Prior to airbag deployment, the hand and wrist are held loosely in place with perforated tape. No simulation of grip force has been attempted in tests conducted to date. Distance from the forearm to the airbag module is controlled using soft foam blocks.

Proximal and distal triaxial radius accelerations, output signals from crack detection gages, and airbag pressure signals are digitized during testing and recorded on analog tape. Lateral and overhead cameras are positioned to film the test at frame rates from one to six-thousand frames per second.

Between deployments the forearms are examined for signs of fracture. Manual palpation of the forearm bones, x-ray and crack detection gage output determine if it is possible to run another test (i.e., if no fracture occurred). Figures #3a and 3b illustrate arm positioning for sequential tests on a single forearm in which the forearm-airbag proximity was reduced from 2.5 cm to contact.

To simulate an arm entrapment scenario, the hand and wrist are placed between the top of the airbag module and the upper portion of the steering wheel rim.



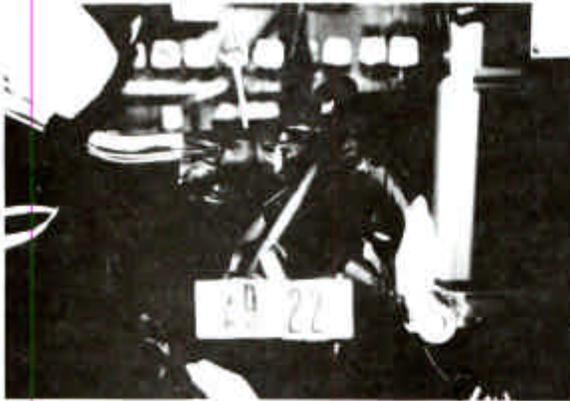
**Figure 3a:** Test setup with cadaver forearm positioned 2.5 cm from airbag module.



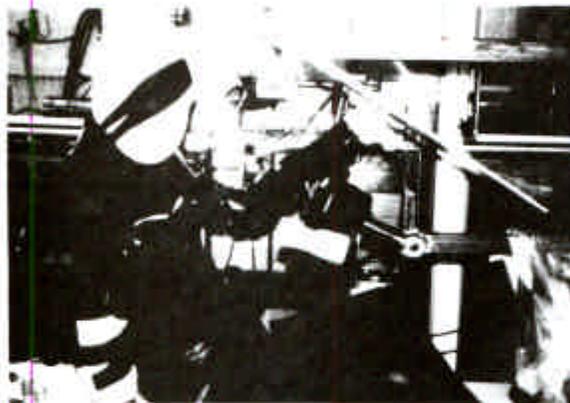
**Figure 3b:** Test setup with cadaver forearm positioned in contact with airbag module.

This is shown in Figure #4. In the flailing injury test, the wrist and hand are placed over the top of the steering wheel rim and the windshield is installed as shown in Figure #5.

After testing, the instrumentation is disconnected and any forearm fractures are splinted. Post-test x-rays are taken, and the arms are harvested, frozen and stored for later autopsy. At autopsy, injuries are assessed, forearm anthropometry is taken, and portions of the forearm bones are ashed. For ashing, 2 cm of the distal one-third of the radii and ulnae are removed and cleaned. Each specimen is rinsed with both distilled water and acetone. The bones are dried in a furnace and weighed. Ashing is performed at 700 degrees C for eight hours. The hands of each cadaver are saved for later Osteogram analysis.



**Figure #4:** Test setup for arm entrapment simulation.



**Figure #5:** Test setup for flailing-into-windshield simulation.

## RESULTS AND CONCLUSIONS

Using these procedures, fourteen deployments have been conducted into ten forearms of five unembalmed cadavers. Tests have been conducted for two different inflator conditions using male and female cadavers, and for a range of pre-deployment arm-to-airbag distances. The established procedures appear to provide sufficiently quantitative information to study subject and airbag factors, as well as test conditions, that contribute to airbag-induced forearm fractures.

Figure #6 provides a view of a 2.5 cm proximity test 9 ms after airbag triggering. This is the same test shown in Figure #3a. Although the image exposure is poor, it is possible to see that the forearm remains essentially straight from the wrist to the elbow.



**Figure #6.** Film frame taken from high-speed film 9 ms after airbag deployment into forearm positioned 2.5 cm from airbag module. No fracture occurred.

Figure #7 shows a view 9 ms into a subsequent test on the same arm. This is the same test shown in Figure #3b. This is a direct-contact test, and a straight path from wrist to elbow is no longer evident. This frame is taken at the time of fracture as indicated by crack detection gages. Figure #8 is an x-ray of the forearm shown in Figures #6 and #7, taken after a test. The forearm is supinated. A complex diaphyseal wedge fracture of the radius can be seen as well as a transverse fracture of the distal ulna and an oblique fracture of the ulna diaphysis.



