AN INVESTIGATION OF TROOP SEAT TESTING METHODOLOGY USING MADYMO MODELS

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ABSTRACT

Energy-absorbing troop seats can save lives and mitigate injury in many military aircraft mishaps. Several designs are currently in the field and research continues to provide additional improvements. When it comes to evaluating performance, however, troop seats raise some issues that normally do not occur for pilot seats. Pilots have hand and foot controls that dictate the logical position for manikins in laboratory tests. The same cannot be said for troop seats, but positional variations can have significant effects on some test results. The first part of this study uses computer modeling with the MAthematical DYnamic MOdel (MADYMO) simulation program to examine the sensitivity of test outcome to troop seat occupant position. The vertical component of the lumbar load, a key performance parameter for troop seats, serves as the principal variable in case comparisons. For some types of seat energy absorbers (EAs), it is shown that changes in arm and leg position can produce lumbar load differences which exceed those that might be expected from normal test-to-test variability. These results point to a need for standardization so that tests of a given seat design, as well as tests of differing designs, can be compared directly. The second part of this paper considers an issue that arises in the testing of both troop and pilot seats: the method chosen to deliver the crash impulse. The two most common methods are a drop tower (DT) test and a horizontal accelerator (HA) test. In the latter, the seat is rotated 90^{o} to vertical so that the seat's Z-axis is aligned with the laboratory X-axis. This leads to questions about the influence of gravity on the test results. Once again, MADYMO simulations are employed to study test result sensitivity, and to determine whether gravity compensation is called for in the form of an HA pulse adjustment or a small forward pitch of the HA seat. The results indicate that the compensation required depends on the test configuration and the relative importance of the measurements taken.

INTRODUCTION

Recent increases in the size and weight range of military personnel have made the task of providing crash protection more difficult. The first generations of crew and troop seats for military rotocraft used seats with constant force EAs. This is also referred to as a Fixed Load Energy Absorber (FLEA). The EA force level was optimized for the protection of a mid-sized male occupant. Such an EA, however, can be too stiff for light-weight aircrew, stroking at a higher G-level and offering less protection. For heavy occupants, the seat can bottom out and

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stop suddenly, also producing high occupant loads. In the case of crew seats, this problem has been addressed in some aircraft by providing an adjustment for occupant weight. The seat occupant can set a dial to his or her weight and change the EA force plateau. This is often referred to as a Variable Load Energy Absorber (VLEA).

VLEAs are a viable option for crew seats, which are normally used by the same aircrew for extended periods of time. Troop seats, however, are much more numerous and are occupied by an ever-changing population. This calls for a more cost effective solution. In addition, in-the-field troop transport operations probably preclude the seat occupants having the time to make such adjustments. These needs have pushed troop seat EAs in the direction of multi-stage force functions. Rather than a constant force throughout the stroke, the EA is more likely to have a short, low-force plateau at the beginning of the stroke and an increasing, or ramped, force behavior for the remainder (Fig. 1). This is also a type of Fixed Profile Energy Absorber (FPEA). The initial plateau is tuned to protect light occupants, while the ramped portion is designed to manage the load on heavier occupants and prevent the seat from bottoming out. When properly adjusted, this ramped style of EA can significantly increase the range of occupant protection, but it also introduces new issues when it comes to testing and certification. A good review of EA types and EA development history is provided in a paper by Desjardins.[1]

Using extensive computer simulation, this paper focuses on two aspects of troop seat testing. In the first part, the sensitivity of troop seat test results to dummy position is examined for both constant and ramped EAs in an HA test environment. The motivation for the dummy position study came from preliminary modeling results that showed sensitivity between peak lumbar load and leg position, and from a crewseat test series in which the influence of leg position was also noted.[2] A subsequent examination of troop seat tests conducted by the Navy showed considerable variation in the arm and leg positions chosen by the tester (Fig. 2). One reason for this is the fact that troop seats, unlike pilot seats, provide few constraints with regard to limb position. There are no hand or foot controls to guide arm and leg placement, so a relatively wide range of positions can be considered reasonable. The modeling results quantify how these variations can affect dummy measurements and provide guidance for standardizing dummy position.

In the second part, the two primary methodologies, HA and DT testing are compared and contrasted for a ramped EA. Each method has its advantages and both are viable ways to test for vertical impact response. It is important, however, to be able to compare and share results from tests conducted with either method. Doing so requires understanding how gravity affects the results and how it can be compensated for in the HA environment. With regard to HA test procedures, several suggestions are made for optimizing the level of equivalence that can be obtained between these two methods as a function of the particular test conditions.

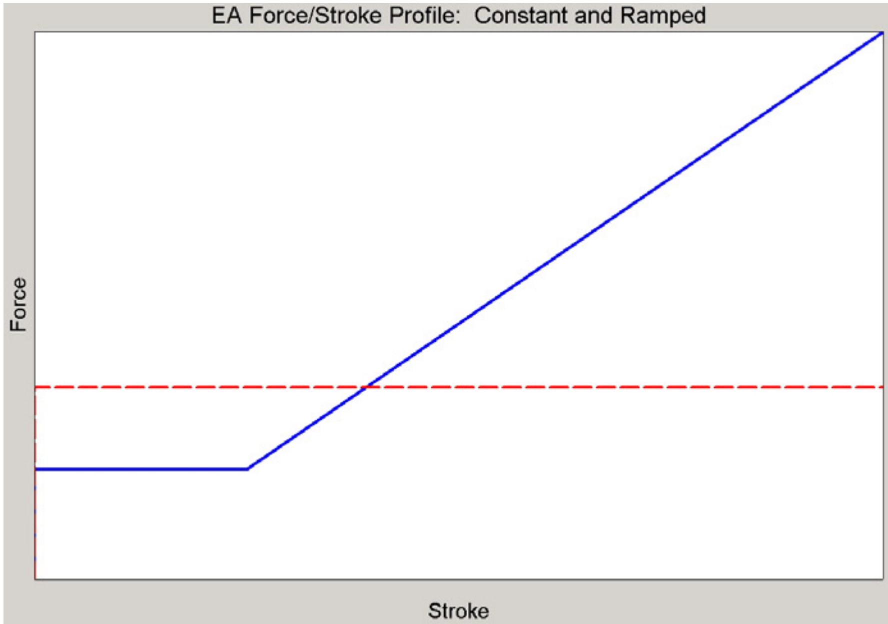

Figure 1: Constant and Ramped EA Force/Stroke Profiles

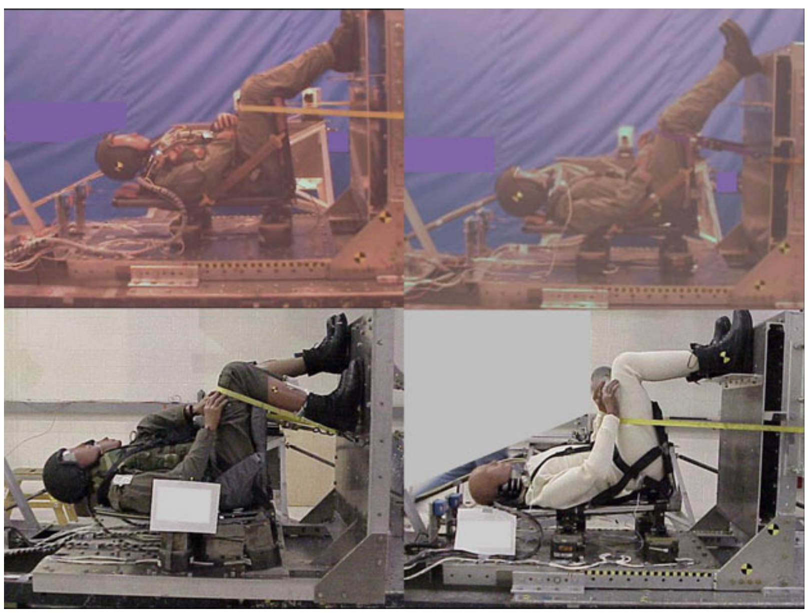
Figure 2: Test-to-Test Position Variations

MADYMO TROOP SEAT MODEL

The primary tool in this study was the MAthematical DYnamic MOdel (MADYMO) simulation code. It is a commercial code, widely used in the automotive and aircraft crash safety communities to study the effects of impacts on vehicle occupants. It comes with an extensive database of test dummy models which users can place in various environments of their own construction. Both multi-body and finite-element objects can be modeled simultaneously.[3] The HyperView postprocessor was used to create pictures and graphs from the results.[4]

To investigate how EAs, test method, and dummy position impact troop seat testing, a series of MADYMO models was developed. Figure 3 shows the baseline troop seat model with a 95th percentile male occupant. The seat is intended to be a generic representation of a typical troop seat, with EA properties based on current designs. It consists of three rigid bodies: the mount, the back, and the base. The mount is fixed to the global reference frame. The back is connected to the mount by a translational joint oriented along the seat mount's Z-axis. The force/displacement function of this joint represents the EA. The base is connected to the back by a pin joint along the Y-axis, and is supported by finite-element models of webbing straps. A finite-element model of a 4-point harness restrains the occupant to the seat. Lastly, a lap strap of simple, spring-damper segments keeps the occupant in contact with the seat bottom and floor prior to the start of HA simulations.

