Evaluating Abdominal Injury in Workstation Table Impacts

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ABSTRACT

In rail passenger seating arrangements with workstation tables, there is a risk of serious thoracic and abdominal injury. Strategies to mitigate this injury risk are being developed through a cooperative agreement between the Federal Railroad Administration (FRA) of the United States and the Rail Safety and Standards Board (RSSB) of the United Kingdom. The approach to developing the protection strategies involves collision investigations, computer simulations of the occupant response, and full-scale testing. During the train collision in Placentia, CA on April 23, 2002, many occupants impacted workstation tables. The investigation indicated the likely modes of injury due to these impacts, the most traumatic being damage to the liver and spleen. A MADYMO computer simulation was created to estimate the loads and accelerations imparted on the occupants that bring about these injuries. Two experiments were designed and executed on a full-scale impact test with an occupant environment similar to the Placentia collision. These experiments incorporated advanced anthropomorphic test devices (ATDs) with increased abdominal instrumentation. The THOR ATD showed a more human-like impact response than the Hybrid III Railway Safety ATD. The full-scale test results are used to refine a MADYMO model of the THOR ATD to evaluate improved workstation tables. The occupant protection strategy that will be developed requires that the table remain rigidly attached to the car body, and includes a frangible edge with a force-crush characteristic designed to minimize the abdominal load and compression. MADYMO simulations of this table design show a significantly reduced risk of severe abdominal injury**.**

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Abstract. In rail passenger seating arrangements with workstation tables, there is a risk of serious thoracic and abdominal injury. Strategies to mitigate this injury risk are being developed through a cooperative agreement between the Federal Railroad Administration (FRA) of the United States and the Rail Safety and Standards Board (RSSB) of the United Kingdom. The approach to developing the protection strategies involves collision investigations, computer simulations of the occupant response, and full-scale testing. During the train collision in Placentia, CA on April 23, 2002, many occupants impacted workstation tables. The investigation indicated the likely modes of injury due to these impacts, the most traumatic being damage to the liver and spleen. A MADYMO computer simulation was created to estimate the loads and accelerations imparted on the occupants that bring about these injuries. Two experiments were designed and executed on a full-scale impact test with an occupant environment similar to the Placentia collision. These experiments incorporated advanced anthropomorphic test devices (ATDs) with increased abdominal instrumentation. The THOR ATD showed a more human-like impact response than the Hybrid III Railway Safety ATD. The full-scale test results are used to refine a MADYMO model of the THOR ATD to evaluate improved workstation tables. The occupant protection strategy that will be developed requires that the table remain rigidly attached to the car body, and includes a frangible edge with a force-crush characteristic designed to minimize the abdominal load and compression. MADYMO simulations of this table design show a significantly reduced risk of severe abdominal injury.

INTRODUCTION

In Placentia, California on April 23, 2002, a standing passenger train was impacted head-on by an approaching freight train on the same track. One hundred and nineteen minor, twenty-two serious, and two fatalities were directly attributed to this collision (*1*). Both of the occupants who sustained fatal injuries were seated at workstation tables. As shown in **Figure 1**, workstation tables are placed in between facing pairs of seats (also known as open bay seats when a table is not present) in many passenger rail cars. Rail seats with tables have contributed to occupant injury in several rail collisions in recent history (*2*). For these reasons, workstation tables have been identified as an area for improvement with respect to occupant safety during a collision.

Injuries caused by impacts with workstation tables are also a concern with the United Kingdom. A Memorandum of Cooperation (MOC) has been adopted between the Federal Railroad Administration, U.S. Department of Transportation, and the Strategic Rail Authority, United Kingdom (UK). In the UK, the MOC is being effected at a working level through the Rail Safety and Standards Board Research and Development Program. Among other areas of cooperation such as glazing, grade-crossing safety, fire safety and emergency evacuation, these agencies will coordinate research and development efforts in the design of improved workstation tables.

There are three necessary elements to protect occupants during a collision. It is first necessary to preserve the occupant volume, which is the area of the train where passengers may be sitting or standing. Once the occupant volume is preserved, it is then necessary to compartmentalize the occupants. Compartmentalization refers to limiting the trajectory of the occupant, usually within the space between the launch seat and the impacted seat. If compartmentalization is lost, there exists a risk that the occupant kinematics are less predictable, and there is a risk of striking more volatile surfaces. Compartmentalization has been shown to be an effective occupant protection strategy (*3*). Finally, the loads and accelerations imparted on the compartmentalized occupants must be within survivable limits.

An important step in the development of an improved workstation table was to conduct a full-scale test of the existing equipment. In order to examine the interaction of the occupant with the workstation table, this full-scale test implemented advanced anthropomorphic test devices with an increased capacity for recording abdominal loads and displacements over the standard Hybrid III 50th percentile male ATD. Results from the full-scale test of the existing equipment are then used to refine a MADYMO (*4*) computer model of the occupant response. This refined model will be used to evaluate improved workstation table designs. An improved workstation table will be developed to compartmentalize the occupants as well as reducing the risk of thoracic and abdominal injuries.

ABDOMINAL INJURY ASSESSMENT

Human Tolerance to Frontal Abdominal Impact

Blunt trauma to the abdomen can bring about severe injury in several ways. Many of these modes of injury were seen in the occupants seated at workstation tables during the Placentia, CA collision. As the abdominal cavity is compressed between the spine and, in this case, the table edge, overall pressure increases. Increased pressure can cause the organs of the abdominal cavity to burst. The compression of the abdomen will initially bring about fractures of the lower ribs, and allow the organs of the abdominal cavity to be compressed and pushed against the spine and fractured ribs, causing ruptures and lacerations. As occupant is likely to impact the workstation table in the upper abdomen region, the liver is initially at risk, followed by the spleen and diaphragm (*5*). For high velocity impacts, the rate of compression of the abdomen can also bring about tearing of the abdominal organs (*6*).

The two fatally injured occupants of the Placentia, CA collision sustained such trauma. One occupant, a 48-year-old male, suffered 9 fractured ribs, lacerations of the liver and spleen. The other occupant, a 59-year-old male, suffered 14 fractured ribs, fractures of two thoracic vertebrae, lacerations of the liver and spleen, and a heart contusion (*7*). The non-fatal injuries sustained also included fracture ribs, as well as facial injuries from impact of the head with the top of the table.

Developing occupant protection strategies is aided by the ability to quantify injury risk. In the past, injury criteria for the testing of rail seats have been adopted from the automotive industry. The modes and severities of rail injuries are similar enough to automotive injuries that the criteria correlate well. In the case of abdominal injury brought about from impact with a workstation table, there are no widely accepted criteria that effectively characterize the injury risk. As airbags have been effective in preventing abdominal impacts with steering wheel rims, the attention of the automotive industry has shifted to lateral impacts. There is a concern for injuries brought about from submarining of seat belts; however, workstation table impacts are much more likely to occur in the upper abdominal region, thus injury criteria characterizing the lower abdomen is marginally useful.

