THE INFLUENCE OF RECLINED SEATING POSITIONS ON LUMBAR SPINE KINEMATICS AND LOADING IN FRONTAL IMPACT SCENARIOS

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ABSTRACT

With the advent of alternative seating positions in Highly Automated Vehicles, vehicle manufactures must take care to ensure the safety of new seating positions. The use of Human Body Models (HBMs) can aid in the use of analyzing these new concepts, as they closely represent a human being. HBMs are constructed with Finite Element (FE) modelled bones, muscles, and organs; whereas crash test dummies are made of foams, rubbers, and metallic structures. Due to these differences. HBMs show a different response compared to traditional crash test dummies. A sensitivity study on spinal posture using the THUMS v5 was performed using a BMW prototype reclined concept seat. By changing the initial of the posture of the lumbar spine, changes in spinal kinematics as well as varying force responses were observed during a frontal load case. This type of study could not be conducted with a crash test dummy as the spine of standard front crash dummies does not easily allow for postural changes. These variations suggest that initial spinal posture plays a role in the overall spinal kinematic response as well as the amount of force seen transmitted through the spine.

INTRODUCTION

As driver assistance systems become more advanced, the possibility that the occupants of vehicles will be able to focus on other tasks besides driving also is becoming more probable. Studies have shown that in cars with higher levels of automation passengers expect to be offered non-traditional seating arrangements [1]. In their *A Vision for Safety 2.0* document, NHSTA has stated that care should be taken to ensure that new non-traditional seating positions are safe for vehicle occupants, and that this evaluation might be made using simulation tools such as HBMs, in addition to the hardware tests which are the current standard [2]. In hardware tests all vehicles are tested according to a predefined protocol; in new seating positions this might not be possible. It is also likely that occupant kinematics in new seating positions will be sufficiently different to traditional seating positions that it would approach the limits of hardware dummy validity. Simulations using HBMs are a good candidate for this type of evaluation because their flexibility allows them to be used in many different configurations.

Traditional automotive safety standards have been adopted in accordance with what has been observed in the field, with the emphasis that predefined crash tests will cover a number of real world accident scenarios. This has been possible through the use of accident analysis which shows which kinds of crashes have a higher risk of injury and are the most prevalent [3].

Based on previous simulation studies of various future seating concepts a series of hardware tests were carried out at BMW to closer investigate a seat in a so called Zero-G reclined position [4]. From this study it was observed that the dummies exhibit a different kinematic chain in the reclined position than they do in the traditional upright position, which can be seen in Figure 1. Other studies have also shown non-standard kinematics in non-standard seating positions [5].

Figure 1: Dummy kinematics comparison: conventional seating configuration, above, and the prototype reclined configuration below, from [4].

The difference in kinematics was especially seen to have a large influence on the forces experienced by the lumbar spine sensors in the dummies. This is an indication that the lumbar spine should be more closely investigated. An investigation with a human body model was undertaken in an attempt to get the most realistic assessment of what happens to the spine during a frontal reclined crash, as the HBM spine more closely resembles that of an actual occupant than the spine of a crash test dummy, as seen in Figure 2.

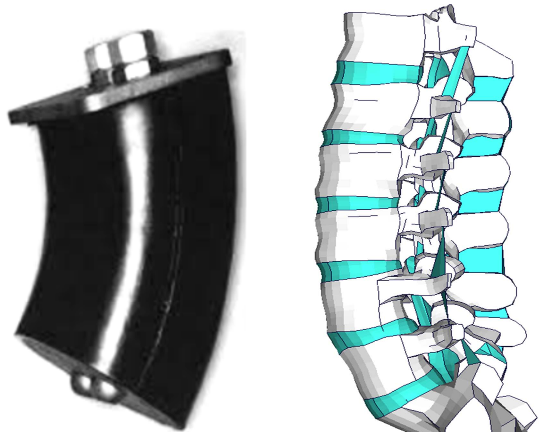

Figure 2: Comparison between a Hybrid 3 50th Percentile Male dummy (H350) lumbar spine [11] (left) and a HBM lumbar spine (right).

METHOD

The human body model chosen for this study was the THUMS v5 50th percentile Male. A preliminary simulation series was run in order to validate the simulation model of the seat with the hardware prototype seat using a H350 dummy.