Because this paper is a comparison of models to models, model validation against a specific test was not critical. The paper does, however, seek to establish a quantifiable difference in occupant response measures when test parameters are changed. For this reason a confidence check is still needed to ensure that the model's qualitative and quantitative behavior is comparable to an actual test. Figure 4 shows a comparison of model kinematics versus an HA test. The measured peak lumbar load was 1767 lbs and the simulation value was 1624 lbs; an 8% deviation. This is good agreement since the modeling work was conducted long after the test. Much closer agreement (1%) was actually achieved by adjusting the predicted EA profile, but the details cannot be released at this time due to proprietary design issues.

Figure 5 shows the occupant/seat positions that were used for this study. Four leg angles, three hand positions, and two seat pitch angles were considered. Some cases were simulated in both DT and HA configurations for comparison. The acceleration pulse used to drive the model is shown in Fig. 6. The 30 G acceleration pulse, with 37 ft/sec delta-V, comes from an actual HA test.

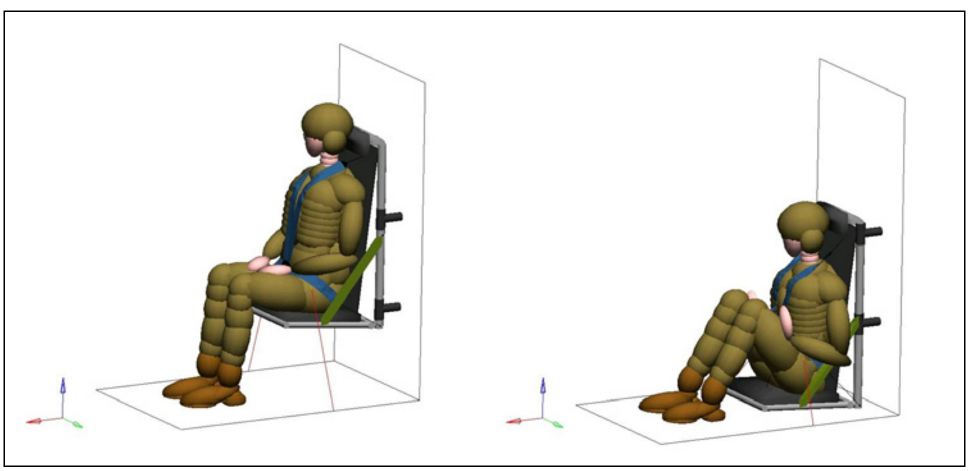

Figure 3: MADYMO Troop Seat Model

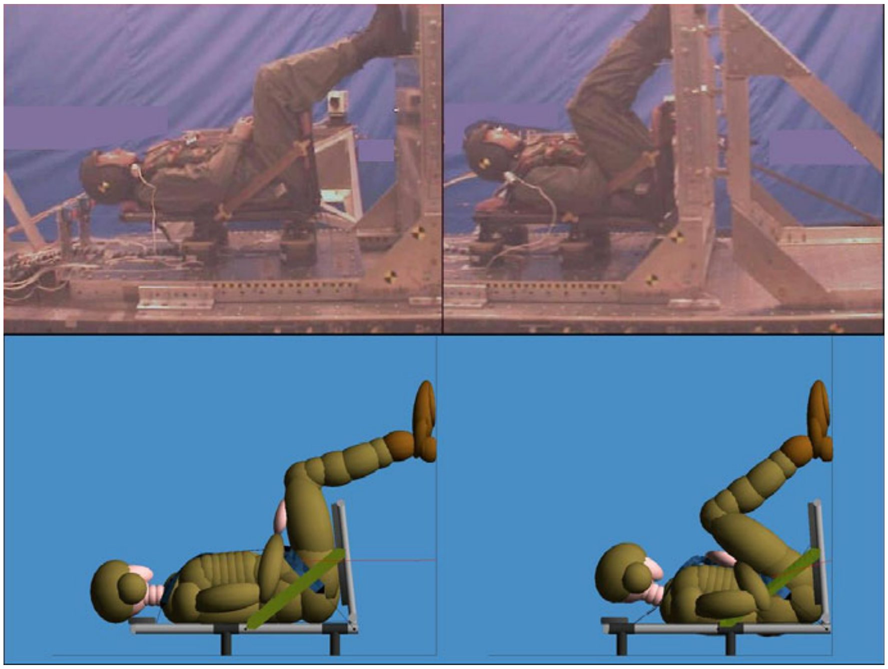

Figure 4: Model Kinematics vs. HA Test

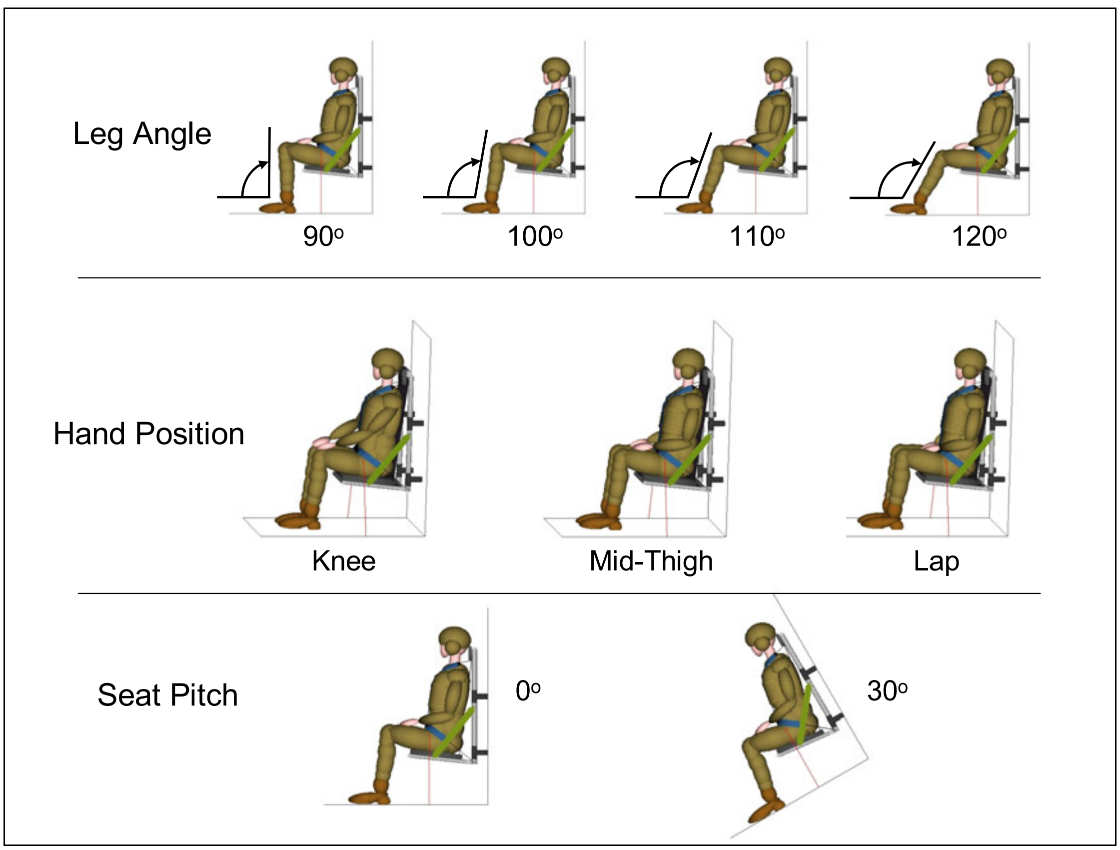

Figure 5: Position Variations

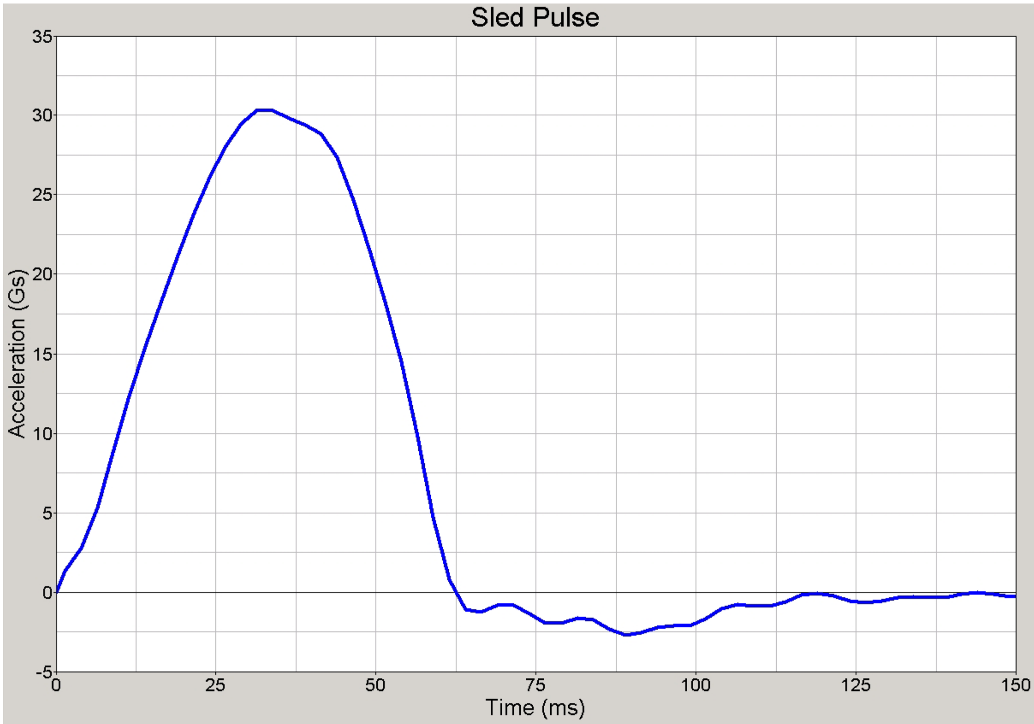

Figure 6: Sled Pulse from HA Test

PART I: EFFECT OF DUMMY POSITION

Constant EAs

Since spinal injury is often a serious problem in otherwise survivable crashes, lumbar load is a primary measure of seat performance. When the EA force is constant, the peak lumbar load for a given sized occupant is very predictable provided the seat does not bottom out. Testing in this case is mostly concerned with seat hardware failure and whether the EA has sufficient stroke. From the lumbar's point-of-view there is little sensitivity to test setup or method. Figures 7-8 show the lumbar load versus leg and arm position for HA simulations with zero seat pitch (G_Z). The peak occurs near the start of seat stroking, and shows only a 76 lb variation from lowest to highest. This is only 5.6% of the mean value. The sensitivity evident later in the event is ignored since lumbar load is not an integrated injury measure like the Head Injury Criterion (HIC).

