QUANTITATIVE EVALUATION OF HUMAN BODY MODEL GRAVITY SETTLING

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ABSTRACT

The simulated action of coupling a computational human body model to a vehicle seat, commonly referred to as model settling, is an essential, initial aspect of any crash simulation. There is a gap in knowledge related to the necessary duration of this activity to sufficiently couple the human model to the seat. In this study, THUMS v4.1 was gravity-settled in two postures, an upright driver and a reclined occupant, into a seat model. Simulations were performed using three seat foam stiffnesses, three friction coefficients and both with and without a constraint on the motion of the pelvis for a total of 18 simulations per posture. Each simulation was run for 800 ms, a time determined to be sufficiently long to identify a settled end state. In separate simulations, a 0.5g magnitude, 200 ms half sine wave pulse was applied to the seat in the backwards direction to measure coupling between the human body model (HBM) to the seat.

Model quality metrics were measured at the first four kinetic energy local maximums and local minimums to compare physically consistent time points between simulations. Kinetic energy, contact penetrations, change in HBM element quality, seated contact area and seat pressure were measured and compared to this settled end state. A pass/fail range was assigned to each metric. A pass was assigned if the value fell within ±1 standard deviation of the average simulated end state value at 800 ms (contact area, seat pressure) or between the simulated end state value and the baseline THUMS value (contact penetrations, model quality, perturbation test). A passing time point for a simulation received a score of 1, a failing time point for a simulation received a score of 0. Scores for all simulations were added and normalized for each local maximum and local minimum, and the first time point to receive a score greater than 3 (out of 5) and pass the perturbation test was determined to be sufficiently settled.

The third kinetic energy local minimum was selected for the upright driver posture and third local maximum for the reclined occupant. Both have average gravity settling times of approximately 405 ms. The pelvis constraint appeared to contribute to a more rapid arrival at the long term settled state for the upright seated posture. Constraining the pelvis is not recommended for the reclined posture. The results suggested that for best practice a settling time of at least 400 ms is required to sufficiently couple the model to the seat in either posture.

INTRODUCTION

Finite element (FE) human body models (HBMs) are detailed models which may be used in the investigation of injury risk and vehicle safety. HBMs such as the Total Human Model for Safety (THUMS) and the Global Human Body Models Consortium (GHBMC)models have been used for pedestrian injury assessment [1] and occupant injury risk evaluation [2, 3]. Simulations of injury are highly complex, and the positioning of the HBM into a vehicle model may affect repeatability and accuracy of the resulting injury predictions [4, 5]. Typical vehicle crash simulation workflow involves a repositioning phase and a gravity settling phase before the crash simulation. Previous work has shown that optimal simulation time for repositioning is 100 ms followed by 30 ms of holding time [6]. This recommendation is consistent across a variety of postures and optimizes for simulation run time and element quality.

While model positioning can be achieved through numerous methods and crash simulation inputs are typically well defined, little attention has been paid to gravity settling. The interaction between the HBM and the seat is critically important as the degree of coupling between the HBM and the seat can influence model kinematics. A HBM that is too tightly coupled or insufficiently coupled to a seat will have unrealistic excursion in a simulated vehicle crash.

No industry standard exists for gravity settling prior to vehicle crash simulations. Gravity settling times between 100 ms and 1 s have been cited [7, 8], but gravity settling time is commonly not explicitly stated in publications. Longer gravity settling simulation time results in longer computation time and higher computation and storage costs. The goal of this design of experiments HBM gravity settling study is to determine best practices to gravity settle seated HBMs in the upright driver and reclined occupant postures.

METHODS

Models Used

The FE models used in the gravity settling simulations were one of the National Crash Analysis Center (NCAC) full-scale vehicle models [9], slightly modified to increase simulation speed, and the Total Human Model for Safety (THUMS AM50) v4.1 50th percentile male HBM [10]. The THUMS model was positioned into two postures using best practices that optimized mesh quality and simulation time per methods in Costa et al. 2020 [6]. An upright driver posture (**Figure 1A**), [11] and a 53° seatback angle reclined occupant posture [12] (**Figure 1B**) were used. . In the upright driver posture, seat position and seat angle were matched to values used in Reed, et al. 2002 [11]. In the reclined occupant posture, the seat back angle was based off of the position used in Reed et al., 2019 [12], with the seat positioned to avoid intersections with the THUMS foot and the front vehicle wall.