**Figure #7.** Film frame taken from high-speed film 9 ms after airbag deployment into forearm positioned in contact with airbag module. This approximately corresponds to the time of fracture.

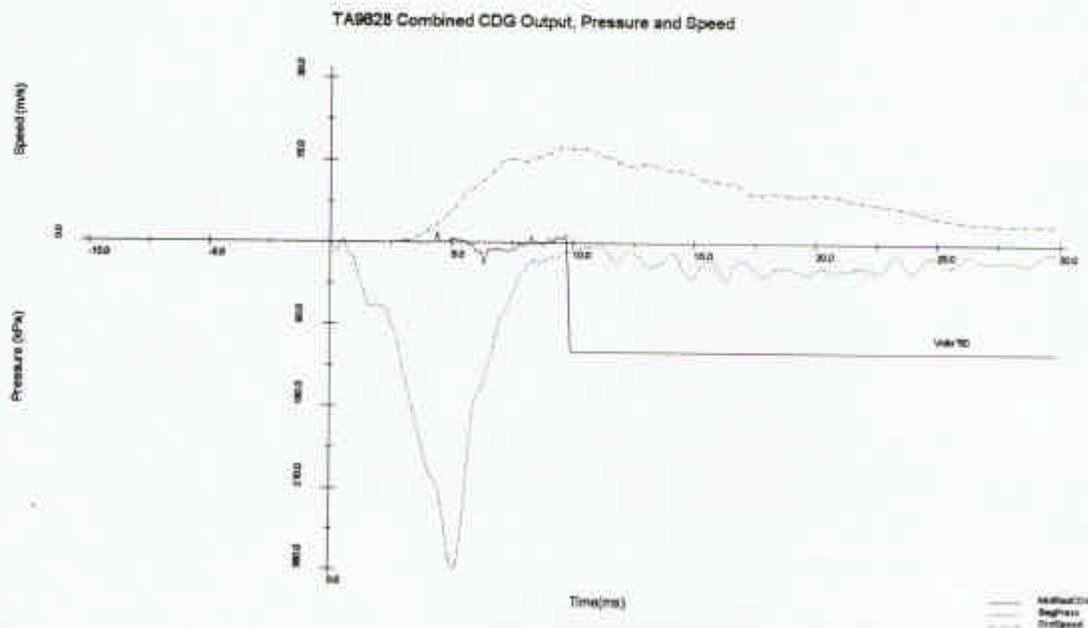


**Figure #8** X-ray of forearm from test in Figure #7 showing diaphyseal wedge fracture of the radius, a transverse fracture of the distal ulna, and an oblique fracture of the ulna diaphysis.

An example of some of the data analysis performed is given in Figure #9. Three parameters are shown, including crack detection gage output from the mid-radius position, airbag pressure (SAE channel class 1000Hz), and distal forearm speed obtained by taking the resultant magnitude of integrated triaxial accelerations.

Although there is no compensation for angular velocity or centripetal acceleration effects, there was little rotation of the distal radius within the first 10 ms of these tests. Distal radius velocities range from 11.4 m/s to 20.6 m/s. Similarly, fracture timing ranges from 5.9 ms to 9.8 ms after airbag triggering. Preliminary analysis of distal speeds, airbag pressures (equal-stress, equal-velocity scaled SAE channel class 180Hz), and crack detection gage output suggests that there may be strong correlation between peak airbag pressure and peak slope of airbag pressure with the resulting distal velocity and incidence of fracture.

To date, fractures have been produced in the forearm bones of both male and female cadavers. Output of crack detection gages indicate that most fractures occur early in the deployment event. Each forearm fracture observed to date can be explained by a combination of arm position relative to the airbag module, arm mass, bone mineral content, and airbag inflator characteristics. Proximity may be an important factor in the mitigation of airbag-induced upper-extremity injuries, as increased initial spacing between the airbag module and the forearm appears to reduce the incidence of forearm fractures caused by direct interaction with the airbag. Additionally, increased initial spacing reduces the speeds ultimately achieved by the distal forearm, thereby potentially mitigating flailing injuries.



**Figure #9:** Sample of transducer data, including output of crack detection gage, airbag pressure-time history, and distal forearm speed calculated from accelerometer signals.

Mid-diaphysis volar wedge fractures predominate in results to date, indicating the presence of bending. In many cases, it appears that the ulna was forced through the radius causing this type of fracture. Fewer distal radius fractures are seen than expected from field accident data. It is likely that these fractures are more closely related to flailing scenarios, and an increase in their occurrence is anticipated in future flailing simulation tests.

The inertial and kinematic effects experienced in an actual crash event may also contribute significantly to the incidence of forearm fracture. The inertial loading due to forearm mass, and the position of the forearm at the time of airbag deployment during an actual crash would differ from the conditions of this static-deployment study and will be simulated in future tests.