Three measures will be used to assess the risk of abdominal injury: compression, rate of compression, and force. Since there are no widely accepted maximum injury criteria levels, these measures of the abdominal response to the impact with the conventional and improved workstation tables will be compared. Ideally, an improved workstation table will limit the abdominal force, which in turn reduces the compression and rate of compression. In order to record meaningful measurements, it is necessary to use ATDs that have a biofidelic abdominal impact response and are capable of measuring abdominal compression.

Advanced ATDs

Hybrid III with Frangible Abdomen

The first ATD to include a method for evaluating abdominal injury was a modified Hybrid III with a frangible abdomen insert (*8*). The frangible abdomen insert is constructed of crushable foam with a defined force-crush characteristic, generally characterized by 30N/mm stiffness. Examination of the foam after the impact test indicates the peak deformation and accordingly an estimate of the peak load. The frangible abdomen insert proved to be most effective in indicating when submarining would occur. The drawback of the frangible insert is that it is difficult to record a time-history of the abdominal penetration or force. Further development of a rate-sensitive abdominal insert for the Hybrid III family of ATDs is currently being developed (*9*).

Hybrid III Railway Safety

The development of the Hybrid III Railway Safety (Hybrid 3RS) ATD was funded and directed by the United Kingdom's Rail Safety and Standards Board, with the assistance of Transportation Research Laboratories, Ltd., along with GESAC, AEA, Millbrook and MIRA. The Hybrid 3RS is a modified version of the stock Hybrid III 50th percentile male ATD, aimed at characterizing injuries perceivable in rail collisions, specifically with fixed tables in seating bays and with seat back tables. Practical problems were encountered with the stock Hybrid III in obtaining concurrent information from the frangible abdomen device and with lower chest intrusions. The developed Hybrid 3RS is equipped with similar instrumentation to the THOR. The Hybrid 3RS is in the experimental stages, and there is only one currently in existence.

The ribcage of the Hybrid 3RS ATD has not been modified from the stock Hybrid III 50th percentile male ATD. However, CRUX units have been added at four locations to measure three-dimensional rib displacements. The lower abdomen insert from the THOR ATD, which consists of layered deformable foam enclosed in a Cordura nylon bag with seams sewn with Kevlar thread, is mounted between the lower rib cage and the pelvis. This insert has two double gimbaled string potentiometer (DGSP) units, one on each side, to measure the three-dimensional displacement of the lower abdomen, as well as two linear string potentiometers at the mid-abdomen level. The Hybrid 3RS includes a three-piece plastic bib that overlaps in front of the gap between the bottom of the ribcage and the top of the lower abdomen insert, preventing impactor penetration. The Hybrid 3RS also incorporates the THOR hip arrangement, improving biofidelity over the stock Hybrid 3. An image of the Hybrid 3RS, detailing the location of these transducers, is shown in **Figure 2**. **Figure 3** shows the force-penetration characteristic of the lower abdomen of the Hybrid 3RS against the expected human impact response determined from previous studies using post-mortem human surrogates.

THOR

The THOR (Test Device for Human Occupant Restraint) 50th percentile ATD was developed by the National Transportation Biomechanics Research Center of the National Highway Traffic Safety Administration (*10*). The THOR was originally developed to investigate the injury risk associated with restraints, such as seat belts and airbags, to the thorax and abdomen. The THOR is currently in the experimental stage of development, and has not been validated as thoroughly as the Hybrid III.

The THOR ATD includes several refinements over the standard Hybrid III and Hybrid III with the frangible abdomen insert. The overall biofidelity of the ATD has been improved, as shown in the THOR Biomechanical Requirements document (*11*). The rib cage of the THOR is representative of the human thoracic structure, and includes three-dimensional displacement measurement at four locations. There are two abdomen inserts: the smaller upper abdomen insert is mounted in the center of the lowest three ribs, and the lower abdomen insert is mounted between the lower rib cage and the pelvis. Both inserts consist of layered deformable foam enclosed in a Cordura nylon bag with seams sewn with Kevlar thread. The upper abdominal insert includes a unidirectional string potentiometer to measure displacement, as well as a uniaxial accelerometer. The lower abdominal insert has two DGSP units, one on each side, to measure the three-dimensional displacement of the lower abdominal surface. An image of the THOR, detailing the location of these transducers, is shown in **Figure 4**.

The improved biofidelity and the comprehensive thoracic and abdominal instrumentation make the THOR a good candidate for testing workstation tables. The upper abdomen impact response is of specific interest, as impact with the workstation table would likely occur directly on the upper abdomen insert. **Figure 5** shows the upper abdomen impact force-penetration response of the THOR in three tests. These tests are compared to the corridor of upper abdominal force-penetration from post-mortem human surrogates from data developed by Nusholtz (*11*, *12*). This data is taken from 18 kg rigid steering wheel impacts at 8.0m/s. The peak load of this impact is roughly 11kN, reached at between 105mm and 110mm. The THOR impact response is within the prescribed corridor for penetrations of less than 90mm.

An additional benefit of using the THOR in testing workstation tables is that TNO Automotive has developed a THOR Alpha model in MADYMO 6.1 (*4*). Previous workstation table simulations using TNO's Hybrid III model indicated the need for a more detailed model to represent the impact of table on the abdomen (*13*). TNO's THOR model includes corresponding output channels for the THOR ATD's thoracic and abdominal instrumentation. Preliminary simulations have shown promising results.

FULL-SCALE TEST

Test Objectives

There were three primary objectives in running a full-scale test of the workstation table environment. The first was to observe the occupant response during a collision of similar magnitude to the Placentia, CA collision. Correlations can be made between the loads and accelerations experienced by the ATDs in the test and the actual injuries sustained by the occupants seated at workstation tables in the Placentia collision. The second objective was to measure the loads imparted on the table by the occupant. This information is necessary for the design of an improved workstation table. The final objective was to add to a growing database of information on the occupant response during rail collisions. A collection of test data from as many different test conditions as possible is very helpful in developing strategies to protect occupants in rail collisions.

The full-scale workstation table tests were conducted as a part of a larger full-scale test of two coupled passenger cars with modified end structures, as shown in **Figure 6**. The design of the end structures is known as crash energy management (CEM), a system by which energy is absorbed through the controlled crush of the end frames. The most important aspect of CEM system is that it preserves the entire occupant volume. More information on the end structure design and performance can be found in References 14 and 15. Since the CEM design satisfies the first element to occupant protection, focus is shifted to compartmentalization and injury risk.