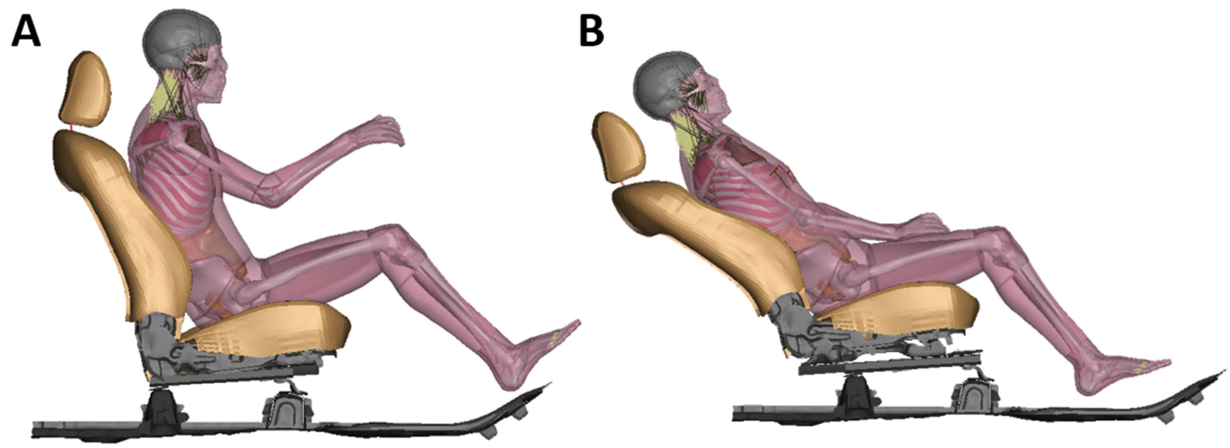

Figure 1: Upright driver posture (A) and reclined occupant posture (B). The THUMS model was positioned in a 130 ms simulation, with 100 ms of repositioning time and 30 ms of holding time.

Simulations

To quantify settling over a range of potential vehicle inputs, 18 test cases were simulated for each posture: 3 seat friction coefficients * 3 seat stiffnesses * 2 constraint definitions for pelvis motion. Three values of friction coefficient that span a large range of potential seat and clothing material combinations were used: 0.2, 0.5 and 0.8 [13-15]. Three seat stiffness multipliers were used: 0.1, 1.0 and 10.0. These were used to scale the y-axis of the load curve for the seat foam material model, and spanned a wide range to account for a variety of seat foam materials available [16].

Simulations were conducted with and without a constraint on pelvis motion. Simulations without constraint moved only under the load of gravity. Simulations with constraint used single point constraints on each pelvis node to limite the pelvis to move only along the vector of the initial THUMS to the target NCAC vehicle H-Point. The NCAC vehicle H-point was determined from a matching New Car Assessment Program (NCAP) oblique offset crash test (National Highway Traffic Safety Administration, NHTSA No: RB5137).

Additional Constraints

For each simulation, several constraints were applied to make the model settle in a physically realistic manner. In both postures, the head was constrained to prevent rotation about the C7/T1 joint Y-axis. This maintained neck posture, preventing the head from slouching forward. In the upright driver posture, the hands were positioned to their final position on the steering wheel, and were point constrained during settling. In the reclined occupant posture, the hands were positioned to touch the upper thigh. This was the desired posture, but to avoid undesired arm and shoulder kinematics the hands were allowed to move along the sagittal plane (e.g. along the thigh length), but motion was constrained normal to the plane. This allowed for natural arm movement during gravity settling, but prevented the hands from falling down the side of the leg.

Simulation Matrix

With the combination of three friction coefficients, three stiffness multipliers and two pelvis constraints, a total of 36 simulations were run (18 simulations for each posture). Each simulation was run for 800 ms of simulation time, a time determined in preliminary simulations to be sufficient to reduce kinetic energy of the HBM to near zero. All simulations were run on equivalent hardware on a high-performance computing cluster using LS-Dyna (v.11.0, ANSYS, Canonsburg, PA).