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## DISCUSSION

**PAPER:** **Methods for the Investigation of Airbag-Induced Upper Extremity Injuries**

**PRESENTER:** Warren Hardy, University of Michigan Transportation Research Institute

**QUESTION:** Michael Kleinberger, NHTSA

In the last talk we saw the significant difference between testing the arm in a normal driving position and then testing it off and I recognize the importance of being able to protect the rest of the torso for other additional studies and that is one of the problems that we may discuss later in our panel discussion. But, do you think you should consider maybe going the way UVA did and try a disarticulated arm or do you have any comments on the position that you are using for your testing?

**ANSWER:** Right now, I don't think that we're going to use a disarticulated arm. That's my own personal thought. It's not impossible that we could run some tests where we do get the forearm chest interaction in the future with the full cadavers. In this particular instance, as we are starting out rather slowly, we wanted to sort of focus in on just a few aspects of what was going on and not complicate things with the forearm and chest interaction. At first, we wanted to see whether or not we could actually produce a fracture. On the first cadaver, we didn't. But on subsequent cadavers, as you saw, we did. But, we wanted to eliminate a lot of extraneous variables at the time and just simply look at a basic simulation of what was going on. In the future, it's certainly not out of the question that we could do testing that would have forearm-chest interaction. For right now, I have to be very protective of the heads because I have to give them back to the Plastic Surgery Department.

**Q:** It is always important to use these specimens in the most effective way and use them for as many tests as possible.

**Q:** Dale Bass, University of Virginia

I share your difficulties with full body cadaveric testing. Your integration of velocity from acceleration. We see in the beginning of our tests very quick rises over 60 radians per second both for the distal and proximal forearm. How long do you think your integration is good for?

**A:** Well, I mean, we're not doing any rigid body kinematics analysis, let's say with a 3222 or rigid body kinematics array or anything like that. These are basically simple tri-axial accelerometer packs. So, what we're doing is looking at the difference between the integrated accelerations, the resultant of that, and what we get from the film. As long as we have a reasonably decent agreement for let's say, the first 10, 15 milliseconds between differentiated film and integrated accelerations, you know, it's just a ballpark figure which is why I say about 15 meters per second. We're getting things anywhere from 12 to 18 but we wanted to have an idea of about where it was. For a lot of our tests, they are largely planar and largely linear, particularly

for the first 8 to 10 milliseconds.

Q: It brings me to a follow-up. We have great difficulty seeing any part of the forearm during the first 10 milliseconds of deployment as it wraps around the arms. Where are your cameras located?

A: We have an overhead camera. We have a lateral view. You may have been able to see the target mass there with the bobbers which are largely exposed for about the first 8 milliseconds. The top bobber is exposed for almost all of the deployment event but they are both obscured for a couple of milliseconds between maybe 9 milliseconds and 12 or so milliseconds.

Q: Guy Nusholtz, Chrysler Corporation

Why do you think males are more susceptible to those injuries that you were showing?

A: Well, maybe I misspoke. What I meant to suggest was that a lot of what we've been hearing is that we should only be concerned with small females but we had some statistical data that would suggest that males are perhaps more susceptible than people would currently believe. Meaning that, don't count out mid-size males as being at risk and in this particular instance, we have obtained fractures with some mid-size males. The next cadaver that's lined up for the study is another small female. We had an extremely small female and then a smaller or a small female already done in the test. We are going to try to do another small female but with mid-size males we had been receiving fractures but we've also had some statistical data which suggests that it's not only small females.

Q: OK. So, you're not saying that males are more susceptible.

A: No. I certainly didn't mean to say that. I'm sorry if I did. No.

Q: And what do you mean by less aggressive?

A: Well, less aggressive on those two particular bags. That's just looking at initial slope.

Q: Do you know how much less aggressive?

A: That's twenty-two versus seventeen.

Q: How much?

A: Twenty-two on one and seventeen on the other.

Q: OK.

Q: Stefan Duma, University of Virginia

Two real quick questions. What's the mass of this rod that has some bobbers coming off.

A: It's a hollow brass tube with some hollow fishing bobbers on it. So, I haven't weighed it but it's incredibly light. I mean it's only a handful of grams.

Q: With your position, do you have any secondary impact? Has it ever touched the face or the seat at all?

A: It has not touched the face and so far we've managed to clear the seat and for most of the runs, we have a large foam pad behind the shoulder and every once in a while, we'll get it to come around very far but we haven't gotten it to actually smack off the bottom of our test fixture or anything like that. That was one of the things that we were worried about. Can we make sure that we can distinguish fractures that are occurring during the deployment event versus some subsequent fracture that might happen from contact interaction so we're taking a very close look at the timing on the crack detection gages and we are taking a very close look at the film? So far, no. I'd have to say basically what you're asking is: "do we think most of these are happening from the airbag?" Yes.