Occupant Environment

The THOR and Hybrid 3RS experiments were set up towards the aft end of the leading car in the CEM two-car full-scale test. The seats and tables, provided by Metrolink, were identical to those installed on the impacted passenger car in the Placentia, CA collision. The attachments of the seats to the seat rails in the floor and the side frame on the wall were consistent with in-service mounting. The table attachment points were strengthened to ensure that the table would not detach during the impact. This was necessary both to ensure that the ATDs were compartmentalized and that the load cells at the table attachment points would accurately read the maximum force imparted on the table by the occupants. In a sled test of these Metrolink seats without reinforced table attachments, the table failed before it arrested the motion of the occupants, thus the maximum load was not determined (*16*).

While the longitudinal acceleration pulse experienced by the ATDs in the CEM two-car full-scale test was notably severe, it was less severe than the estimated acceleration pulse in the Placentia, CA collision (*12*). Furthermore, there were additional vertical and lateral accelerations experienced by the occupants in the Placentia collision because of the unique mode of deformation of the impacted car. Since the CEM end structures are designed for controlled crush, vertical and lateral accelerations are negligible. The occupant environment in the CEM two-car full-scale test was not meant to reenact the Placentia collision; rather, it was a convenient and economic venue on which to carry out the workstation table experiments. Nonetheless, the measurements taken by the ATDs should be consistent with the modes and severities of the injuries sustained by the occupants in the Placentia collision, as frontal impact of the workstation table to the upper abdomen of the occupants is the prevailing factor.

Hybrid 3RS

A MADYMO model of the Hybrid 3RS does not currently exist, thus pre- and post-test simulations were not conducted. There is the potential for modification of TNO's Hybrid III model to account for the differences in thoracic and abdominal impact response and instrumentation at a later date.

Kinematics. As the leading car in the two-car consist impacts the wall, the Hybrid 3RS ATD initially translates forward with an increasing velocity relative to the car. The shoes drag on the floor, and do not translate forward as quickly as the femurs. The upper abdomen impacts the table slightly before the lower legs impact the facing seats. As the upper abdomen impacts the table, the pelvis continues to translate forward for several milliseconds before coming to rest relative to the abdomen. The upper body rotates a small amount about the point of impact with the table, and the head rotates forward about the torso upon maximum compression of the abdomen. The Hybrid 3RS quickly rebounds off of the table and returns to the initial position. **Figure 7 (top)** shows the time-history of the Hybrid 3RS kinematics during the impact.

Injury Measurements. The upper abdominal compression (read at the lower CRUX units) reached a maximum of 73mm on the right and 79mm on the left. The maximum viscous criterion calculated was 1.08m/s. The highest resultant chest acceleration maintained over a 3ms window is 46.48g, measured between 103.5ms and 107ms. The peak upper abdominal load reached 29.25kN. The maximum calculated HIC15 was 288.

Discussion. As opposed to the THOR, the abdominal compression measured by the CRUX units in the Hybrid 3RS is in good agreement with the high-speed film. The PTFE bib successfully prevented penetration of the table edge between the bottom of the rib cage and the top of the abdominal insert. While the chest acceleration and HIC measurements were relatively low, the high abdominal load and abdominal compression are of great concern. The Hybrid 3RS performed well in this test, with no signs of wear or necessary maintenance.

THOR Response

Pre-Test Predictions

A MADYMO occupant response model was created before full-scale test was run. The seat model was created and refined based on three sled tests of facing commuter seats (*16*). However, the facing seats sled test simulation that included a workstation table was not refined as part of this report. This model has been used for several other purposes, including an estimated recreation of the occupant response during the Placentia collision (*13*). This full-scale test was the first opportunity to refine the workstation table element of the facing seats model based on test measurements.

The tabletop is defined as a lumped mass rigid body, since the tabletop itself was not expected to deform during the impact. Point restraints at the location of each of the load cells in the test support the tabletop. An unmodified THOR ATD model is positioned on the window side of the seat pair, facing the impacted end of the car. A three-dimensional collision dynamics model of the CEM two-car full-scale test produced the input to the occupant response model (*15*).

Kinematics. During the impact, the THOR translates forwards toward the table and impacts directly on the ellipsoid representing the upper abdomen insert. As the upper abdomen compresses, the ellipsoids representing the lower three ribs move in unison. The compression of the upper rib cage is completely independent of the motion of the lower three ribs. As the THOR rebounds from the table, the neck flexes forward, allowing the head to impact the tabletop.

Injury Predictions. During the impact with the table, the THOR upper abdomen (read at both the upper abdomen string potentiometer and lower CRUX units) compresses 78mm. The peak upper abdominal load reaches 22kN. The viscous criterion reaches a maximum of 2.36m/s, and the 3ms chest acceleration reaches 76g. A HIC15 calculation for the impact of the head with the tabletop results in a value of 733.

Discussion. All of injury predictions presented above exceed the maximum injury criteria values, which is consistent with the injuries seen in the Placentia collision. The occupant does, however, remain compartmentalized. This deformation of the lower thorax is questionable, and will be a focus of the model refinement after the test.

Full-Scale Test

During the CEM two-car full-scale impact test, the modified end structures of the passenger cars performed exactly as expected. The impact speed of the two coupled cars with the wall was 29.3 miles per hour. Nearly all of the data channels were successfully recorded, and both of the workstation table experiments were successfully captured on high-speed film.

Kinematics. As the leading car in the two-car consist impacts the wall, the THOR ATD initially translates forward with an increasing velocity relative to the car. The shoes drag on the floor, and do not translate forward as quickly as the femurs. Immediately after contact with the table occurs, the upper body begins to rotate down towards the tabletop and the pelvis and femurs rotate upwards towards the bottom of the table, forming a “C” shape about the point of contact. The upper body rotation continues rapidly until the head impacts the forward edge of the tabletop, and passes between the knees on the far side of the table. The THOR then rebounds gradually, and the final resting position is partially slumped over the table. **Figure 7 (bottom)** shows the time-history of the THOR kinematics during the impact.

Injury Measurements. The upper abdominal compression (read at the lower CRUX units, since the upper abdominal string potentiometer saturated before the impact was complete) reached a maximum of 52mm on the right and 58mm on the left. The maximum viscous criterion calculated was 1.30m/s. The peak chest acceleration in the longitudinal direction was 93g, which occurred at a time of 103ms. The peak chest acceleration in the vertical direction was 293g, which occurred at a time of 109ms; however, this peak is less than 3ms in duration, and does not contribute to the 3ms chest injury criteria. The highest resultant chest acceleration maintained over a 3ms window is 73.27g between 102ms and 105ms. The peak upper abdominal load reached 30kN. The maximum calculated HIC15 for the impact of the head with the forward table edge was 530.