Data Extraction

Kinetic energy of the HBM, and the contact penetrations, contact area, seat pressure and perturbation displacement were extracted using LS-PrePost v4.8.18 (ANSYS, Canonsburg, PA). Distortion index, a measure of HBM element quality, was measured using ANSA (ANSYS, Canonsburg, PA) and Matlab (Mathworks, Natick, MA).

Kinetic Energy Features

Kinetic energy was measured in the THUMS HBM parts only, with total kinetic energy reported. To maintain consistency across the physical features of settling, the first four local maximums and local minimums of the kinetic energy traces were extracted (**Figure 3**). These were used to measure the other model features at times that were kinetically consistent, but may not be consistent in simulation time.

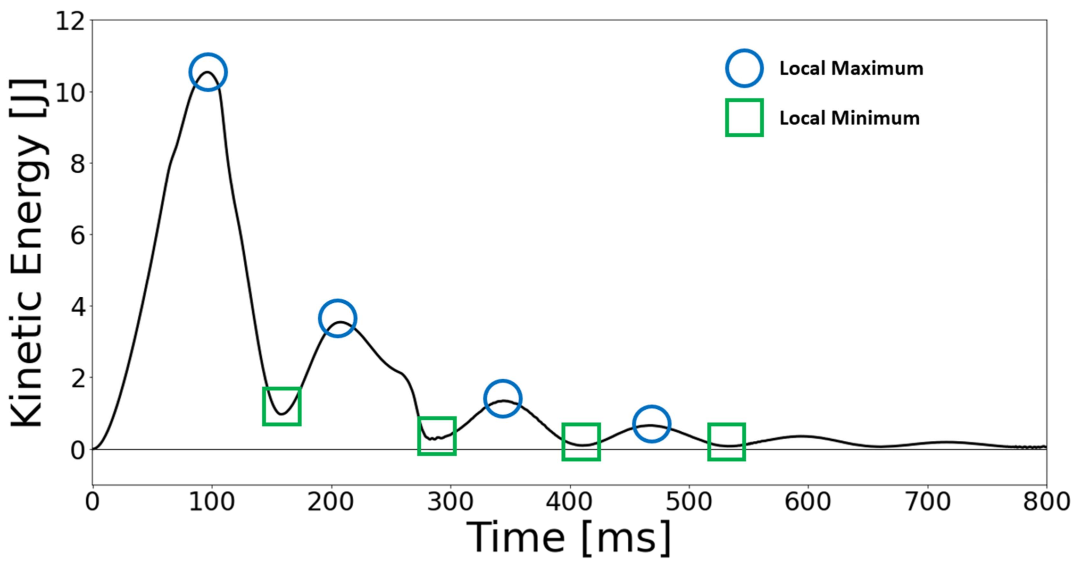

Figure 2: Kinetic energy (KE) features are the first four local maximums and local minimums. Example kinetic energy plot from an upright driver simulation.

Contact Penetrations

Contact penetrations were measured at each kinetic energy feature for each contact defined in the THUMS HBM (skin, right leg, left leg, organs, right arm, left arm, head, pia sagittal-falx and body). A cutoff threshold of 0.0376 mm (1% of average element length) was applied to exclude small penetrations that do not significantly contribute to model quality. The mean contact penetration length and the 95th percentile contact penetration length were measured.

Contact Area

The HBM-to-seat contact area was measured using the nodal force outputs from the seat contact. Each seat shell element that had two or more of its nodes with a force greater than zero was considered to be in contact with the seat model. Elements with all four nodes with non-zero force were fully in contact, elements with only two or three nodes with non-zero force were counted as partially in contact. The full area of each full contact element was measured and half the area of each partially contacted element was measured.

Seat Pressure

Seat pressure induced by the HBM was measured from simulation d3plot data in LS-PrePost. A subset of elements from the seat pan and seat back that fully encompassed the extent of the contact area of the seat were selected. The average pressure of the elements in this region was measured.