This insensitivity to test setup is significant. It means that the results of previous test series with constant EAs should still be valid regardless of dummy position, but it also means that there was little motivation to develop standardized test procedures. The simulation results show that the situation is very different for ramped EAs; they indicate that more attention to protocol is needed if test results are to be compared with one another.

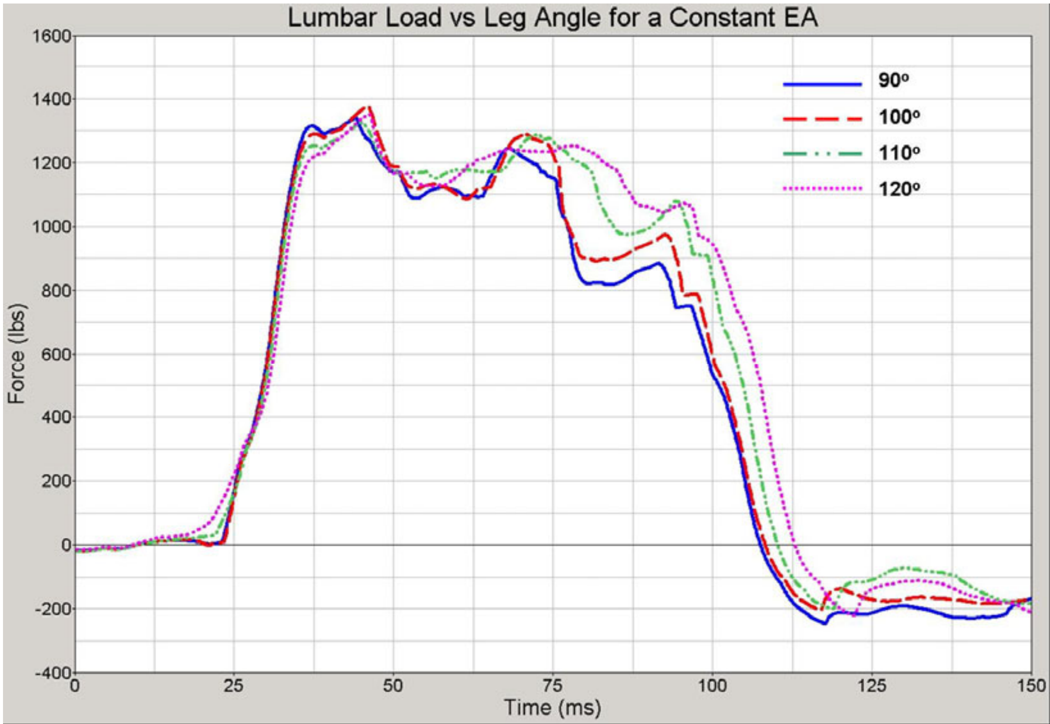

Figure 7: Lumbar Load vs. Leg Angle for a Constant EA

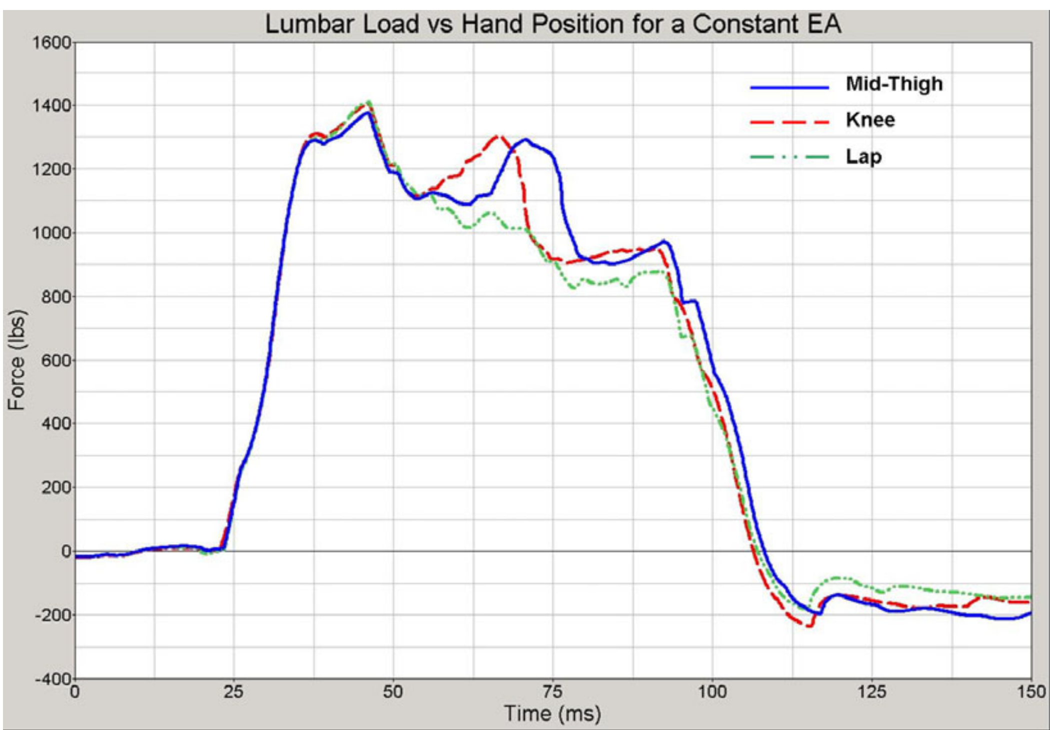

Figure 8: Lumbar Load vs. Hand Position for a Constant EA

Ramped EAs: Leg Position

Because the force level of a ramped EA changes, and generally increases with the amount of seat stroke, the lumbar load is much more sensitive to the maximum seat displacement and the load path by which this displacement is achieved. A change in occupant position, which only produces an extra inch of seat stroke with a constant EA, may produce hundreds of pounds of additional lumbar load when the EA is ramped. Figure 9 shows the sensitivity to leg position of lumbar loads in four HA G_Z simulations. Unlike the constant EA, where the peak load variation was only 5.6%, the ramped EA produces a variation of 589 lbs or 33.5% of the mean value. There are two reasons for this leg position sensitivity.

The first reason is directly related to the ramping of the EA force. Changes in leg position affect how much load is supported by the feet versus the seat. As the leg angle increases, the seat must absorb more energy, which results in more stroke. For constant EAs this does not translate into higher lumbar loads, but for a ramped EA it does.

The second reason is the difference in peak lumbar load timing for these two EA types.[2] In the constant EA case, the peak occurs early in the event before the seat has stroked very far. This keeps the leg-hip-torso interaction from influencing the results because there has been little change in the initial angle between the torso and thigh. With ramped EAs, however, the peak usually occurs much later in the run as the seat stroke is near maximum. At this point the thighs have been pushed up toward the chest, and the hip joint can reach the limit of its range-of-motion. When this happens, the pelvis can rotate significantly and change the alignment of the lumbar region. This effect is seen in the simulation animations and can be observed in test videos as well. For pure vertical tests there is generally a reduction in lumbar load since the lumbar spine is no longer in line with the pulse vector. The magnitude of this effect is influenced by both the initial thigh-to-torso angle and the amount of seat stroke.