Discussion. The measurements from the lower CRUX units are not in agreement with the upper abdominal compression seen in the high-speed film. The upper abdomen appears to compress at least half of the depth of the THOR upon initial impact with the table. As the upper body rotates about the contact point, the table appears to penetrate through to the spine. This would indicate a compression of roughly 130mm. Inspection of the THOR after the impact offered further evidence. The THOR jacket, which is essentially a vest that covers the entire torso, was wedged between the upper and lower abdominal inserts. This suggests that the table itself penetrated the area below the bottom rib, where the lower CRUX units are attached, and traveled as far as the spine. This would account for the fact that the CRUX units did not measure the full extent of the upper abdominal compression. Additionally, it was found that the lumbar spine pitch change joint had fractured during the test. This joint, a significant structural element in the spine of the THOR, is constructed of 1¼-inch by 1¾-inch hardened steel (see **Figure 8**). Fracture of this piece suggests that the table directly impacted the spine. The high peak in the vertical direction of the chest acceleration time-history suggests that this joint fractured at a time of 109ms.

Post-Test Simulation Refinement

In the pre-test simulation of the THOR impact with the workstation table, the rotation of the upper body towards the tabletop and the pelvis and femurs towards the bottom of the table was not as pronounced as in the full-scale test. The measurements of the abdominal response to the table impact, however, were more severe than measured in the test in all categories except for chest acceleration. Refinement of the simulation entailed making changes to TNO's THOR model to allow the magnitude of rotation about the table contact point. The most significant change to the THOR was to allow rotation about the lumbar spine pitch change joint, which was fractured during the test. This allowed the THOR upper body to rotate about the table contact point close to the extent seen in the high-speed film. Another modification to the model was to increase the friction in the contact between the shoes and the floor. This brought the impact of the tibias with the facing seat pan to closer to the feet, allowing the pelvis and femurs to rotate upwards towards the bottom of the table.

The input to the post-test simulation was the crash pulse measured by the accelerometer at the center of mass of the lead car in the CEM two-car full-scale test. To smooth out the relatively noisy longitudinal acceleration pulse, it was integrated twice, and the relative displacement was applied to the reference frame of the seats and table. The lateral acceleration was not applied to the THOR, since the lateral motion relative to the car was negligible during the impact. A vertical acceleration pulse consisting of the measured vertical acceleration at the rear end of the lead car combined with gravitational acceleration was applied directly to the THOR.

Kinematics. As the THOR begins translating forward, the shoes drag on the ground and begin to rotate forward about the toes. The table impacts directly on the upper abdomen ellipsoid, and the lower ribcage begins to compress. At a time of 108ms, the lumbar spine pitch change joint becomes unlocked. This allows the severe upper body rotation towards the tabletop and pelvis rotation towards the bottom of the table, forming the "C" shape as seen in the full-scale test. As the upper body rotates forward, the head impacts the top of the table at a time of 153ms. The THOR then rebounds and comes to rest partially slumped over the table. A time-history of the post-test simulation kinematics is shown in **Figure 9**.

Injury Predictions. During the impact with the table, the THOR upper abdomen (read at both the upper abdomen string potentiometer and lower CRUX units) compresses 84mm. The peak upper abdominal load reaches 28.7kN. The abdominal viscous criterion reaches a maximum of 1.27m/s. The chest acceleration is very similar to the full-scale test measurements. The peak chest acceleration in the longitudinal direction was 89g, which occurred at a time of 107.5ms. The peak chest acceleration in the vertical direction was 307g, which occurred at a time of 108ms; however, this peak is less than 3ms in duration, and does not contribute to the 3ms chest injury criteria. The highest resultant chest acceleration maintained over a 3ms window is 64.98g between 106ms and 109ms. A HIC15 calculation for the impact of the head with the tabletop results in a value of 953.

Discussion. Refining a simulation based on the THOR response in the CEM two-car full-scale test proved difficult. The kinematics of the THOR in the test were influenced by physical characteristics (i.e. the ability of the table to penetrate the space between the upper and lower abdominal inserts) that are not represented in TNO's THOR model. The time-histories of chest acceleration, head acceleration, and abdominal load of the refined model, as well as the overall kinematics, correlate very well with the full-scale test results. However, the abdominal compression in the model is much higher than that measured in the test. This evidence supports the theory that, in the full-scale test, the THOR CRUX units did not measure the full extent of the upper abdominal compression. It is unknown whether the modifications made to the THOR to reproduce the full-scale test response adversely affect the biofidelity of the model in other impacts.

Comparison of THOR and Hybrid 3RS

In the CEM two-car full-scale impact test, the response of the THOR and Hybrid 3RS ATDs differed significantly. In terms of abdominal impact response, the Hybrid 3RS showed a higher stiffness than the THOR. While this is a desirable feature for the repeatability of a test device, a stiffness that is too high can yield a response that is not representative of a human occupant. In laboratory tests using post-mortem human surrogates (PMHS), the measured stiffness of the middle and upper abdomen is between 50N/mm and 75N/mm for high-speed impacts (*5*). Since there is no upper abdominal insert in the Hybrid 3RS, the impact is concentrated on the rib cage, which was not modified from the stock Hybrid III. Thus, a high stiffness response of 380N/mm results. Assuming an upper abdominal compression of 130mm (enough to impact the spine), the THOR shows a stiffness of 230N/mm.

Although the Hybrid 3RS showed a stiffer abdominal response to the table impact, it proved to be very robust. Since it is based on a thoroughly validated ATD, the Hybrid 3RS benefits from years of testing experience. The THOR, however, is still in the experimental stages. This contrast can be seen in the fact that, unlike the Hybrid 3RS, the THOR required maintenance after the table impact in this CEM two-car full-scale test. One item of concern is that the table penetrated the gap between the upper and lower abdomen inserts and impacted the spine of the THOR. There are rib stiffeners installed in the jacket of the THOR to prevent exactly this; however, it is doubtful that these stiffeners are designed for as concentrated a load as the table edge. On the Hybrid 3RS, a PTFE bib successfully prevented penetration of the table into the gap above the lower abdomen insert. It is recommended that this bib be adapted for use with the THOR in future tests.

Both the THOR and the Hybrid 3RS ATDs will be included in future testing of workstation tables. This will allow a comparison of the recorded thoracic and abdominal measurements in order to quantify the performance of an improved table.

DEVELOPMENT OF IMPROVED WORKSTATION TABLE

The results of the workstation table experiments on the CEM two-car full-scale impact test confirmed the need to develop occupant protection strategies for this seating arrangement. As stated earlier, compartmentalization is the second necessary element of occupant protection, after preserving occupant volume. This strengthening of the table attachments in the CEM two-car full-scale test successfully compartmentalized both of the ATDs. Compartmentalization by the table prevented further impacts of the ATDs with additional interior structures of the train. Had the table not compartmentalized the occupant, impacts with interior structures further away from the initial seating positions would have occurred at a higher velocity, thus creating an increased injury risk. Furthermore, the kinematics of these impacts are somewhat unpredictable, and the potential for serious head and neck injuries would be high.