Distortion Index

A HBM quality metric called the distortion index was used to measure how model quality changed over time. This metric was explained in detailed in Costa et al., 2021 [6] and is explained briefly here. The distortion index quantifies the whole model element quality by assigning a score for each element and summing over all elements to give a score for the HBM. The score for each element is based on the value of several measurements of element quality (such as skew or Jacobian) and their difference from the element's ideal value. A value of 0 is given for a perfect element, and 1 is given for exceeding specified criteria for each measure of element quality. The average score of each element's quality metric scores are summed over the whole model to give a total score. This score can then be used to quantify changes in element quality, with higher numbers having poorer element quality.

Perturbation Test

An additional subset of simulations were run to measure the coupling between the HBM and the seat. The simulation was a perturbation test of the settled model at the eight kinetic energy features as well as at the simulation end time, 800 ms. The model was allowed to settle to its specified time, after which an acceleration pulse was applied to the seat in the positive X-direction (**Figure 6**). The pulse was a 200 ms half sine wave with a 0.5g magnitude, similar to perturbation pulses used in human subject experiments [17-19]. Relative displacement of the THUMS H-Point to a node on the rear of the seat was measured. Zero relative displacement would indicate that the HBM was fully coupled to the seat, while 65 mm of relative displacement (acceleration pulse twice integrated) would indicate no coupling between the HBM and the seat. The perturbation test was run for each kinetic energy feature (four KE local maximums and four KE local minimums) and the simulation end state (800 ms) in all three seat stiffness values (0.1x, 1.0x and 10.0x) and one seat friction coefficient (0.5) for each posture.

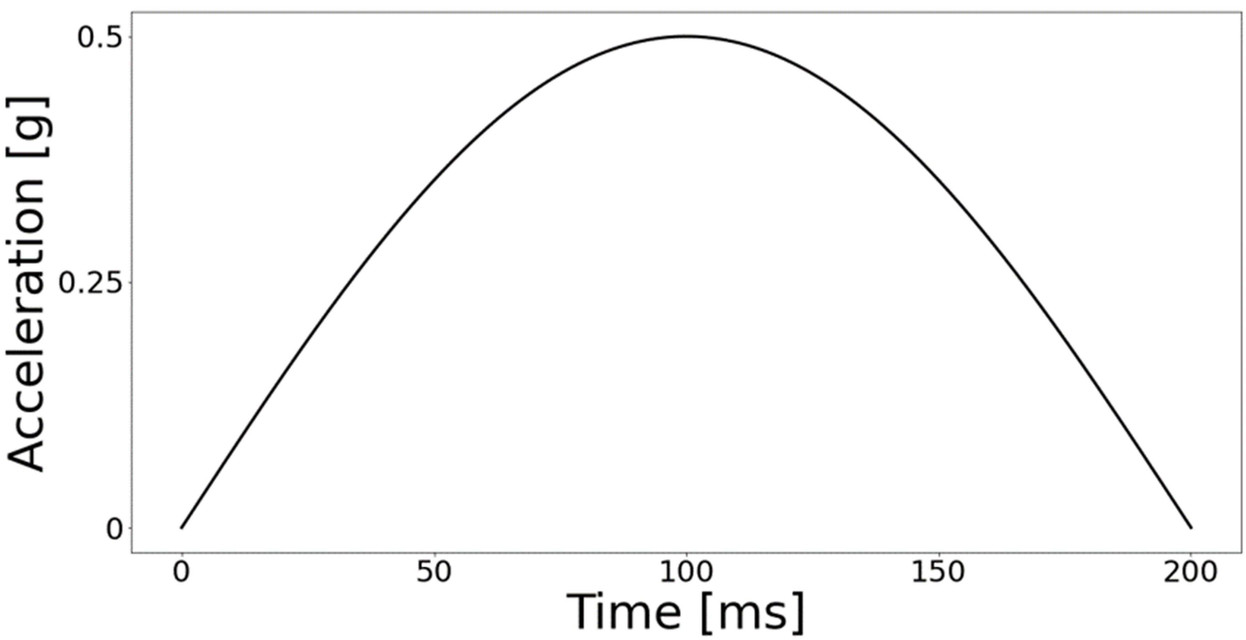

Figure 3: The pulse applied in the perturbation test, where acceleration is applied to the seat in the negative X-direction after gravity settling.