The THUMS model was positioned first in a comparable manner to the H350 dummy which was used for the seat validation, but this position was ultimately found to be inadequate, because the H350 was not designed to be reclined. It is too stiff in some key areas relating to positioning, most notably resulting in a large gap between the head and the headrest. A second position was therefore derived combining two separate data sources. The first source of data is a set of anatomical landmarks found by probing a 50th percentile male occupant sitting in the seat using a Faro Arm. The second source was an Upright Magnetic Resonance Imaging (MRI) dataset from a different 50th percentile male used to estimate the angles associated with the lumbar spine in a reclined seat. These two sets of data complement one another: one for the superficial surface and one for the internal spinal geometry. A comparison between the MRI data and the positioned human body model can be seen in Figure 3.

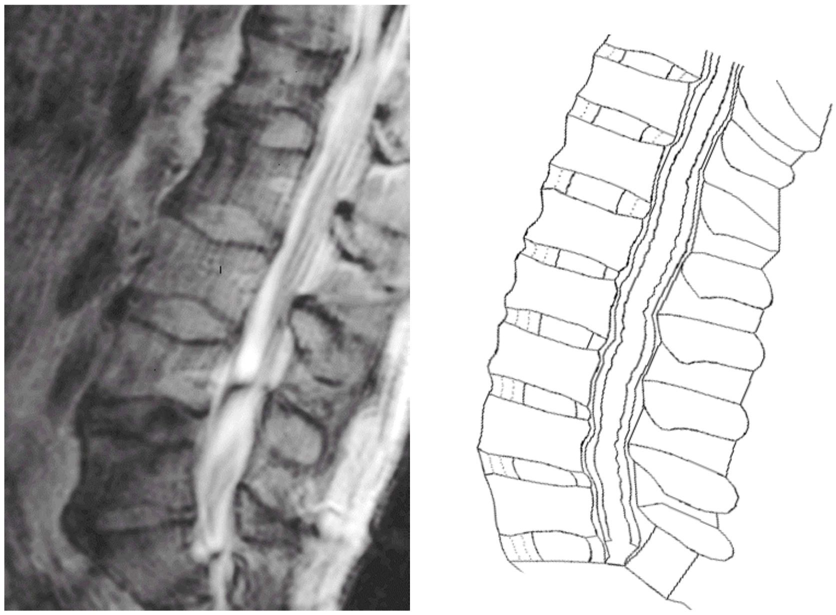

Figure 3: Lumbar spine position as measured using an Upright MRI, and the positioned THUMS 5 lumbar spine.

After the H350-based position was compared with the MRI based position it was found that there was a difference in peak lumbar spine forces, and that the models exhibited differing spinal and global kinematics, as well as different lumbar spine force responses. The differences between the H350-based and the MRI-based models can be seen in Figure 4.

A sensitivity study was then performed using the model with the MRI based seating position as a baseline. For the sensitivity study the pelvis angle and the lumbar spine curvature were varied to see how small changes in the lumbar spine posture affect the kinematics and force response in a frontal crash scenario. This positioning was performed using the Piper positioning tool [6]. Spinal rotation centers were defined in all of the intervertebral disks between the sacrum and T12. The pre-positioning module was then used to vary the spinal position with all bones being held fixed except for the pelvis, sacrum, and the lumbar spine. Then, a prescribed angle was given to all of the rotation centers and the lumbar spine was made to bend. After positioning in the pre-positioner module, the nodes were exported to a standard pre-processor, and smoothing operations were performed. The original position and the modified positions can be seen in Figure 4. Two positions were investigated, one where rotations were prescribed to make the initial geometry more lordodic, extended to be more like an s-curve, and one where the initial position was more kyphotic, or flexed like a c-curve. The more kyphotic state does not exhibit a pure kyphosis, but more so than the baseline position. This type of investigation could only be performed using a HBM: changing the spinal position of a dummy would either not be physically possible (i.e. H350 has no movable lumbar spine joints) or would result in a global change of position, with no possibility to isolate only the spine.

The new models were then run under the same boundary conditions as the MRI-based position model, with the same pulse, and the same restraint system.