The present study did not isolate the relative importance of these two effects. To do so requires artificially adjusting the foot placement so that the tibia angle can be changed while keeping the thigh angle constant, or vice versa. The focus here was to highlight the differences that can be expected from realistic variations in actual test conditions. Future work will explore each effect individually.

When the seat is pitched forward 30^o (G_{XZ}), there is a change in leg-position sensitivity. The trend in lumbar load actually reverses from 90^o to 110^o before changing drastically at 120^o (Fig. 10). The initial trend appears to be associated with the forward motion of the dummy and the tendency to submarine the lap belt. Submarining increases with increasing tibia angle. This, in turn, leads to more pelvic rotation and a decrease in lumbar load. At 120^o, however, the feet slip (Fig. 11). This increases the load on the seat and reduces the rotation of the pelvis. The net result is the highest overall lumbar load.

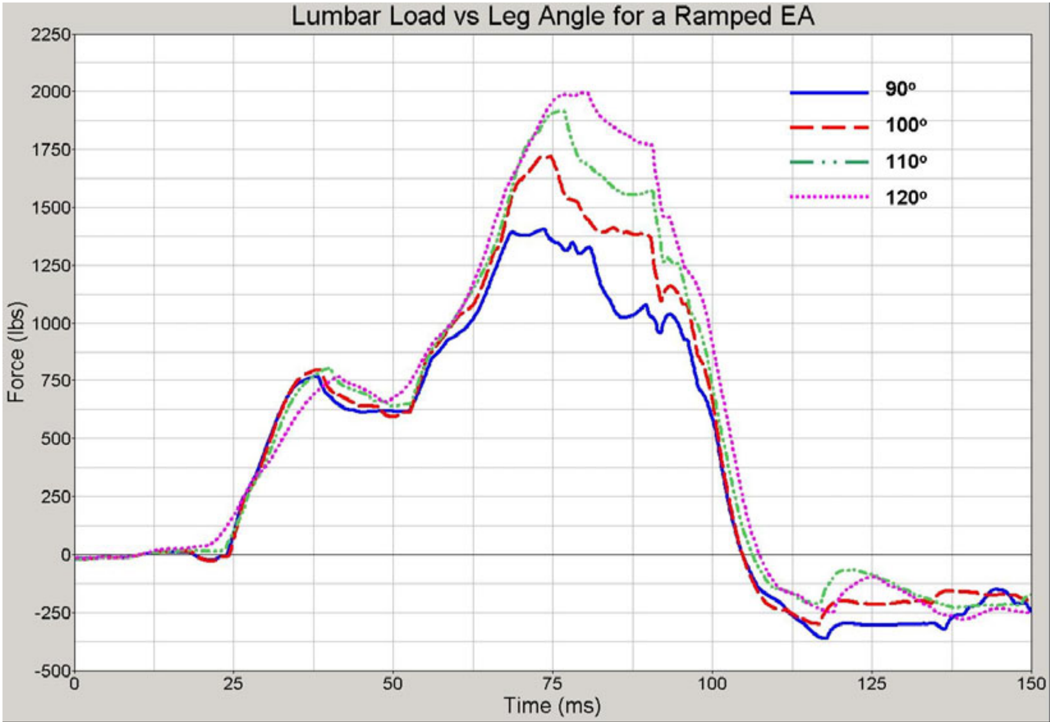

Figure 9: Lumbar Load vs. Leg Angle for a Ramped EA

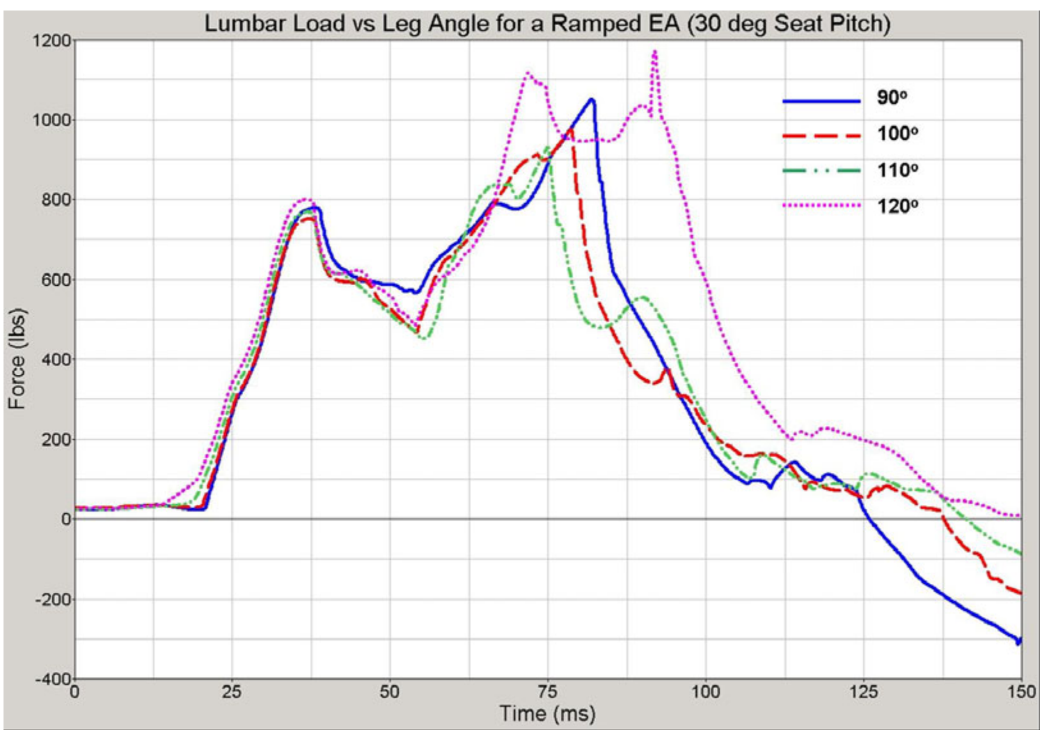

Figure 10: Lumbar Load vs. Leg Angle for a Ramped EA (30° Seat Pitch)