Scoring and Target Criteria

To determine whether the pelvis should be constrained or unconstrained, the time for kinetic energy to be consistently below 10% of the peak kinetic energy was measured. The constraint (with or without pelvis constraint) with the lower average time to be consistently below 10% peak kinetic energy for each posture was determined to reach equilibrium faster, and therefore reach an end state faster. Only the constraint with the lower time to be consistently below 10% peak kinetic energy was used in further analysis.

To identify the ideal settling time, by way of kinetic energy feature, each of the above values (distortion index, contact penetrations, perturbation test, contact area and seat pressure) were assigned a score of 1 or 0 based on their proximity to the average end of simulation value (average value at 800 ms simulation time). Each metric was scored at each kinetic energy feature for the 9 simulations (3 seat stiffnesses, 3 friction coefficients and 1 constraint for each posture) to identify the highest scoring time point.

For metrics independent of the seat (contact penetrations and distortion index), the score was based on whether the value fell within the range of the baseline THUMS value and the simulation end point value (800 ms settling time). A score of 1 was assigned if it fell within this range, a score of 0 was assigned if it fell outside of this range. For metrics dependent on the seat (contact area and seat pressure), the score was based on whether a value fell within ± 1 standard deviation of the average end of simulation value (**Figure 7**). For the perturbation test, a score of 1 was assigned if a value was less than or equal to the end time point (800 ms) perturbation test's relative hip displacement and a score of 0 was assigned if it was greater than the relative hip displacement.

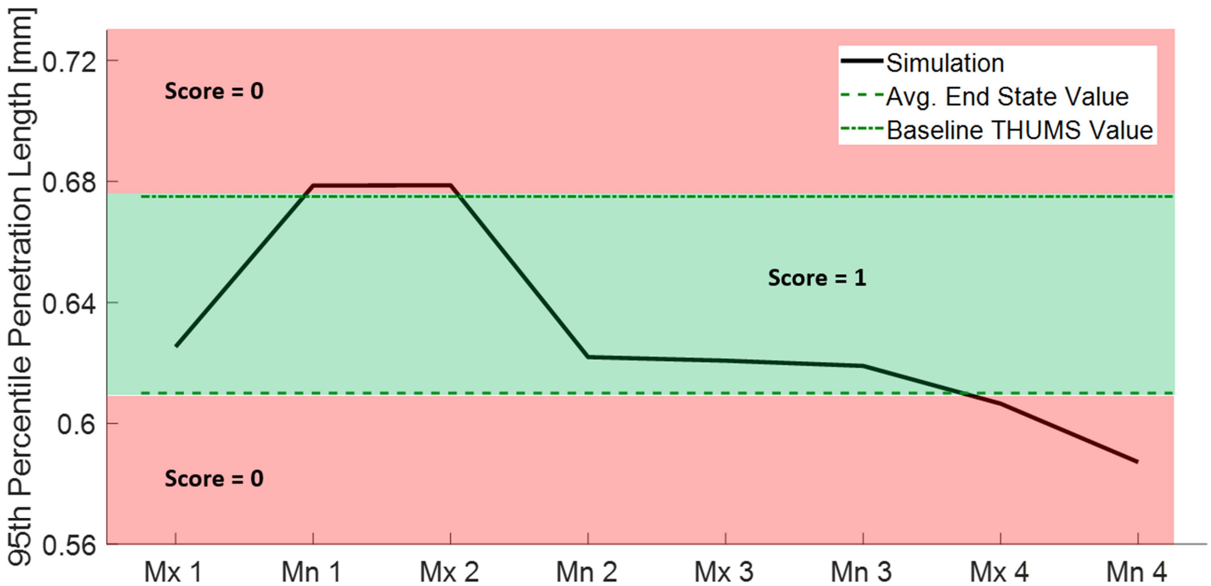

Figure 4: Example scoring of contact area for a single simulation. Local maximums 1 and 3 fall outside of ±1 standard deviation of the mean end state (800 ms) contact area and receive scores of zero. Local minimums 1, 2 and 4 and local maximum 4 fall within of ±1 standard deviation of the mean end state (800 ms) contact area and receive a score of 1. (Mx is local maximum and mn is local minimum).

For each metric and each time point, the total score was normalized by the number of simulations run for that metric. This was performed to weight all of the metrics equally. At each time point, the normalized score of each metric was summed to give a score for the kinetic energy feature.The ideal time point was the first time point that both scored in the perturbation test and had a total score greater than or equal to 3. This enabled selection of a settled model that best approximated a fully settled state at a shorter simulation time.