On the other hand, the third requirement for occupant protection is that the loads and accelerations imparted on the occupants by the interior structures that provide compartmentalization must be survivable. The ATDs in the table experiments on the CEM two-car full-scale test showed a very high risk of thoracic and abdominal injury, indicating that this third requirement was not fulfilled. Therefore, the workstation table seating arrangement must be redesigned to reduce the injury risk to the occupants.

The occupant protection strategy that will be carried out has two necessary elements. The first is that the table must remain firmly attached to the car body in order to compartmentalize the occupant. This must remain true independent of the number and mass of the occupants seated at the table. The second requirement is that the table limit the load imparted on the upper abdomen of the occupants. In the CEM two-car full-scale test, the measured loads reached and exceeded 30kN. This number exceeds any documented abdominal impact tests of PMHS or ATDs, and must be significantly reduced. Implementing a frangible edge on the table allows energy to be absorbed by the table during the impact, which limits the load imparted on the occupant.

A MADYMO simulation has been created to demonstrate this occupant protection strategy. An optimal force-crush characteristic is being currently developed for improved workstation table edge. Initial estimates suggest that a table edge that can crush 15cm at a load of 5.5kN can significantly reduce the thoracic and abdominal injury risk to occupants seated at the table during a collision. In the simulation of an 8g triangular acceleration pulse sled test, thoracic and abdominal injury risk is reduced significantly. Compared to the rigid table condition, the upper abdominal displacement is reduced from 80mm to 46mm; the upper abdominal viscous criterion is reduced from 0.62m/s to 0.33m/s; the 3ms chest acceleration is reduced from 38.1g to 21.5g; and the abdominal load is reduced from 19.5kN to 5.5kN. Once the improved workstation table design is finalized, the table will be constructed and tested in both static and dynamic environments. The improved tables will be included on the CEM train-to-train full-scale impact test to ensure that the injury risk measured by the THOR and Hybrid 3RS ATDs has been significantly reduced.

CONCLUSION

In a cooperative effort between the Federal Railroad Administration of the United States and the Rail Safety and Standards Board of the United Kingdom, several steps have been taken towards improving occupant protection in rail passenger seating arrangements with intervening workstation tables. Conventional workstation tables pose a severe injury risk to the upper abdominal region of 50th percentile male occupants. Such injuries have been witnessed in real-world accidents, such as the April 2002 collision in Placentia, CA. Full-scale testing has been conducted to measure the abdominal response to impact with workstation tables. This testing required the use of advanced ATDs with increased abdominal instrumentation over the standard Hybrid III 50th percentile male ATD. The THOR and Hybrid 3RS ATDs provide both the improved biofidelity and instrumentation necessary to evaluate workstation table performance.

The results from the occupant experiments on the CEM two-car full-scale test indicated that the conventional workstation table with strengthened attachments was successful in compartmentalizing the occupants. However, impact with this table brought about an abdominal load higher than measured in any documented PHMS or ATD testing. The high abdominal load relates to a high risk of life-threatening injury, which indicates the need to design an improved workstation table.

The MADYMO computer simulation exercised before the CEM two-car full-scale test allowed a good estimation of the loads and accelerations imparted on the THOR ATD. The model was further refined based on the data collected in the test, and the subsequent simulation shows good agreement with all of the test measurements. This model will be used to evaluate improved workstation table designs. A MADYMO model of the Hybrid 3RS ATD will be created and refined in the future.

An improved workstation table will both compartmentalize the occupants and reduce this high abdominal load. The performance of the improved table will be examined in dynamic sled testing, as well as inclusion on the full-scale train-to-train impact test of crash energy management equipment. The Hybrid 3RS and THOR ATDs will be used on these tests to ensure that the abdominal load, compression, and rate of compression resulting from impact with the improved table are reduced.

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Ongoing work on occupant protection in rail passenger equipment is being conducted cooperatively with the United Kingdom's Rail Safety and Standards Board. This work is being coordinated with Alan Lawton, Head of Technical Services, Rail Safety and Standards Board.

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TABLE OF FIGURES

Figure 1. Facing seats with workstation table seating arrangement.

Figure 2. Diagram of Hybrid 3RS thoracic and abdominal instrumentation.