RESULTS

Positioning

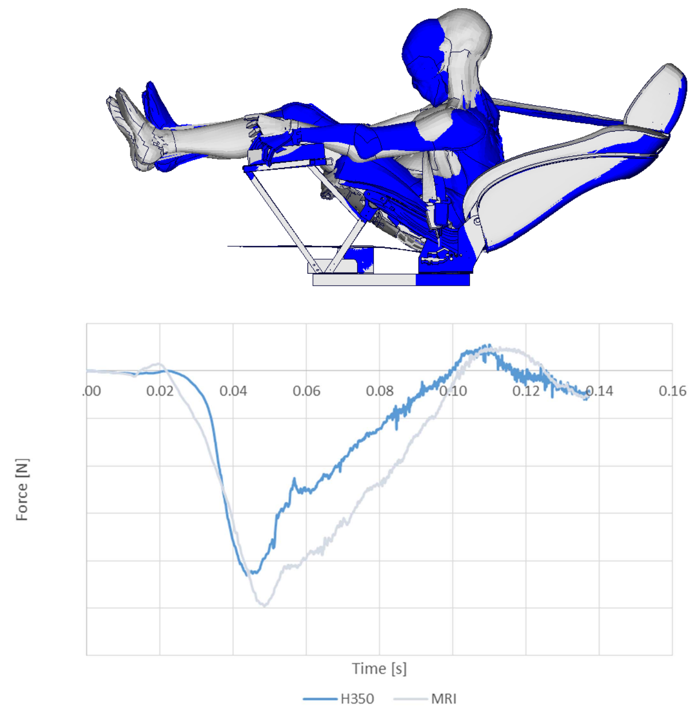

Figure 4: Differences between the H350-like positioned model, in blue, and the MRI-based positioned model, in grey. Forces are measured in the L5 vertebrae.

In Figure 4 large kinematic differences can be seen between the two original HBM positions, as well as a large difference in the peak force observed and the force development profile.

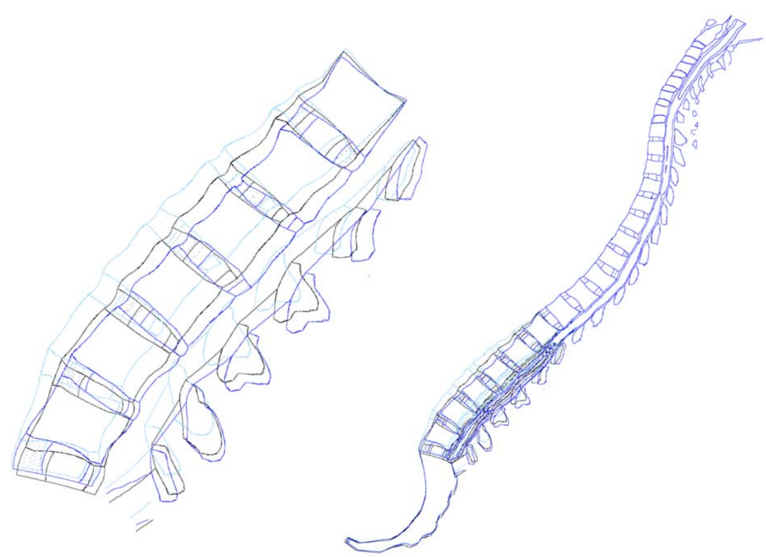

Figure 5: Model orientation after postural positioning, black is the original MRI based position, dark blue is the more kyphotic position, and light blue is the more lordotic position. Left is the lumbar spine where model differences can be easily identified. On the right hand side it can be seen that all the models have the same positioning in the cervical and thoracic spine.

After the postural positioning the two models had only minor differences. In Figure 5 one can see that the light blue and black colorations of the lordotic and baseline models, respectively, are only visible in the lumbar spine and surrounding soft tissue, in the upper body and lower extremities the models exhibit no visible differences, as the dark blue of the kyphotic position is overlaid on the topmost layer in the graphic.