RESULTS

Upright Driver Posture

Pelvis Constraint

For the upright driver posture, the average time to be consistently below 10% of peak kinetic energy was 530 ms in the unconstrained pelvis simulations and 390 ms in the constrained pelvis simulations. The constrained pelvis simulations were selected for the upright driver posture analyses, as applying this constraint improved settling time.

Scoring

To avoid overweighting contact penetrations, the scores for mean penetration length and 95th penetration length were averaged to give a single score for contact penetrations called the penetration score. Individual normalized metric scores can be seen in **Figure 5**. For example, at the kinetic energy local maximum 1 (Mx1) no simulation was within ± 1 standard deviation of the average end state contact area, so it received a score of 0. At the kinetic energy local minimum 3 (Mn3), four of the nine simulations had contact areas within this range, giving a score of 4/9. The internal HBM metrics (distortion index and penetration score) are generally stable, having higher scores throughout all kinetic energy features. The external metrics (contact area, seat pressure and perturbation test) are more variable, but have a slight trend of increasing with more settling time.

Both kinetic energy local minimum 3 and local maximum 4 have a passing score ≥ 3, and also were consistently below 10% of the peak kinetic energy in the perturbation test. Thus, for the upright driver posture, local minimum 3 is recommended to achieve HBM-to-seat coupling that meets the target criteria for metrics of HBM mesh quality and HBM-to-seat interaction. This is a settling time of 402 ± 21 ms.

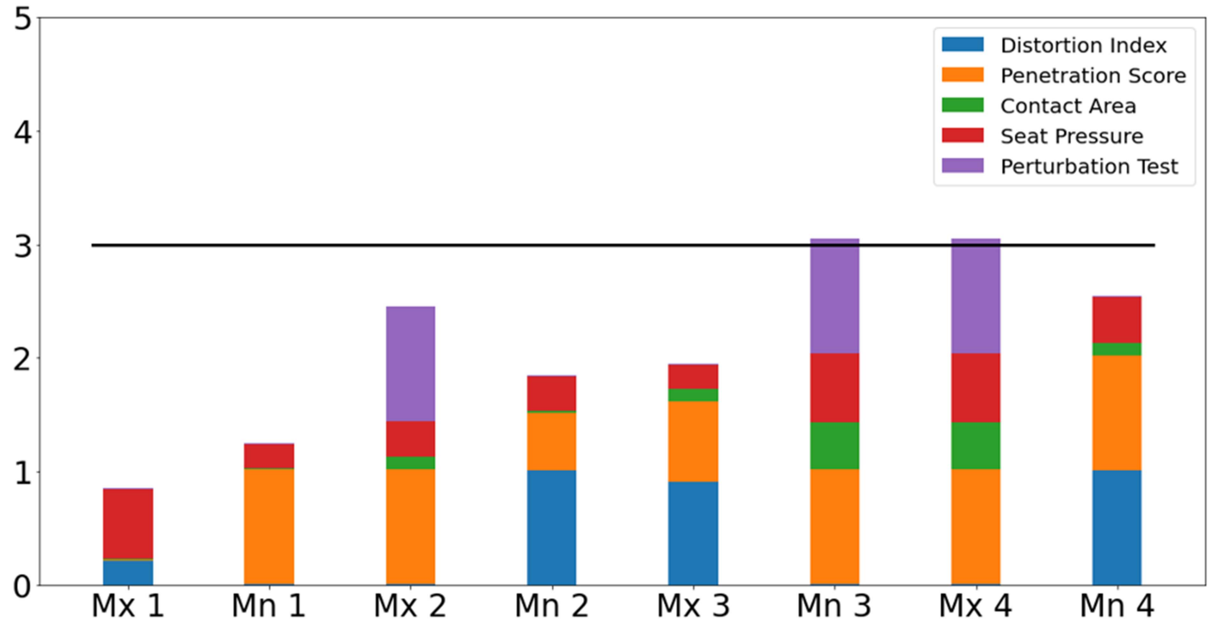

Figure 5: Normalized scores for each metric at each kinetic energy feature time point (max: Mx, min: Mn) for the upright driver posture simulations with pelvis constraint. Higher scores indicate better settling performance. Kinetic energy local minimum 3 (Mn3) is the first time point to meet the target criteria (≥3). Black line is a score of 3, passing.