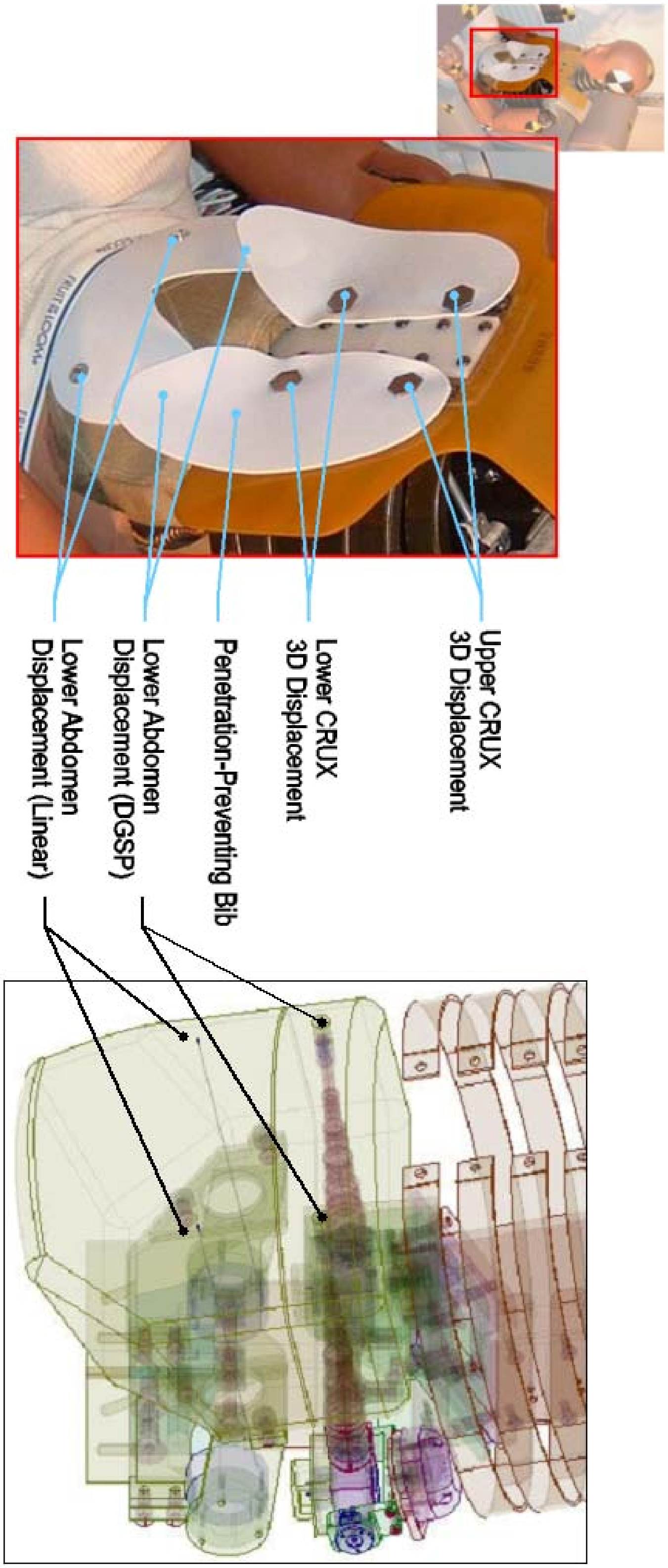
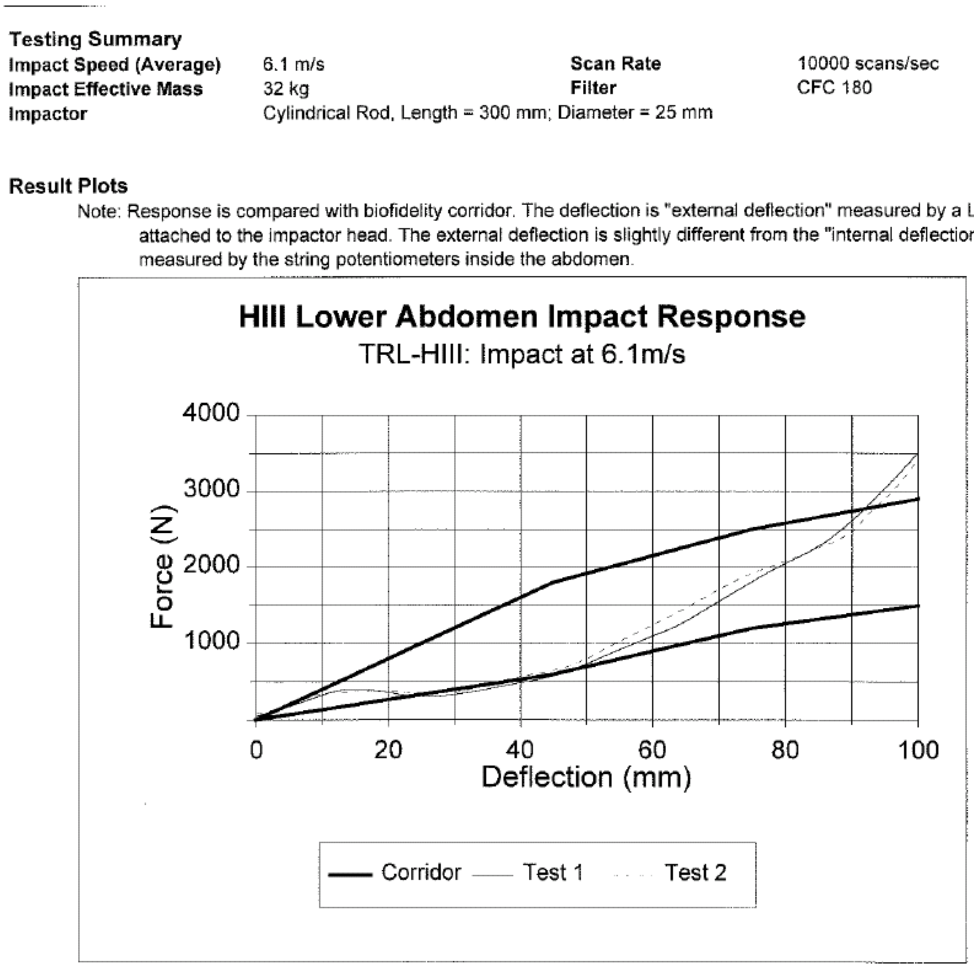


Figure 3. Graph of H3RS abdominal impact response



Testing Summary

Impact Speed (Average)	6.1 m/s	**Scan Rate**	10000 scans/sec
Impact Effective Mass	32 kg	**Filter**	CFC 180
Impactor	Cylindrical Rod, Length = 300 mm; Diameter = 25 mm		

Result Plots

Note: Response is compared with biofidelity corridor. The deflection is "external deflection" measured by a LVDT attached to the impactor head. The external deflection is slightly different from the "internal deflection" measured by the string potentiometers inside the abdomen.

Figure 4. Diagram of THOR thoracic and abdominal instrumentation.

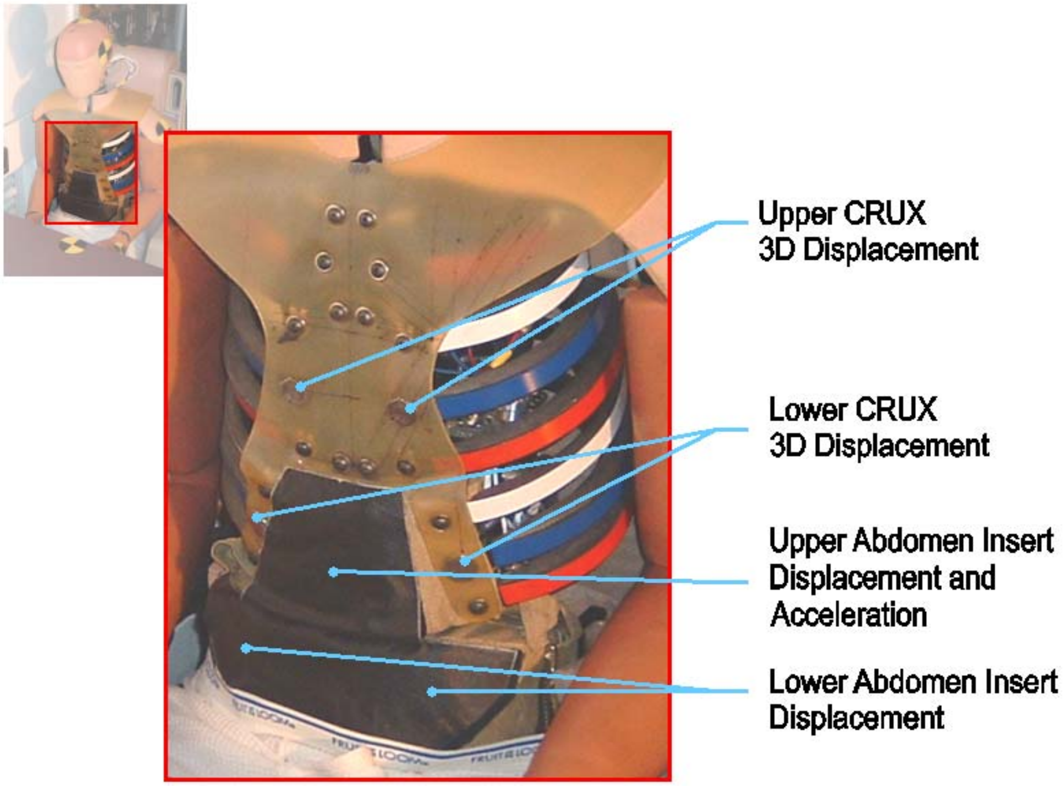


Figure 5. Graph of THOR upper abdomen impact response.