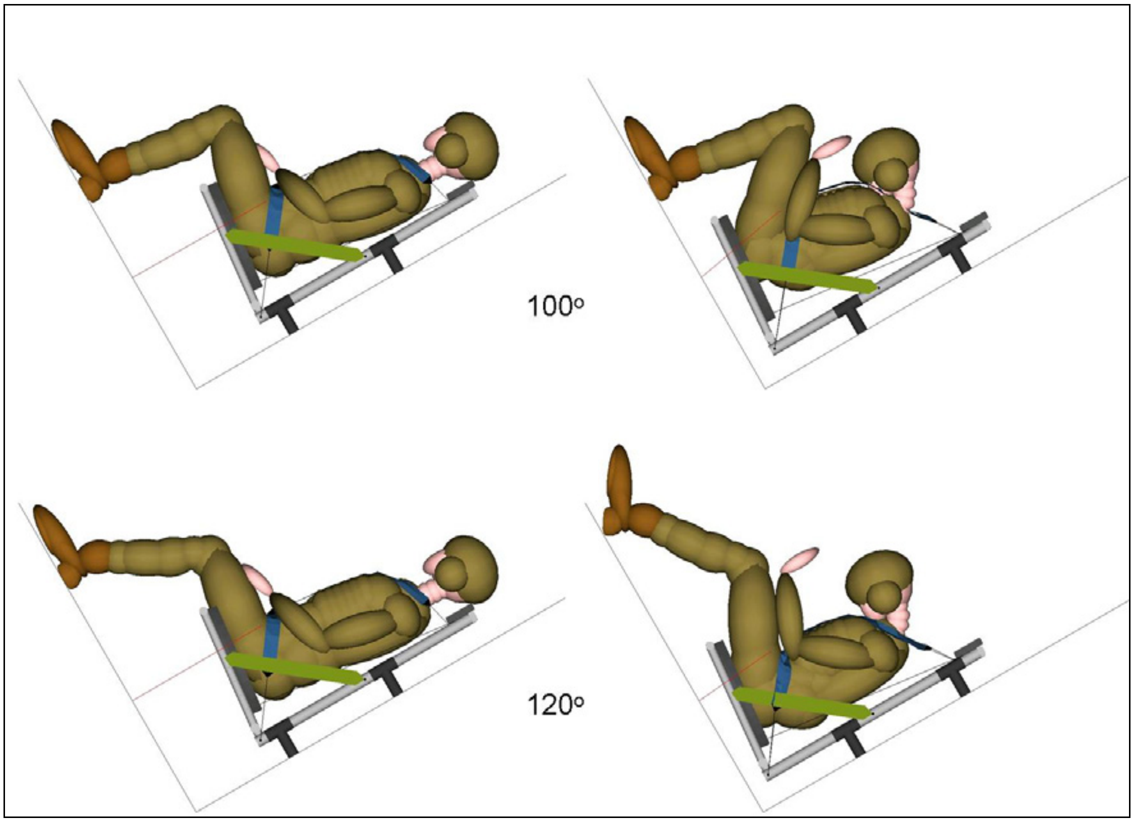

Figure 11: 30° Seat Pitch Tests with 100° and 120° Leg Angles

Ramped EAs: Arm Position

Sensitivity to leg position may seem obvious in retrospect, but arm position can have a surprisingly large effect as well. Figure 12 shows the lumbar load comparison for three different arm positions. The peak variation from lowest to highest is 232 lbs or 14.7% of the mean. Placing the hands on the knees appears to reduce the lumbar load because the arm mass is not coupled tightly to the torso. The arms move independently of the torso to a large extent and do not contribute as much to the lumbar load compared with the mid-thigh case. Placing the hands in the lap with the forearms close to the torso creates a different situation. In this case, as the legs are pushed up, the forearms are pushed into the torso. Ultimately, they catch under the ribcage and resist its downward motion. This also reduces the peak lumbar load. It is not clear whether the same interaction with the ribcage would occur for an actual dummy wearing a flight suit or fatigues, but the model result does point to a possible, undesirable effect. A similar type of interference could also happen when testing with dummies wearing survival gear on the front of the torso.

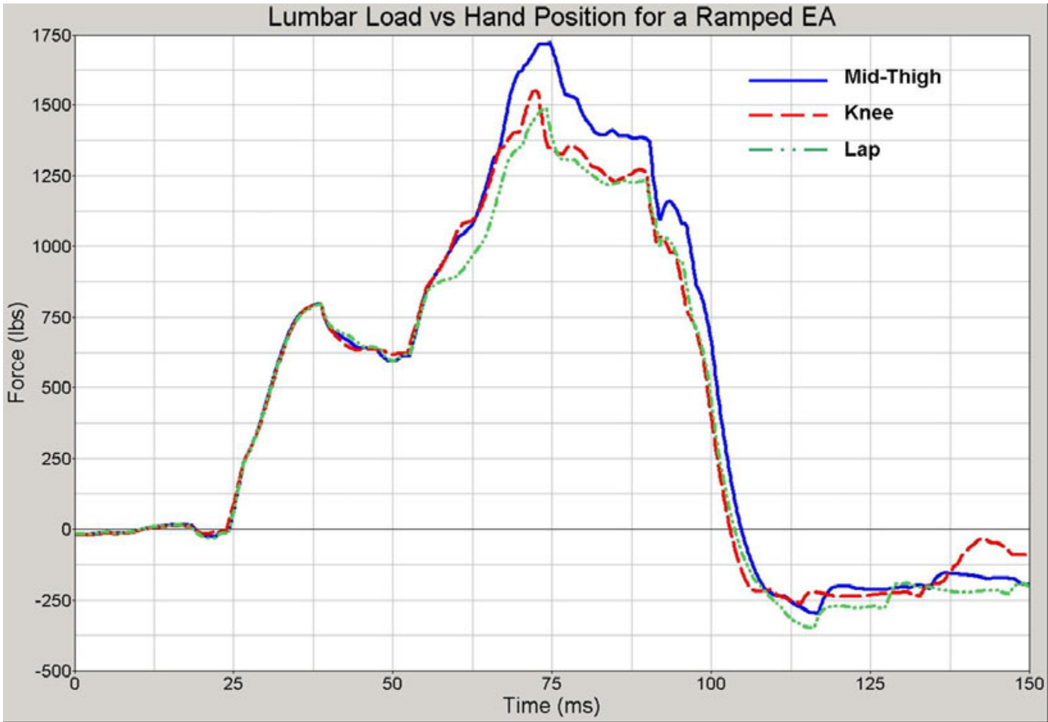

Figure 12: Lumbar Load vs. Hand Position for a Ramped EA

Recommendations for Testing

When testing ramped EAs, the spread in peak lumbar load, as a function of body position, is far greater than one would like if tests are to be comparable and repeatable. Based on the findings from the Part I study, the following recommendations are made with regard to test setup protocol.

1. *Use a tibia-to-floor angle close to 100^o.* This should produce a reasonable sitting position for a wide range of occupant sizes. It reduces the chance of foot slippage that can occur at higher angles. Compared with 90^o, it reduces the chance for seat/leg interference that can occur for some seat configurations and it will induce less pelvic rotation with high seat stroke. For small manikins whose feet may not reach the floor, a standard position also needs to be determined, but this was beyond the scope of this paper.

2. *Place hands mid-thigh on top of the legs*. This position should ensure good coupling of the arm mass to the torso without the risk of interference from direct contact. Note that the hands should be on top of the thighs, not to the side. A side placement will allow the arms to swing free early in the test, and this will tend to reduce the lumbar load.

3. *Start with a straight torso*: Starting with a slumped torso can artificially reduce lumbar loads by misaligning the spine and can also lead to increased pelvic rotation and submarining.

PART II: TEST METHODOLOGY – DT VS. HA TESTS

Model Setup Issues

The standard dummy position recommended in Part I was used to conduct a comparison of DT and HA results. Only a ramped EA is discussed since the constant EA produces the same lack of sensitivity that was noted in the position study. It was assumed that the same test-sled acceleration pulse could be obtained for both approaches. The difference between the methods is therefore reduced to the effects of gravity.

Some care must be taken to ensure that the MADYMO models correctly account for gravitational effects. In simulations of HA tests, it is customary to take a measured sled pulse from an actual test, and apply its negative to the contents of the sled along the sled's X-axis. Gravity is applied along the sled's Z-axis. The sled itself is held stationary. This is equivalent to placing oneself in the sled's reference frame. This method works well for horizontal tests because the applied pulse and gravity vectors are orthogonal.

In the case of a DT test, the sled pulse vector and gravity are parallel. It is not easy to combine the two into a single sled pulse that can be applied to the contents of the sled in the manner described above. The best way to ensure that the physics is properly represented is to apply the primary acceleration pulse directly to the sled, while the sled contents are subjected only to gravity. The sled in this case will move. The seat and occupant will react to the sled's motion through contact forces and EAs, while also feeling the effects of gravity.

Another difference in pulse application concerns the behavior after the primary acceleration phase. The HA pulse changes sign at about 65 ms. The sled is no longer being accelerated by the pneumatic piston at this point; rather, it is being decelerated slightly as the occupant and seat approach maximum stroke. The higher the ratio of seat/occupant mass to sled mass, the greater this effect will be. In applying this pulse to the DT simulation, it was assumed that the effective sled mass after hitting the ground is nearly infinite. Therefore, the acceleration of the DT sled after 65 ms was set to zero.

The last difference in the modeling approaches relates to the establishment of initial conditions prior to time zero. In an HA test, everything is static prior to firing the piston. In these simulations a short, 100 ms pre-simulation period (with gravity only) is sufficient to allow the occupant and seat to approach equilibrium. A DT test, however, is usually a free-fall event. Initially, the dummy is sitting in the seat under a 1 G load. When the sled is released the system becomes effectively weightless for a brief time. The dummy will unload from the seat and the dummy's lumbar spine will also unload. The simulations show that this happens very quickly (< 100 ms), so there is no question that this will happen in reality. It was found that 500 ms of pre-simulation was adequate to establish DT-like initial conditions. The first 250 ms allowed gravity to properly load the seat and lumbar, while the next 250 ms allowed the system to unload in a free-fall. Figure 13 shows how this relates to lumbar load. The key is to approach equilibrium, indicated by a constant load, before proceeding with the next phase of the simulation.