Force Response

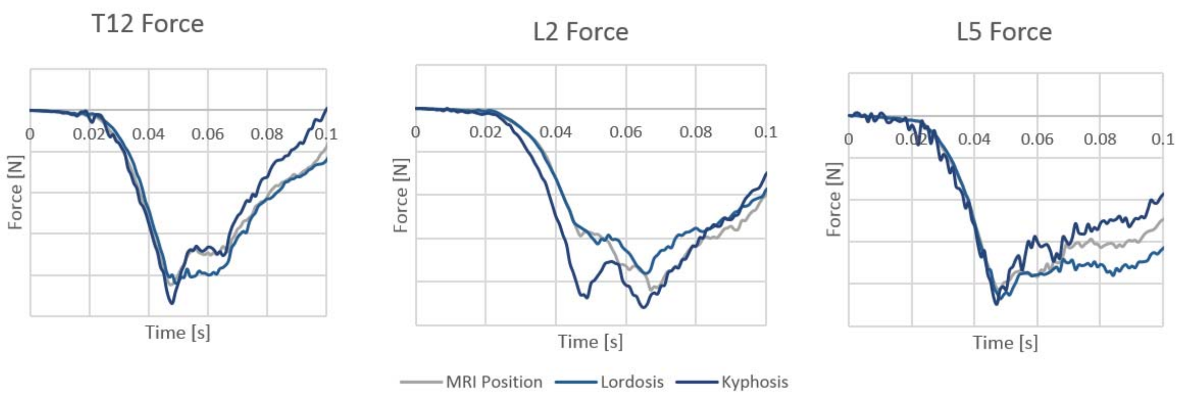

Figure 4: Force histories in selected thoracolumbar vertebra. MRI initial position seen in grey, the more lordodic position in light blue and the more kyphotic position in dark blue. Loading of the T12 and L5 vertebra are consistent across all configurations, whereas no trends hold true for unloading for of the states.

The first thing to note is that the peak force measured in the HBM is much lower than that measured in the dummy. In the HBM H350-like position, the forces are less than 60% of the peak force seen in the hardware tests. In the force time histories of the various postures as seen in Figure 6, one can see differences in the peak force values as well as in the general curve development, though the differences are not consistent across the spinal levels. In general the kyphotic case has the highest peak force, the lordotic case the lowest peak force, and the MRI-based position, a force level somewhere in between.

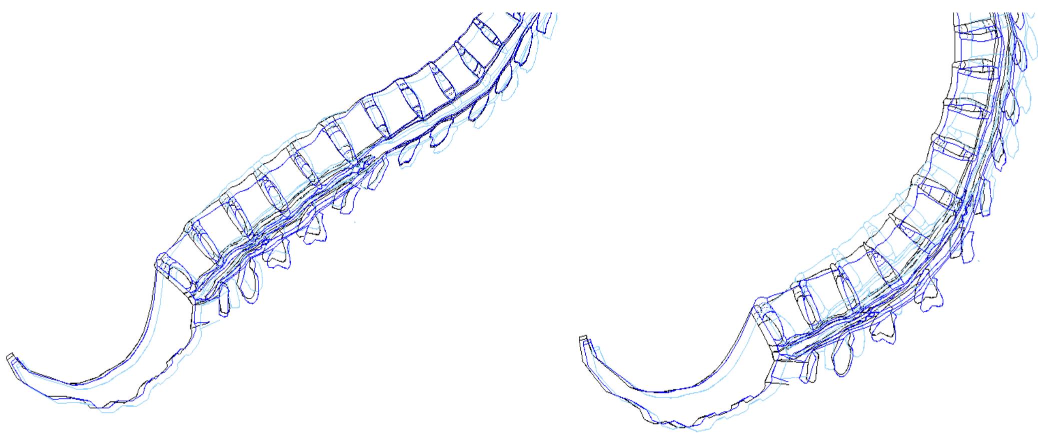

Figure 7: Spinal position at 50ms after the onset of the pulse left and 100ms after the onset of the pulse, right. Black is the original MRI based position, dark blue is the more lordotic initial position and light blue is the more kyphotic initial position.

Kinematics

The kinematics of the lumbar spine remain relatively consistent between the MRI-based and the more lordotic positions, but the kinematics of the more kyphotic position does not follow the same chain. The locations of the pelvis in each position are also quite divergent, and the position of the thoracic spine also shows a large disparity between the positions especially for the more kyphotic position. All of these differences can be seen in Figure 7. Head kinematics appear to be relatively stable between positions, as seen in Figure 9.