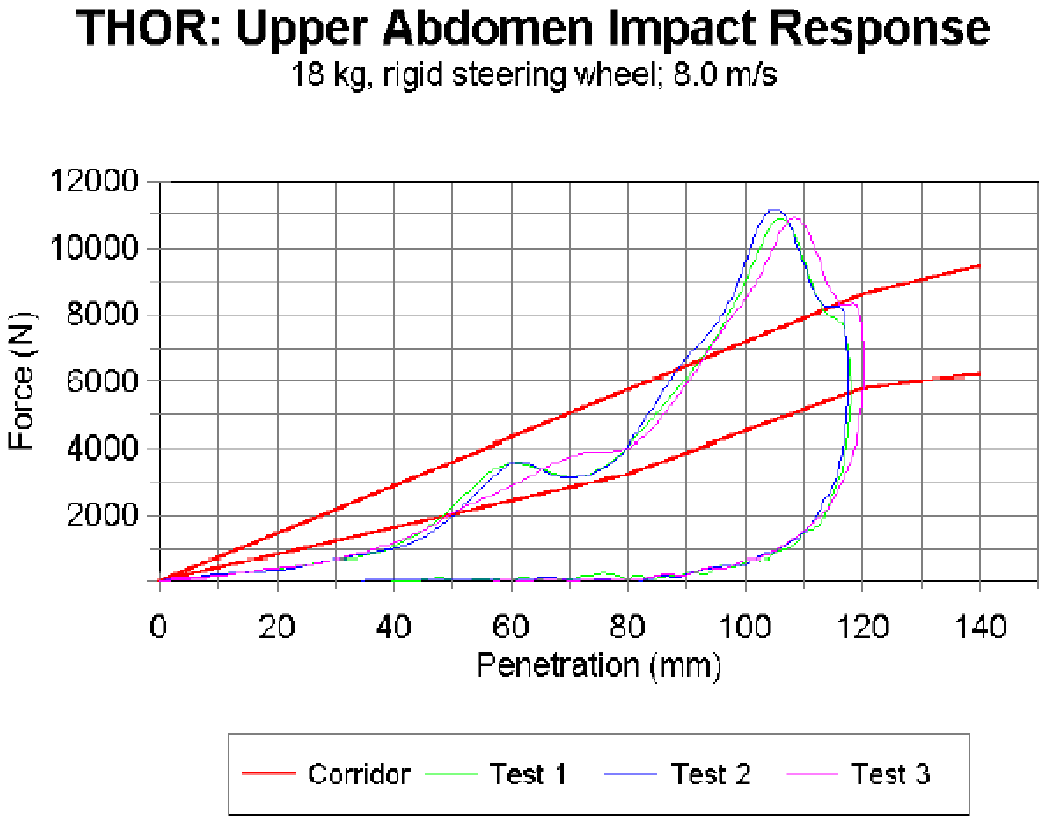


Figure 6. Diagram of the CEM two-car full-scale test setup.

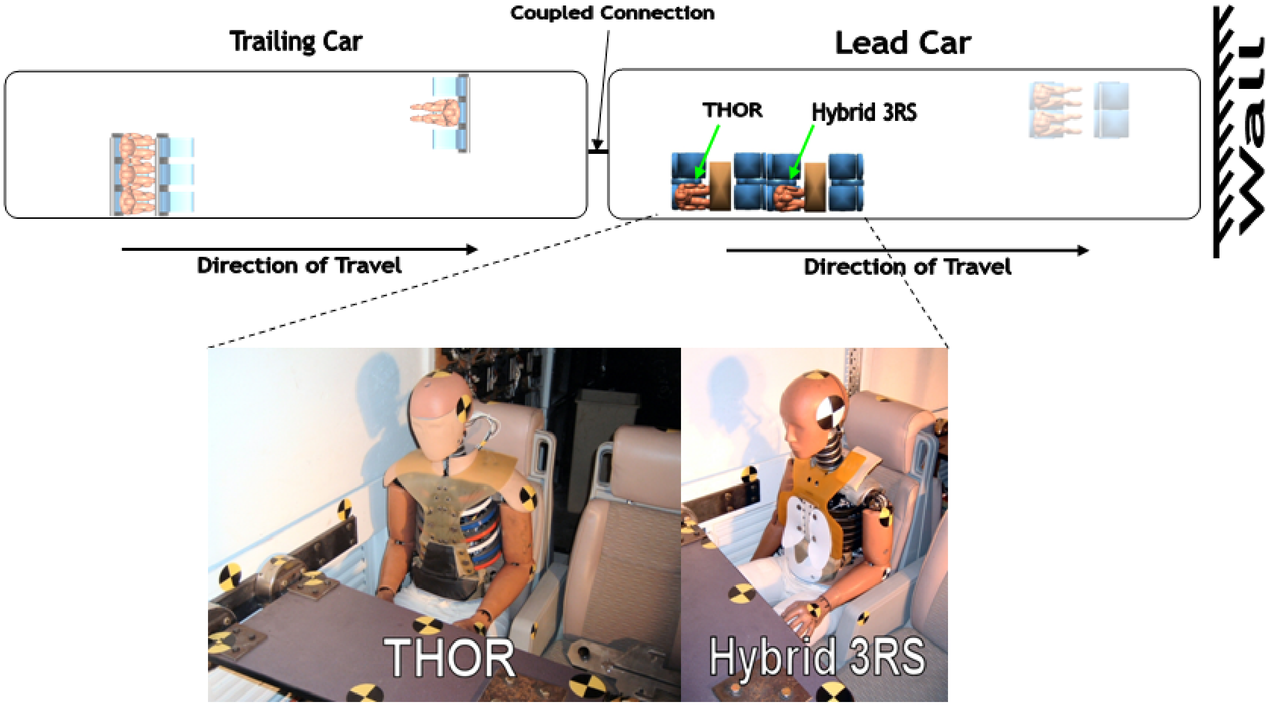


Figure 7. Kinematics of the Hybrid 3RS and THOR response in the CEM two-car full-scale test.