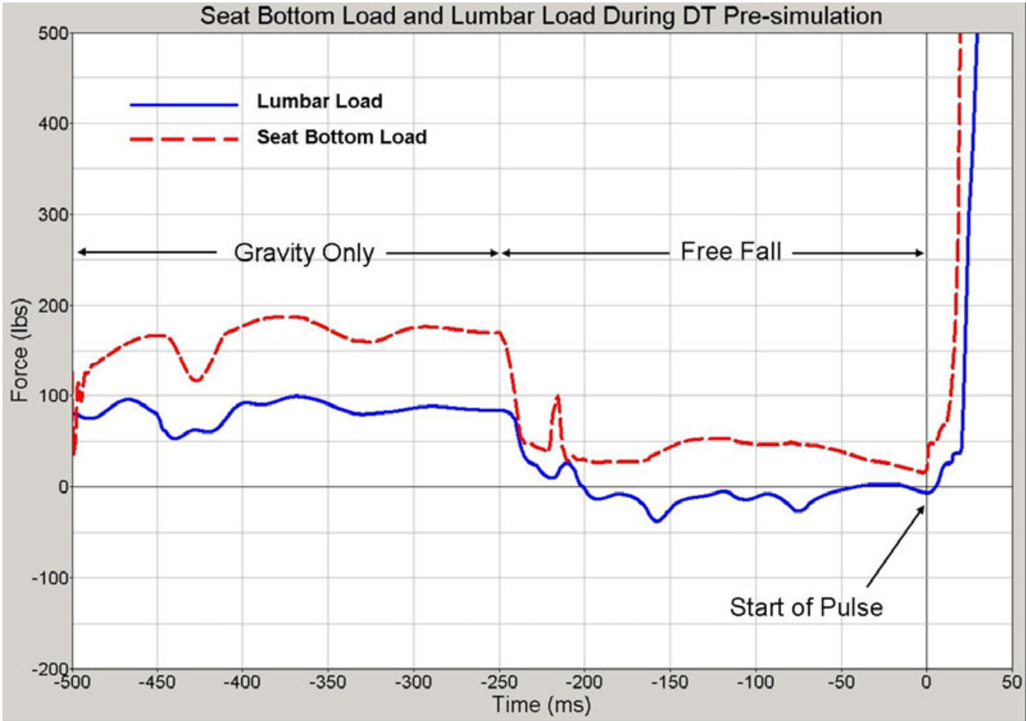

Figure 13: Seat Bottom Load and Lumbar Load During DT Pre-simulation

DT vs. HA Comparisons

The blue (solid) and red (dashed) curves in Figs. 14-17 show DT and baseline HA results respectively. In Fig. 14, the HA lumbar load for 0^o seat pitch falls below the DT result by 227 lbs, or 11.7 %. The width of the load pulse is also less. Both of these results are consistent with the additional gravitational component that is present in the DT configuration. Figure 15 shows that the neck moment agreement was much better, but its magnitude is also small since little head rotation occurs. Figures 16 and 17 show the same comparison for a 30^o seat pitch. The situation is now reversed. The lumbar load is much lower and agreement is good. The neck moments, however, are now much larger and differ by 1202 in-lbs, or 16.3 %. Once again, gravity is a major factor. In the HA case, gravity resists head rotation; while, in the DT case, it enhances it. This is illustrated in Fig. 18.

To obtain better agreement between the two methods, some “compensation” for gravity is called for in HA tests. One approach is to compensate the sled pulse itself by adding 1 G to all of the points. The new pulse is shown in Fig. 19. This reflects the fact that within the reference frame of the sled, the DT test’s occupant “sees” an acceleration field of Pulse+1G relative to the floor of the sled. Note that the pulse is unchanged beyond 65 ms because the sled is no longer under the influence of the piston.

Rerunning the HA simulations with this pulse produces the green (dash-dot-dot) curves in Figs. 14-17. For the 0^o pitch case, this improves the lumbar load result considerably, with the peak difference reduced to 1 lb. Neck moment agreement is not quite as good, but, again, there is little head rotation anyway. At 30^{o} seat pitch the lumbar load overshoots slightly while the neck moment discrepancy has been reduced to 6.0 %.

Another means to compensate addresses the difference in the way gravity affects head and torso rotation. In this approach, the seat fixture on the HA sled is pitched forward 4^{o} from its "official" position. This is illustrated by the overlays in Fig. 20. This number was derived from the fact that many constant EA seats were designed to stroke at 14.5 Gs for a mid-sized occupant. It turns out that the sine of 4^{o} (0.06976) times 14.5 equals 1.01; or approximately 1 G. Thus a 4^{o} pitch increment creates an acceleration component that is nearly perpendicular to the direction of the sled's pulse and balances gravity.[2]

Adding the 4^{o} pitch compensation to the existing 1 G pulse compensation produced the results shown by the purple (dotted) curves in Figs. 14-17. For the 0^{o} pitch case, both the lumbar load and the neck moment show increased disagreement. However, for the 30^{o} case, both measures improve. The neck moment in particular now agrees to within 2.8%, down from the previous value of 6.0%. The lumbar load agreement is back to where it was prior to pulse compensation.

Overall the effect of pulse compensation improves agreement for both the 0^{o} pitch and 30^{o} pitch cases, but the results for the 4^{o} pitch compensation are mixed. It appears that the extra 4^{o} is not beneficial in the 0^{o} case, while being very beneficial in the 30^{o} case. The reason appears to be the following. At 0^{o} seat pitch the occupant is leaning backward slightly in the drop test configuration and experiences little forward rotation during and shortly after the impact. In fact, the pulse will initially cause the torso to rotate backward into the seat. Adding an artificial forward pitch to the HA setup can actually predispose the occupant to forward rotation that is not experienced in the drop test itself. At 30^{o} seat pitch, however, the occupant is already predisposed to experience significant forward rotation. In this case, compensating for gravity's retarding effect in the HA setup is important.

Recommendations for Testing

1. *Shift a DT pulse up 1 G to obtain an equivalent HA pulse*. This adjustment increased overall DT vs. HA agreement for both the 0^{o} and 30^{o} cases. It is recommended that this compensation become standard procedure when setting up DT-equivalent tests on an HA.

2. *Selectively add a 4^{o} forward pitch to the HA test fixture.* The pitch compensation must be used carefully. For tests where there is a predisposition toward forward head and torso rotation, adding forward pitch compensation can greatly improve DT and HA agreement. However, in DT tests where forward rotation is not significant, the pitch compensation is not recommended for the HA equivalent test. Note also that 4^{o} was based on a 14.5 G EA stroke level for a mid-sized occupant. For ramped EAs, it is more difficult to choose a value for pitch compensation since the EA stroke load is changing. In this comparison, 4^{o} still worked well, but further study is needed to determine how EA profile shape and occupant size might affect the choice of pitch angle.