DISCUSSION

Positioning

During the initial positioning using the Upright MRI and Faro arm data, a discrepancy between the model lumbar spine and the lumbar spine which was used to generate the MRI data was observed. It would have been impossible to position the model into alignment with all aspects seen from the MRI: either the positions of the vertebral bodies could be aligned by changing the pelvis rotation, or the observed disk angles could be made the same with the pelvis rotation being kept in the initial state. This is because the subject of the MRI has a different spinal geometry than that which is found in the THUMS HBM. The second approach was the one which was chosen: the pelvis was held fixed and the relative vertebral body angles were used as targets. In the MRI scan, the position was achieved using rigid foam blocks which were very dissimilar to the actual prototype seat. The Faro arm data on the other hand was taken using the prototype seat itself. Due to this it was decided that the pelvic angle should be used from the data were there was a higher confidence in its accuracy in the context of a real world setting. The MRI data was then incorporated in the form of the disk relative angles, starting from the sacrum. Another challenge associated with this position is that the MRI images, and what was measured in the ergonomics lab were two different subjects, whose spines are presumably different. But there is no way to know how different, as the MRI data was gathered as part of a different and separate study by the Ludwig-Maximilians-University in Munich. The study used a seating geometry designed to mimic a reclined position, but this geometry was different than the protype seat currently being studied, which means there are differences in the positioning. Any differences in positioning are also only part of the difference: differences in material properties, and age can also play a role, one which cannot be easily investigated with the present tools and methods.

The spinal rotation is achieved using the Piper positioning tool [6], using kinematic rotation centers defined at the disk center. The Piper approach is used because it allows for changes in the disk shape without causing any bulging that might result from a simulation based positioning process. Another added benefit of the Piper framework is that because the postural changes were localized, the soft tissue changes were also only seen the lumbar region, making the subsequent simulation more stable. The positioning resulted two separate initial postures, each chosen to be on either side of the baseline position. For the lordosis case the lumbar lordosis angle as measured from the top of L1 to the bottom of L5 as defined by Sato [7] was increased by 10°. The Pelvic angle as measured from the vertical to the line between the ASIS and the pubic symphysis [8] was decreased by 1.5°. Both of these changes fall within the range of normal physiological variation according to studies performed by Izumiyama [9], although the authors note that subjects fell into groups of spinal posture and so it can be assumed that the transfer from one posture to the other is likely not physiologically feasible. The kyphotic position saw a change in the lumbar lordosis of -15°, which is a large amount of variation, but yields a position, which is close to the mean values reported by Izumiyama [9]. The pelvic angle for the more kyphotic posture is almost the same as that of the lordodic posture: and both are lower than the pelvic angle of the baseline. This is likely an artifact of the positioning process, where artificial forces are applied to move the spine which resists with an artificial stiffness. It is likely that the kyphotic spine generated enough force to overcompensate the motion of the pelvis, pulling it the opposite way of what was prescribed.

Force Response

It was noted that the in HBM H350-like position, the forces are less than 60% of the peak force seen in the hardware tests. This is in part due to the positioning used to bring the HBM to match some of the H350 landmarks, does not match the reality of how an occupant would sit in the reclined seat. With the head lifted off of the headrest less axial forces are generated in the spine from the inertia of the head moving forward. This difference of position accounts for less than 10% of the difference in the peak force: the MRI based force response as seen in Figure 4 has a higher peak force than the H350-like position, but is still substantially lower to the forces seen in the dummies. Comparing forces measured in the dummies to forces measured in the HBM should also be done cautiously. The models have different geometries, so forces cannot be measured at exactly the same locations across models. These differences in geometry, as well as the use of materials with different stiffness moduli across models, also has an effect on the magnitude of these forces.