Reclined Occupant Posture

Pelvis Constraint

For the reclined occupant posture, the average time to be consistently below 10% peak kinetic energy was 290 ms in the unconstrained simulations and 410 ms in the constrained pelvis simulations. The unconstrained pelvis simulations were selected for the reclined occupant posture analyses, as not applying a constraint improved settling time.

Scoring

As in the upright driver posture, mean penetration length and 95th percentile penetration length scores were averaged to give a penetration score. The normalized metric scores can be seen in **Figure 6** The internal HBM metrics are generally stable, having higher scores throughout all kinetic energy features. The external metrics are more variable, but have a slight trend of increasing with time. From kinetic energy local maximum 3 onward, the reclined occupant posture has a score of 3 or above, and kinetic energy local maximum 3 through kinetic energy local maximum 4 score were consistently below 10% of the peak kinetic energy in the perturbation test. Thus, for the reclined occupant posture, the third kinetic energy maximum is recommended to achieve HBM-to-seat coupling that meets the target criteria for metrics of HBM mesh quality and HBM-to-seat interaction. This is a settling time of 405 ± 67 ms.

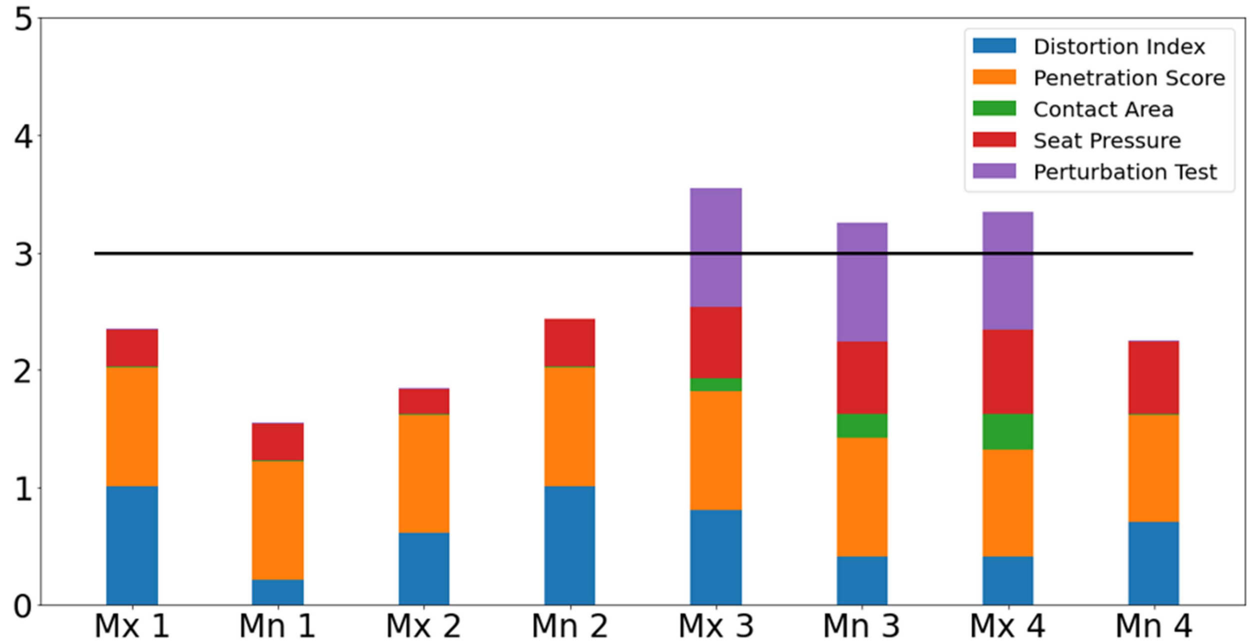

Figure 6: *Normalized scores for each metric at each kinetic energy feature time point (max: Mx, min: Mn) for the reclined occupant posture simulations without pelvis constraint. Higher scores indicate better settling performance. Kinetic energy local maximum 3 (Mx3) is the first time point to meet the target criteria (≥3).). Black line is a score of 3, passing.*

DISCUSSION

The goal of this work was to use model agnostic, repeatable methods to establish best practices for gravity settling HBMs. For the two postures examined, a gravity settling time of approximately 400 ms was sufficient to settle the model into the seat. This was determined by comparing earlier time points in a simulation to a later time point with negligible kinetic energy. This indicates that an earlier time point for gravity settling can save computational cost with little to no effect on model performance. By further comparing earlier time points to a later time point in a perturbation test, earlier time points can be tested for target suggest levels of HBM-to-seat coupling.