Q: Right. Well, I also wanted to discuss that in some testing that we did, we had about six inches of foam and we still got an artifactual fracture of the metacarpal and I just wondered. You need to be real careful what kind of foam you use and how thick it is because even if it looks like a lot, with the high velocities we still got injuries. Right now, we have about twelve inches of foam on the back but it totally catches the arms.

A: Yes. We haven't received any metacarpal injuries.

Q: Craig Morgan, Denton

Warren, I'm well aware of the difficulty of applying these crack detection gages to bone and with the strain gage problems University of Virginia had. The question is: "have you looked at unfiltered accelerometer data to see if you can sort of acoustically listen for the bone breaking compared to your crack gages?"

A: Well, that's another thing, you know. We have a lot of accelerometry data that we haven't had time to process yet but that's sort of on the agenda. Another thing that we were looking at was using acoustic emission for assessing the fracture. But, as of this time, I have to say I can't answer that because I haven't looked closely enough at the accelerometer data.

Q: Shashi Kuppia, Conrad Technologies, Inc.

When we did the RAID tests, we did notice that the system H and the system K were a lot more severe than the system L but when UVA did the same tests, it did not generate injuries, saying that maybe the system H is not as aggressive as we thought. When I look at the airbags that you tested, they seem to be less aggressive than the system H and you are generating injuries

and I'm wondering what's happening here because you generate injuries almost every time, even with the big males. Whereas, UVA says that it can only happen with a small female.

A: Yes. So far we've definitely had success generating fractures.

Q: What do you think is the difference? Why is this happening?

A: Right now, I'm not sure that I could answer that question but only speaking from our data, it certainly seems like it is possible to break the arm in the laboratory setting for mid-size males.

Q: OK.

Q: Jeff Pike, Ford Motor Company

The bone loss in males as they get older is slower than females but there is still some bone loss so it doesn't seem surprising that you'd see some fractures in the older males as well.

A: Well, that's one of those things we're going to look at. Most of our subjects interestingly enough, were hovering right around 77 years of age. We had one that was about 70. One of the things that we were going to look at is bone mineral density and a number of other things. Particularly, when we had a male with what we're calling right now, a less aggressive bag. On one particular male, it did break the arm and another it did not. So, I mean it seems there that what we really need to look at is the condition of the bone. So, that's coming up.

Q: John Melvin, General Motors Corporation

This is probably more of a comment rather than a question but something that might relate to some of the differences you are getting here is that these are all static tests with no inertial effect to the arm. In a real situation, the car is in a crash and I would imagine the driver is forcing his arm onto the steering wheel, due to his own inertia. We found that our out-of-position testing of the chest, for instance, that just having the weight of the dummy on the module, makes a big difference in repeatability and in the severity. So, you are really allowing the bag to get around where it might not, in the case of an inertial load forcing the arm against that bag and trapping it, we found that you can destroy the chest with the bag not even coming out of the module. It swells and if you're well coupled, you'll get a very high force, even before it breaks out of the module.

A: Yes. That's a very important point, probably the most important point to all of this and we haven't quite wrestled with the issue completely and determined how we're going to move onto the next phase of this. Whether it is a simulated pre-load that might give us a little better idea, a little better simulation of the dynamic condition or eventually going to a full fledged dynamic deployment testing. For the beginning, and I emphasize again, this is very, very, very much a beginning. We wanted to keep it simple and we wanted to get at least some small idea as to what was going on. But, in no way, shape, or form does this represent the complete picture and dynamic deployments can certainly be an important part of that. However, there are so many parameters and variables there that we wanted to avoid that, at least in the first stage.

Q: Dale Bass, University of Virginia

I'd just like to point out that it's 20G's, that the deceleration is 20-25G's. We're seeing 300G's at the wrist.

A: The arm G's are large.

Q: We also saw in our ATB modeling, there was very little difference in the contact force between a fixed shoulder, a shoulder that is just fixed in space, and one that could fly and that seems to indicate that the dynamic consequences might not be all that important.

A: (John Melvin) I don't think that you have a model of a deploying airbag that's folded in a module. What you'll find in the dynamics is that if you trap it and don't let it out of that module, you won't believe the forces you can generate. It doesn't have to go anywhere. It's broken before it starts.

A: (Warren Hardy) Yes. That's true. I mean, that's very important. Just the inertia of the forearm itself, the mass seems to be controlling the whole event right now, even in the static deployment. With an additional load on there, who knows what's going to happen. And sure, we're receiving extremely large forearm accelerations, 400, 500, 600G's easily but everything is really happening with the inertia of the arm, keeping it on the bag as it's deploying. If we add an additional load to that, I'm not exactly sure what would happen but it's certain to be worse in my opinion.