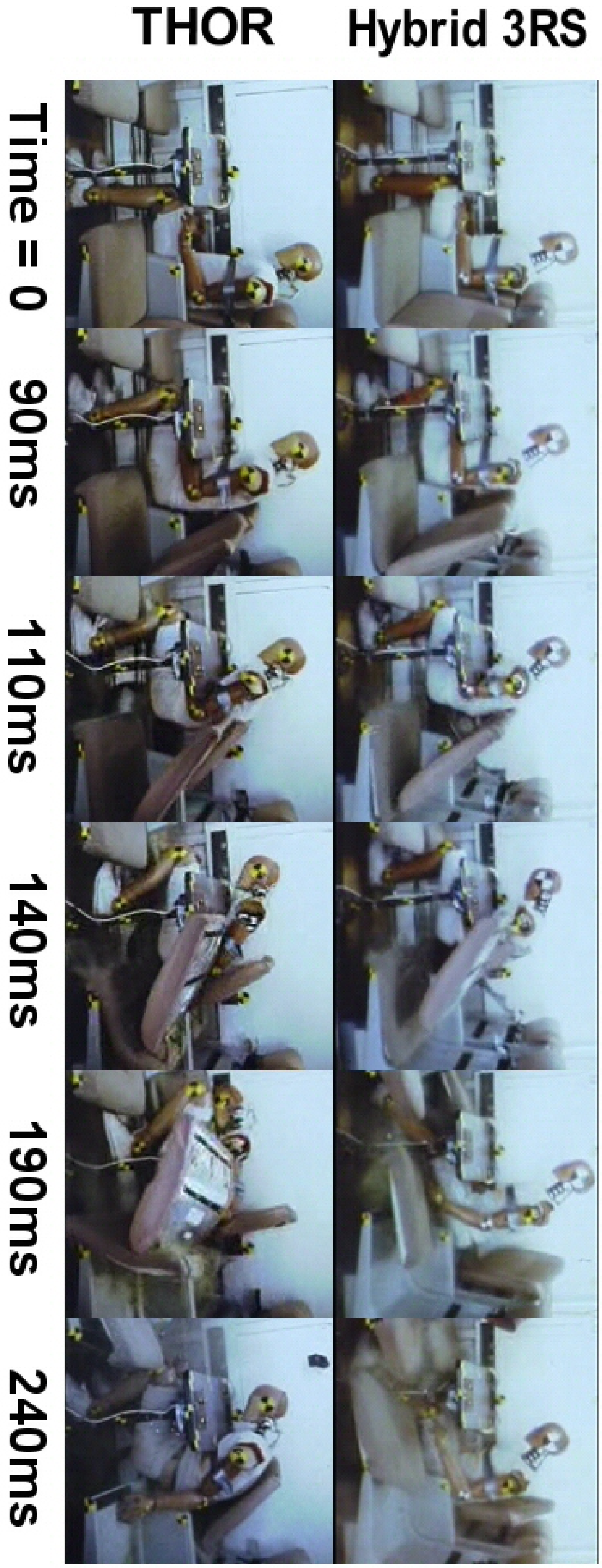


Figure 8. Image of the THOR lumbar spine pitch change mechanism after the CEM two-car full-scale test.

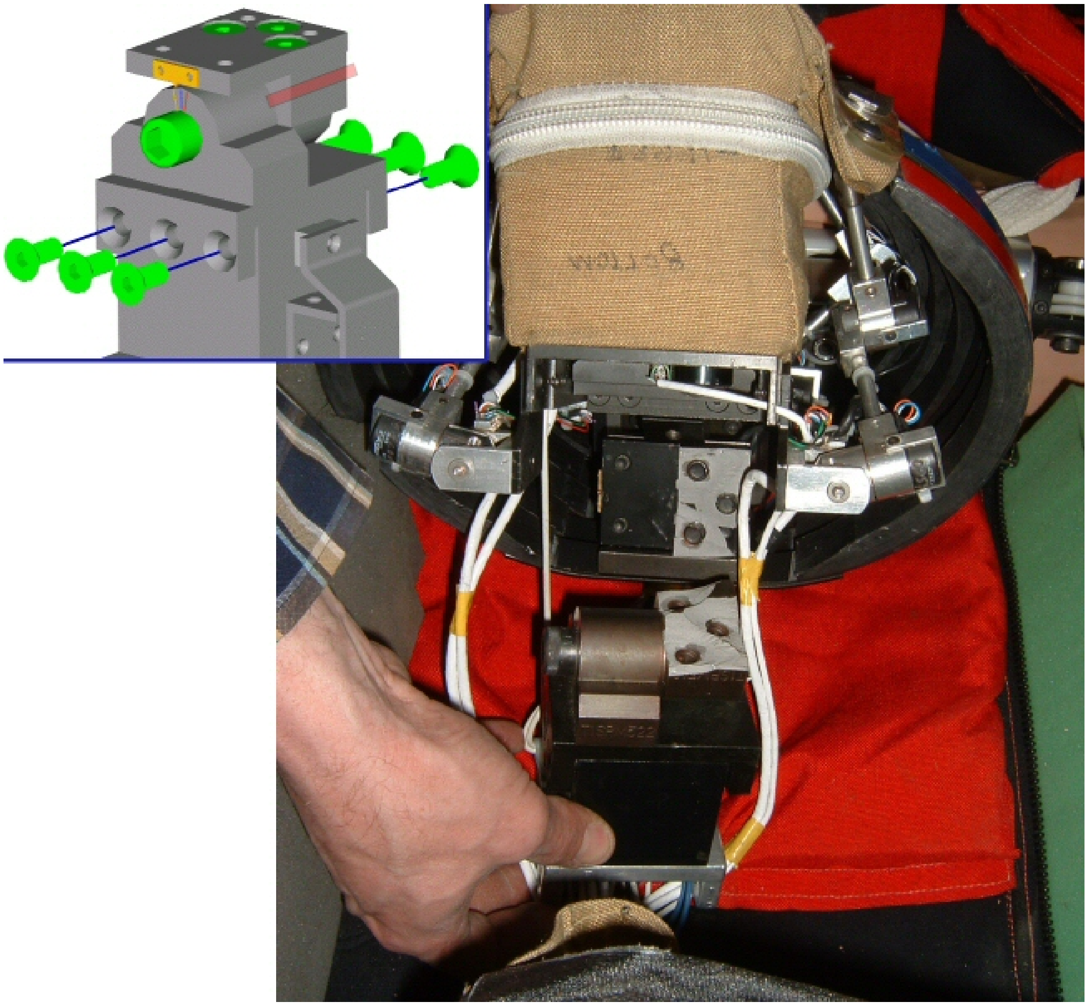


Figure 9. Kinematics of the THOR response in the post-test MADYMO simulation of the CEM two-car full-scale test.