Comparing the forces across postures for the same HBM, as seen in Figure 6, the maximum force occurs when the pelvis is fully coupled with the seat. All configurations are seen to have a similar response for forces measured in the

T12 and L5 vertebrae. The kyphotic configuration for the force measured in the L2 vertebra shows a different response than the others with a faster ramp up to peak force, a higher peak force overall, and a double peaked curve behavior. The kinematics in the thoracic spine, as seen by comparing Figures 5 & 7, no longer have any overlap, which holds for all positions. The initial differences in pelvic position propagate, and causes similar changes in displacement and rotation then goes up the kinematic chain into the lumbar spine and the thoracic spine. Head position remains fairly consistent, as seen in Figure 9, likely due to inertial effects and the low relative stiffness in the cervical spine.

It can be seen for all of the various levels in Figure 6, that the peak force is influenced by the initial posture. At the L2, which experienced the largest influence due to the positions; the more lordotic posture had an 8% smaller peak force as compared to the MRI positioned posture, and the more kyphotic posture had a 9% larger peak force. Also at the L2 level, but not for the other levels plotted, the loading curve is significantly different for the more kyphotic posture: it experiences a double peak. The MRI position and more lordotic position both also have a small quasi peak at the same time, but they are more of a slight plateauing than a fully defined peak. At the time of the first peak the pelvis experiences maximum forward excursion before it begins to rotate. The more kyphotic posture experiences a larger force at this point because it has almost no curvature and can therefore maintain its position without deforming. The MRI position and the more lordotic position both have some curvature at this time, so they deform more easily, which doesn't allow the force peak to develop. Given this spread in forces, it is conceivable that there is a posture which exhibits the highest force for a given seating configuration. If future injury criteria are based on the force transmitted, then this posture should be the one which is always evaluated.

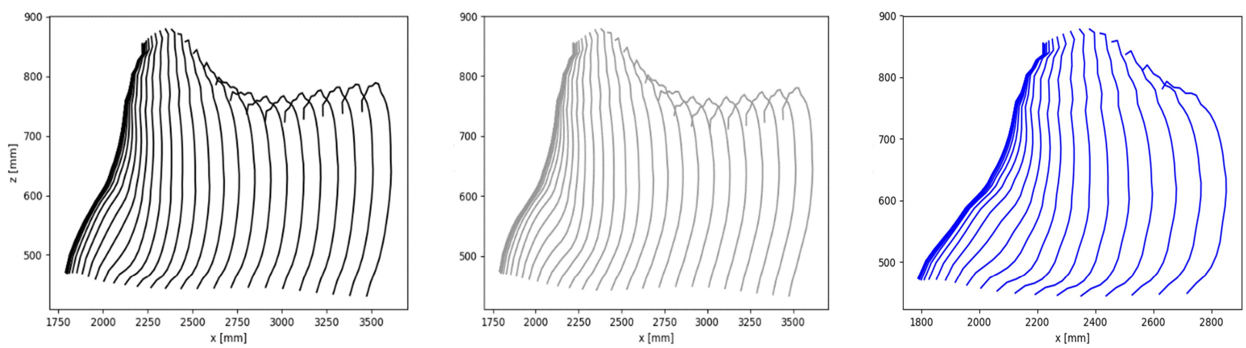

Figure 7: Global spinal kinematic time histories, black is the MRI position, grey is the more lordotic position, and blue is the more kyphotic position.

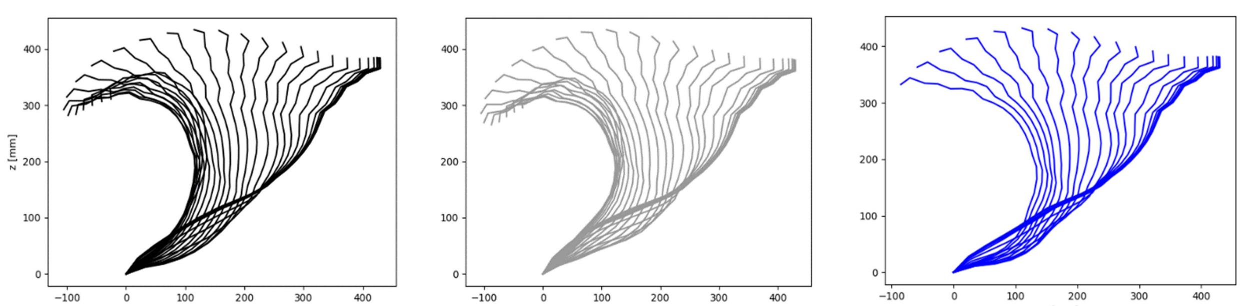

Figure 8: Relative spinal kinematics with the view fixed about the sacrum, black is MRI position, grey is the more lordotic position and blue is the more kyphotic position.