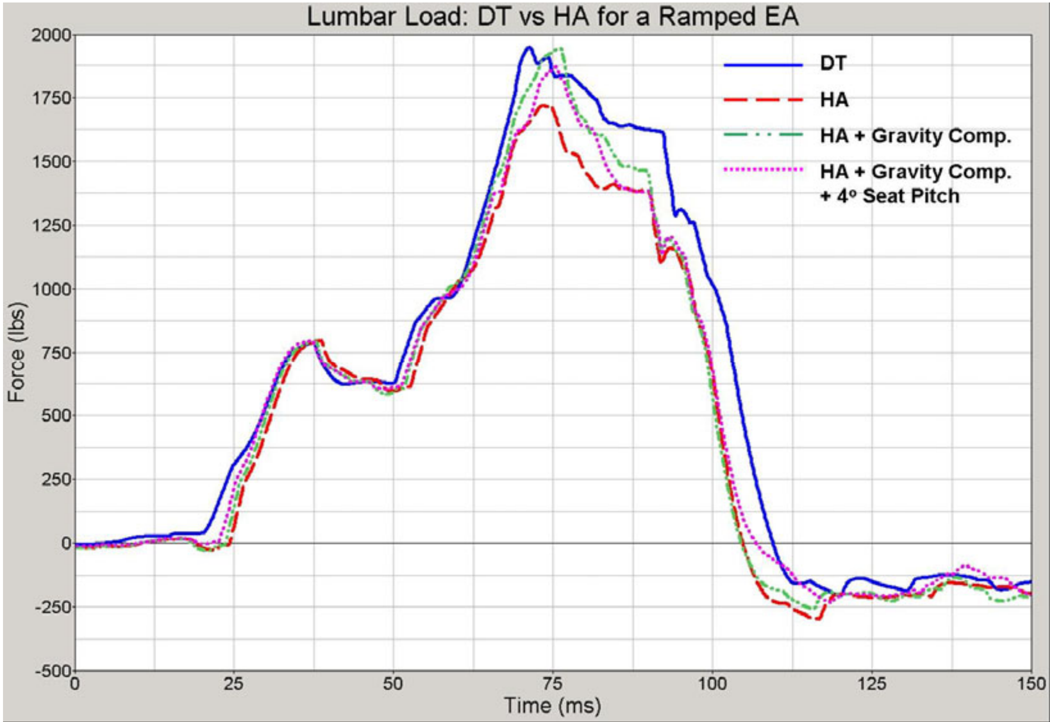

Figure 14: Lumbar Load - DT vs. HA for a Ramped EA

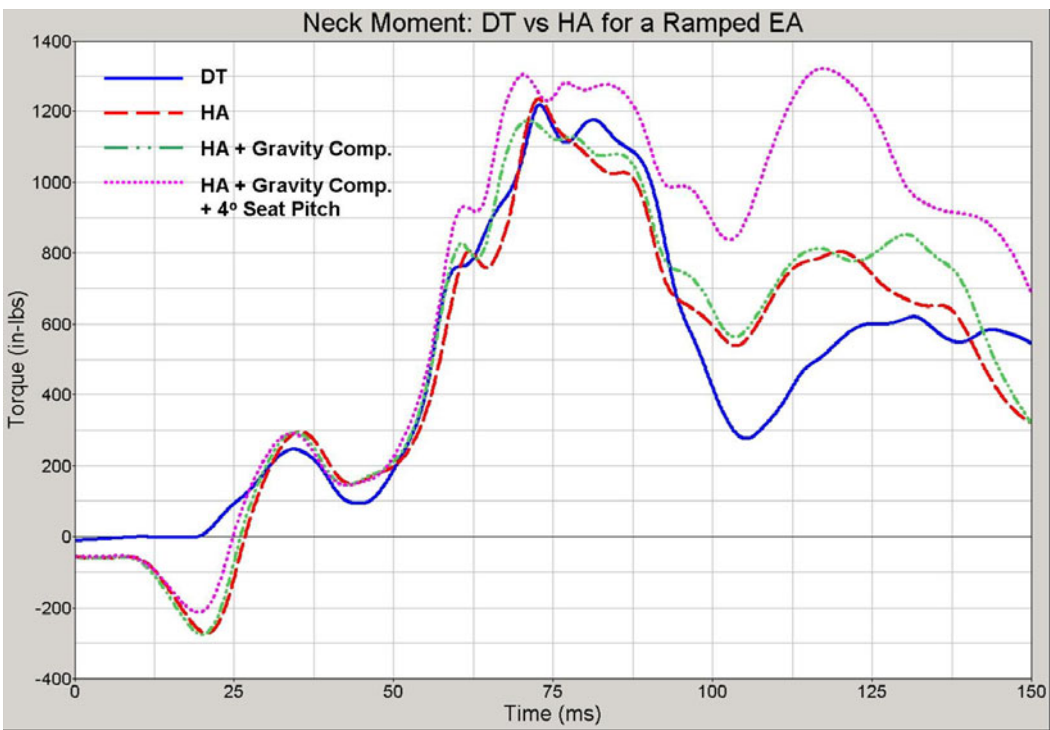

Figure 15: Neck Moment - DT vs. HA for a Ramped EA

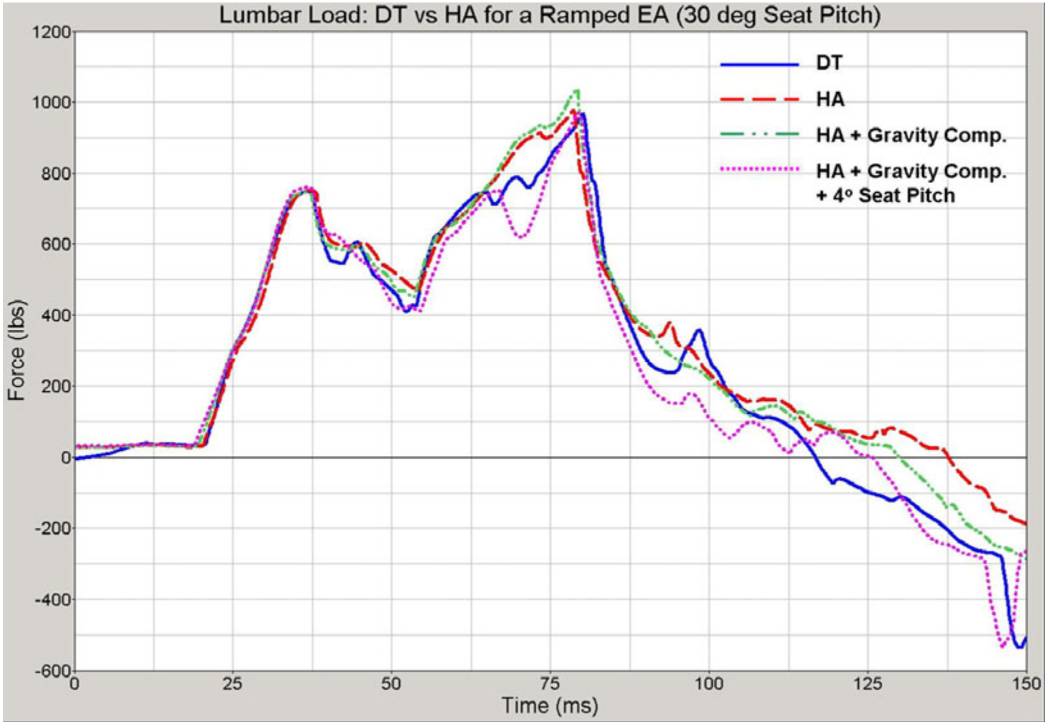

Figure 16: Lumbar Load - DT vs. HA for a Ramped EA (30° Seat Pitch)

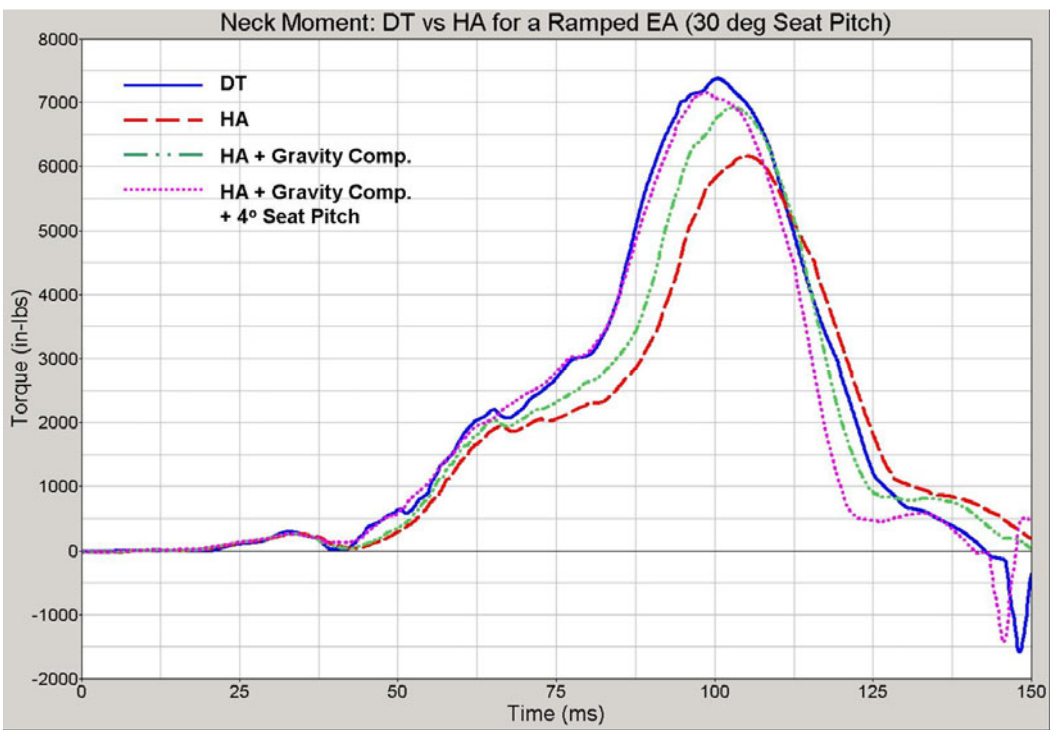

Figure 17: Neck Moment - DT vs. HA for a Ramped EA (30° Seat Pitch)