In the upright driver case, results indicate that using a constraint on the motion of the pelvis and gravity settling for roughly 400 ms yielded results similar to a much longer settling time. For the reclined occupant, using no pelvis constraint yielded improved results based on the metric presented, and gravity settling for roughly 400 ms was similar to a much longer settling time. Both of these were tested across a combination of seat parameters, and both postures had similar or superior model quality metrics than the simulation's final 800 ms state. These settling times also exhibited similar coupling to the seat as the simulation's final state.

Poor coupling of an HBM to a seat can yield unrealistic simulation results, so particular attention was paid to the perturbation test in this study. The pulse used was similar to pulses used in human subject observation in the literature [17, 18]. Requiring that the selected time points pass the perturbation test ensures that the time points are adequately coupled to the seat and saves computational cost. Relative to the simulated end point, the selected time points save an average of 21.5 hours (43 hours to 800 ms versus 21.5 hours to 405 ms) on the hardware used.

The differences in the recommendations for the pelvis constraint of each postures raises the question of what is the best practice in gravity settling. Without a large combination of postures, H-point targets, and seat models it would be difficult to test, however one explanation is that the precision of the H-point definition influences the outcome. The upright driver posture H-point was based on physical testing and therefore is well quantified. However in the reclined occupant posture the H-point target was not experimentally derived. The H-point target was based on the upright driver posture and adjusted for the seat pan movement. In this case, using the pelvis constraint was found to increase the settling time. It also resulted in different H-point trajectories than not using a pelvis constraint. While a true target H-point is unknown, it is likely that the final H-point in the unconstrained posture is more realistic. It was also determined that in the absence of a known target, it was best to let the physics of the simulation dictate the location of the H-point. These results suggest that the best practice in selecting pelvis constraints when settling is to use a constraint when the target H-point is well defined, and not use a constraint when a target H-point is not experimentally defined or measured.

Limitations

Several limitations exist in this work. One is that only two postures were examined, and that both were symmetric. These postures were selected for their broad applicability across a span of seat back ranges and broad use in driver and occupant seated postures. Another limitation of this work was the use of a single HBM and seat. The results of this study are specific to the THUMS AM50 and NCAC seat model, however the methods are model agnostic and can be repeated for other HBMs and seats. While only one seat was used, a wide range of seat stiffnesses and seat friction coefficients were used to represent a diverse range of seats.

CONCLUSIONS

In this study gravity settling simulations were performed to identify settling times with results similar to long duration gravity settling simulations. Gravity settling simulations using the THUMS HBM in an upright driver posture and a reclined occupant posture in a NCAC seat were run for 800 ms under combinations of seat stiffness (0.1x, 1x and 10x baseline stiffness) and friction coefficients (0.2, 0.5 and 0.8). The utility of constraints on the motion of the pelvis were also investigated. The simulations were investigated at 8 kinetically identical time points for metrics of model quality and coupling to the seat and evaluated against the baseline HBM and final end state of the settling simulation. Recommendations for pelvis constraint were made based on the time to reach 10% of the peak kinetic energy. In the upright driver posture the pelvis constraint reduced that time and we recommend using the constraint. In the reclined occupant posture the pelvis constraint reached 10% of the peak kinetic energy more slowly than without it, and it is not recommended. This is likely due to the H-point not being experimentally defined in the reclined occupant posture. Based on the scores of each posture, a gravity settling time of approximately 400 ms is recommended, as it was found to be optimal based on performance relative to the final end state and simulation time. Because a wide range of seat foam stiffnesses and seat friction coefficients were tested, gravity settling for 400 ms is likely sufficient for most postures.

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