Kinematics

During the loading phase initial posture effects can be seen in the kinematic development of spinal motion. The MRI based position shows an initial instability during the early phase of the crash where the spine goes quickly into flexion around the L3 level. This can be seen in Figure 7, where the black plot can be seen to develop a curvature in the lower left corner. The lordodic initial position on the other hand, shown in grey in Figure 7, exhibits no such instabilities. In Figure 8 this can be seen in the location of inflection in the lower right of the respective subfigures: for the lordotic case the inflection is milder and occurs higher up the spine than is the case for the baseline. This instability immunity is because the lordotic case has more room to deform before it reaches the bifurcation point. One might think of this as a pendulum, where the MRI case is closer to the middle of the pendulum, and ends of crossing to the other side, and the lordosis case is further from the middle, and so never reaches the other side.

The more kyphotic case shows a different response. Towards the bottom of the blue subplot in Figure 8 one can see that the curves run almost horizontally. This leads eventually to an inflection point which is further left than the MRI position shown in black. This tighter, further forward inflection might be due to straighter spinal alignment, which is also seen in the higher force response and steeper ramp up that the kyphotic variant has in the L2 plot in Figure 6.

Also of note is that this local instability has very little effect on the global behavior. This can be seen in the overlay plot in Figure 9: all three models are visible, meaning there is some difference, but the composite result still looks like a coherent model, showing the differences to be small. This means that the head and other global kinematics are insulated from lumbar spine effects. One cannot speculate if this will hold for more pronounced lumbar spine positions, and this should be further investigated.

What can also be seen in Figure 9 is the differences realized between a traditional dummy and the HBM in the reclined seating position. The dummy sits much more upright at the point of maximum excursion as its spine does not allow for bending in the thoracolumbar region. This can be clearly seen in the dummy's very straight back as seen in the figure. Also related to the HBM's more flexible spine changes in the lateral position of the HBM, but not in the dummy. Being less flexible means that the dummy torso bends forward as a complete unit, whereas the HBM wraps around the belt causing a difference between the left and right sides of its torso.