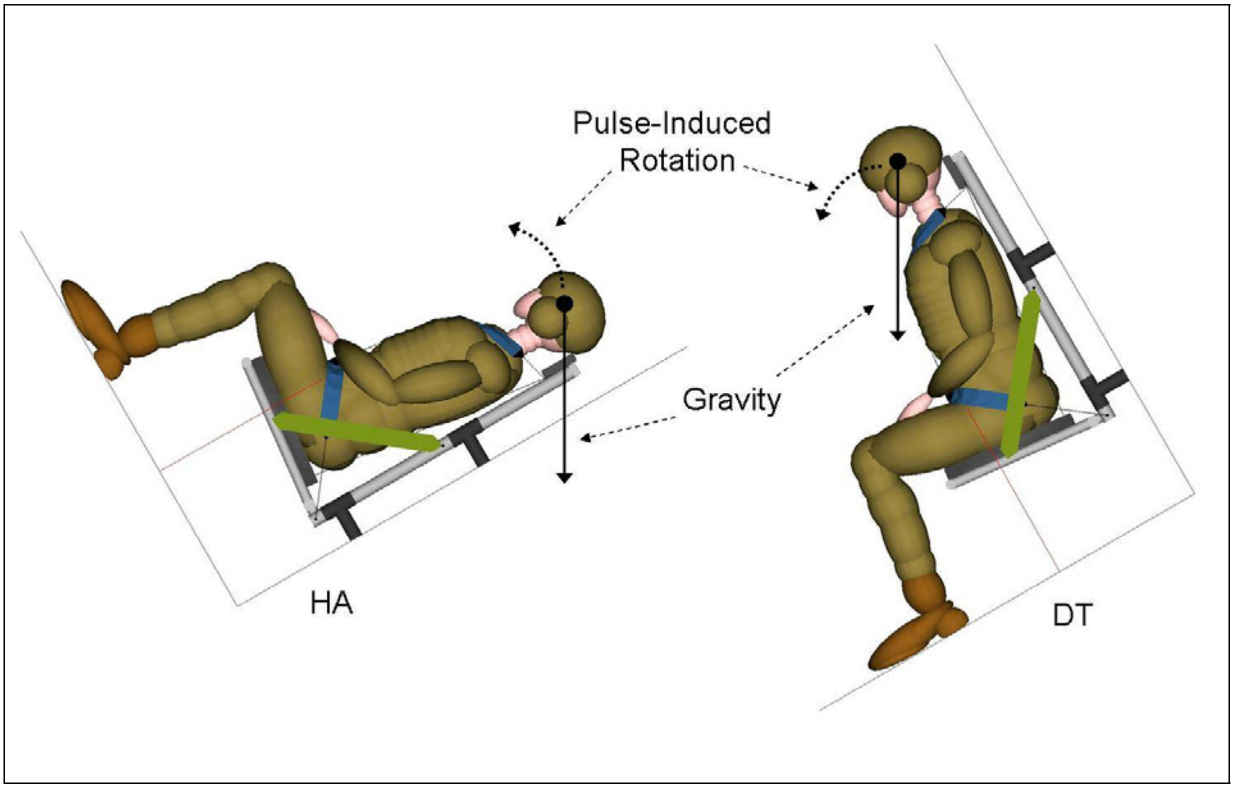

Figure 18: Gravity's Influence on HA and DT Tests with 30° Seat Pitch

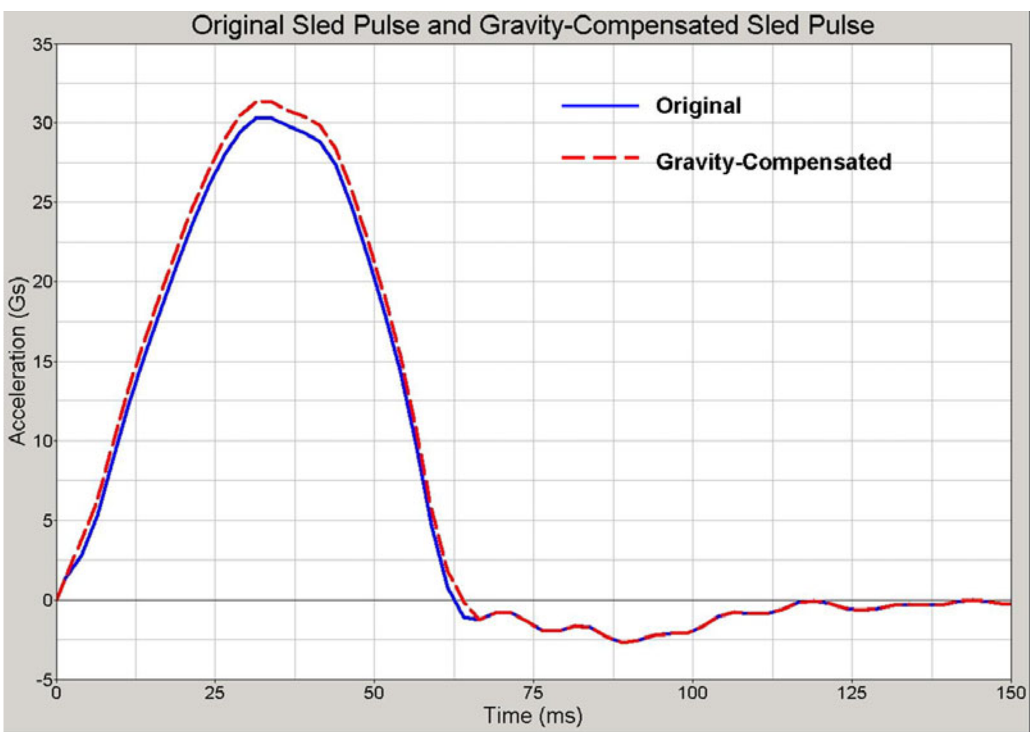

Figure 19: Original Sled Pulse and Gravity-Compensated Sled Pulse

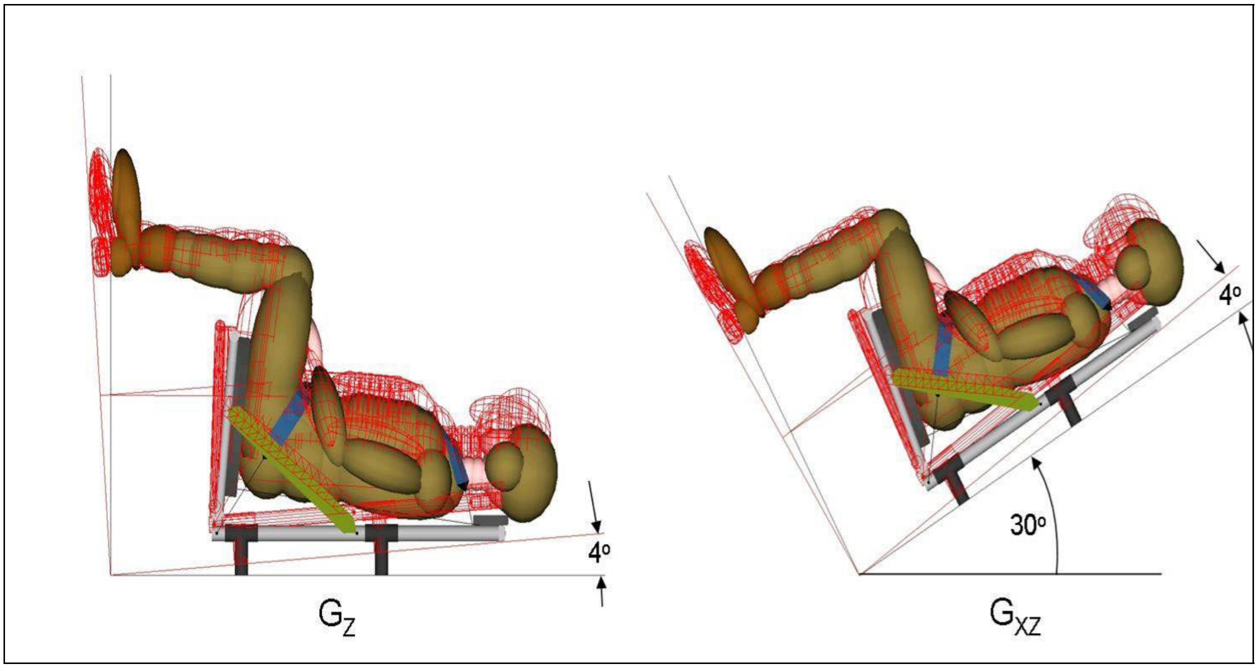

Figure 20: 4° Seat Pitch Gravity Compensation for G_Z and G_{XZ} Tests

CONCLUSIONS

Using computer modeling, the effect of limb position on occupant lumbar load has been examined for two standard test configurations. Computer modeling ensured that the seat hardware and test acceleration pulse were identical from case-to-case so that the influence of limb position could be isolated. It was determined that limb position alone can cause variations in lumbar load which far exceed the <10% deviations that one would hope to achieve for otherwise identical tests. It was recommended that test manikin position be standardized as much as possible to avoid artificial scatter in the test results and to permit the quantitative comparison of results from different seats and test series.

The paper also analyzed the differences between the DT and HA methodologies to establish an approach for achieving greater equivalence. It was demonstrated that the difference in orientation does lead to significant differences in manikin response and that creating identical crash pulses does not produce the highest level of agreement. It was shown, however, that these differences can be minimized when simple compensation techniques are applied to HA tests. In particular, globally shifting a DT pulse up by 1 G can improve the agreement considerably when defining an equivalent HA pulse. Pitch compensation to deal with the different rotational moments created by gravity can also produce significant improvement, but needs to be used selectively.

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BIOGRAPHIES

Dr. Ed Sieveka has worked in the field of crash safety for nearly 20 years. He has focused on the use of computer modeling as a tool to understand the highly dynamic and violent environment experienced by vehicle occupants during a severe impact. At the University of Virginia Mechanical Engineering Department, he worked extensively with the ATB and MADYMO codes to simulate automotive crashes. In 2001, Dr. Sieveka joined the Escape and Crashworthy Systems Division of the Naval Air Systems Command (NAVAIR). With an emphasis on the mishap environment of the naval aviator, a vertical component was added to his modeling effort. At NAVAIR, he uses the MADYMO, LS-DYNA and DYTRAN codes to investigate many aspects of aircrew crash safety; including energy absorbing pilot and troop seats, cockpit airbags, mobile crewman tethers, and ejection seat head-neck response. The Escape and Crashworthy Systems Division runs the Navy's ejection tower, windblast facility, and horizontal accelerator lab. Dr. Sieveka's modeling work often plays a key part in prototyping and analyzing the tests at these facilities.

Dr. Levent Kitis joined the Escape and Crashworthy Systems Division of the Naval Air Systems Command in August, 2003. He uses MADYMO and LS-DYNA to study various impact dynamics scenarios of interest to the U. S. Navy.