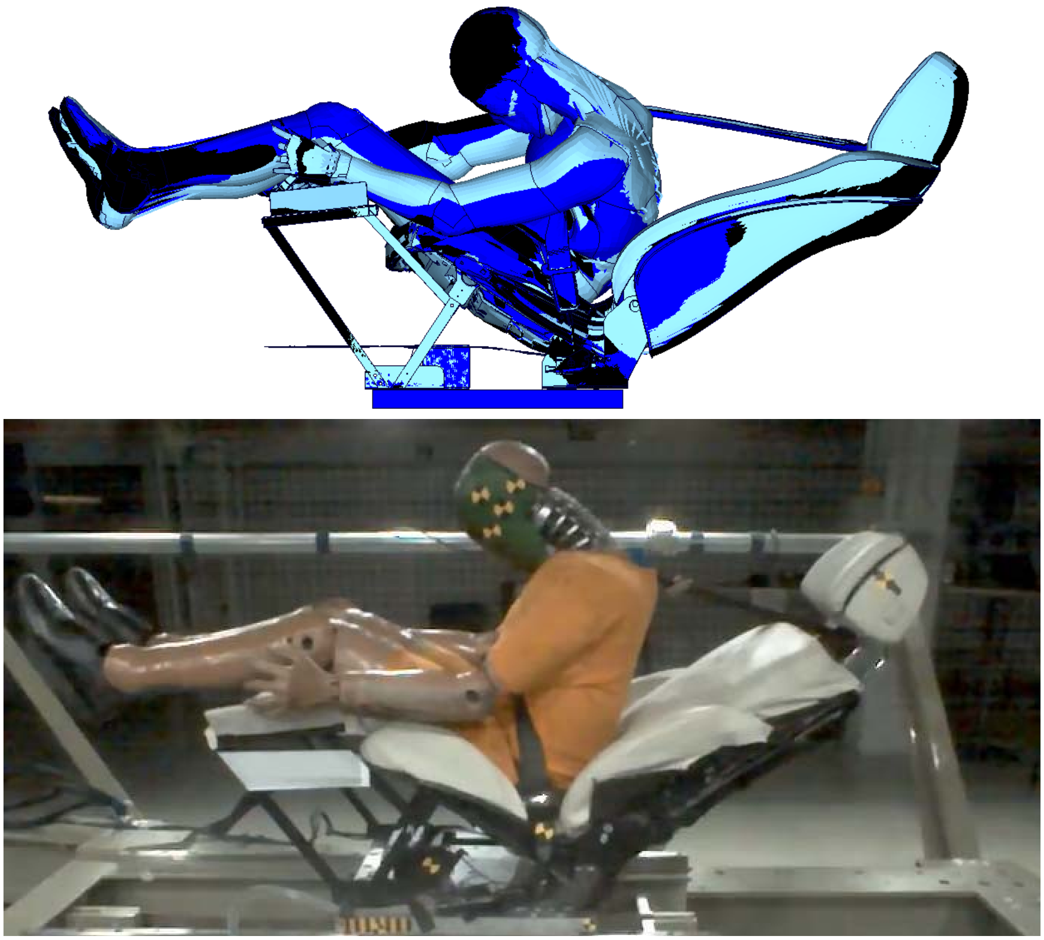

Figure 9: Comparison of global kinematics 100ms after the onset of the pulse. In the upper image are the FE simulations, with the MRI positioned model in black, the more lordotic model in dark blue and the more kyphotic model in light blue. In the lower image is the hardware test of a H350 dummy at 100ms after the onset of the pulse from [4].

Validity

These various results beg the question, what happens in actual humans who have varying spinal geometries? This is a difficult question to answer. The validity of human body models have been improving, but there are still large gaps of validity. One such gap has to do with the spine. As of now, no published studies exist with which to explicitly validate human body models in a reclined seating configuration, with respect to their spines. The spine is difficult to validate as tracking it is difficult. It is also difficult to measure the forces transmitted through the spine. In this simulation series the disks were compressed beyond the physiological levels observed in non-injurious tests [10], but there is a lack of data to say where the level of injury starts. The human body models themselves are also not validated in these regions and in these modes of excitement. Even with newly defined allowable safe levels of force, experiments are still needed to see if what the models predict matches the reality fot actual occupants. This study also shows that posture has an influence in HBM simulations, but the actual range of postures in a reclined seating concepts is currently unknown, and there is no best practice for measuring the spinal position to the accuracy needed to validate HBM simulations. There is a similar story for any sort of safety criteria. More research is required from governing bodies and original equipment manufacturers in order to define and harmonize safety standards.

CONCLUSIONS

The kinematic response of the Human Body Model simulation is very different to the response of the dummies in the reclined position. The HBM kinematic looks more realistic than the crash test dummies, as can be seen in how its spinal curvature develops in the HBM, as opposed to the permanently straight-backed dummy. However, there is no way to objectively evaluate how realistic current HBMs are in this kind of positions. The HBMs also experienced notably smaller forces in the lumbar than the dummies, of which only a small part can be attributed to difference in position. By making small changes to the initial spinal posture of an HBM sitting in a reclined seating configuration, changes of up to 9% were observed in the subsequent spinal kinematics and peak force response. As these changes were small, it is possible that larger changes will have larger effects. These postural changes have no analog in dummy testing, due to how dummies are constructed, and as such can only be investigated using HBMs.

Further work

The next steps to be undertaken should involve looking into larger changes in posture, as larger changes could result in still further divergent kinematics as to what has already been observed. Another area of exploration would be to investigate if one posture or group of postures experiences higher forces, or divergent kinematics, which might require special attention, i.e. the definition of a worst case scenario posture. As changes in posture were shown to have effects on kinematics and force response, validation experiments in the future should also consider and, if at all possible, measure and document initial spinal posture. In order to establish how accurate the HBM models are, more validation experiments are needed. The overall validity of HBMs in reclined positions should also be more closely investigated, which would require that more experiments designed to improve HBM validity in these new seating positions.

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