Multi-Scale Validation of Multiple Human Body Model Functional Spinal Units

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A validation comparing five Human Body Model (HBM) lumbar spines is carried out across two load cases, with the objective to use and apply HBMs in high strain rate applications such as car occupant simulation. The first load case consists of an individual intervertebral disk (IVD) loaded in compression at a strain rate of 1/s by a material testing machine. The second load case is a lumbar functional spine unit (FSU) loaded in compression using a drop tower setup, producing an strain rates of up to 48/s. The IVD simulations were found to have a better agreement with the experiments than the FSU simulations, and the ranking of which HBMs matched best to the experiment differed by load case. These observations suggest the need for more hierarchical validations of the lumbar spine for increasing the utility of HBMs in high strain rate loading scenarios.

1 Introduction

The use of Human Body Models (HBMs) to evaluate performance of advanced safety systems is increasing due to their omnidirectional usability, which is an advantage they have over traditional crash-test dummies [1]. The use of HBMs can be especially useful for investigating loading of the human body in new alternative seating positions associated with automated driving during the event of a crash as traditional crash test dummies have an associated loading direction which may not capture important behaviour in these new seating configurations [2] [3]. One body region of interest for alternative seating positions which needs to be investigated is the lumbar spine, as some new seating positions have been shown to generate higher lumbar loading than traditional seating positions in frontal car impacts [4].

HBMs must first be validated with respect to these new load scenarios before they can be used to make meaningful evaluations [5]. The most common way to achieve this is to compare their responses against experimental data from the literature. This approach can be greatly improved upon by having the modellers, who are doing the validation simulations, work closely with the experimentalists, who perform the reference experiments in order to ensure that the reference experiments are being modelled correctly in the numer-

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ical environment [6]. Additionally, the modellers can investigate aspects of the physical experiments before they are performed to help make recommendations on the development of enhanced validation studies of numerical models [7].

In this paper, model performance and experimental results were analysed at two different levels of engaged structures of the spine. This is a hierarchical approach adopted by many authors [8] [9] [10]. First the responses under compression of Intervertebral Disks (IVDs) of several full-scale human body models for crash simulation were compared with the results of validation experiments. This represents the assessment of model validity in the classical sense with a sufficient number of IVD specimens tested to create experimental response corridors.

The next step was to use the results of an existing experiment of a single Functional Spine Unit (FSU) as a test validation case for higher strain rates and more biomechanical complexity, again with the same HBMs as in the first step. The simulation was then used to investigate which experimental parameters could be simplified and / or modified for future experiments such that they would be the best compromise between experimental efforts and HBM validation needs.

2 Methods

This study looks at the response of the lumbar spines of five Human Body Models in two loading environments, the first, is a simple axial compression experiment on individual IVDs, and the second a more complex impact of intact FSUs. The HBMs can be seen in Figure 1, and a more detailed description of their differences can be seen in Table 1.

2.1 Validation of the Intervertebral Disc models

First, the IVDs of 5 commercially available human body models were compared with the reference experiments performed by Newell et al. [11] conducted under moderate strain rate and resulting in no injury.

In the reference experiment IVDs were obtain at the L1-L2, L2-L3, and L3-L4 levels. The samples included the vertebral bodies which had been cut through their mid-section with the posterior elements removed. The samples were positioned within pots such that the disc was horizontal, and then held in place with fixation screws before PMMA was poured into the pot to permanently hold the sample in place. The potted samples were then loaded at a constant velocity to a predetermined final strain of 15% using a materials testing machine, ensuring a consistent loading profile. The velocity of interest for the numerical modelling was the fastest velocity tested, corresponding to a strain-rate of 1/s, as this is the closest strain rate to what would be expected in an automotive safety application. In the reference experiment, force was measured using a sensor attached to the crosshead of the materials testing machine. The vertical deformation of the sample was measured using linear variable displacement transducers (LVDTs).

The IVDs were isolated from the full-scale HBMs in the same manner that the physical specimens were excised from the donors. Care was taken to position each HBM IVD according to how the physical IVDs were positioned for the experiments. The experimental displacements as measured from the LVDTs were used as input boundary conditions for the simulations. The output force quantities were measured in the simulation at the same location as the force sensors for the experiments.

Force-displacement corridors were constructed from the experiments by finding the mean and standard deviation force-displacement response across all specimens and vertebral levels, for the 1/s loading rate. The corridor is considered as the average curve plus/minus one standard deviation.

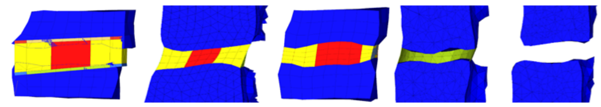

Fig. 1: The five human body models investigated. From left: THUMS 3, THUMS 4, THUMS 5, GHBM, VIVA. The vertebral bodies are shown in blue, the nucleus pulposus is highlighted in red, and the anulus fibrosus is colored in yellow.

Table 1: Table describing the various selected modelling conventions used in the HBMs under investigation

Model	THUMS 3 (TUC)	THUMS 4	THUMS 5	GHMBC	Viva
Nucleus	Linear Elastic	Elastic Plastic	Hyper-elastic	6DOF Curves	6DOF Curves
Annulus Matrix	Linear Elastic	Visco-elastic	Visco-elastic		
Annulus Fibers	Linear Elastic	Linear Elastic	Nonlinear Elastic	Linear Elastic	
Disk Height [mm]	8.7-10.5	5.6-9.8	5.3-8.2	7.3	NA
Mean Disk area [mm]	1110.46	1098.07	1161.5	1161.92	NA
Mean Nucleus Area [mm]	203.3	217.83	414.84	NA	NA

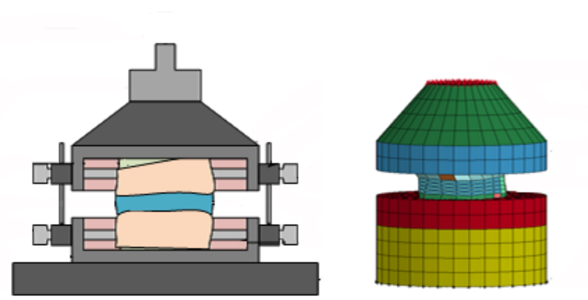

Fig. 2: Diagram of the IVD reference experiment (Left) and the numerical validation of the reference experiment (Right)

For the HBM simulations the corridors are constructed using the same methodology, but separated such that each HBM has its own corridor. The HBM corridors are then compared with one another and with the experimental corridor . How well each HBM fits into each corridor was then evaluated using a CORA analysis [12], comparing the mean curve of the HBM corridor to the entire experimental corridor. A figure comparing the experimental setup to the HBM simulation can be seen in Figure 2.

2.2 Investigation of a Functional Spine Unit

The next step in the study was to look at the response of intact lumbar FSUs; these consist of two intact vertebral bodies with the IVD between them, and the posterior elements and connecting ligaments left intact. This investigation was a finite-element comparison of the original experiments performed by Christou et al [13].

For the FSU reference experiments two FSUs were harvested from the same donor, one at the L2-L3 level and one at the L4-L5 level. The samples were then potted using both a PMMA matrix and fixation bolts. The loading was achieved using a drop tower setup, where a weight of 7kg was dropped onto the samples from increasing heights until failure occurred. After every drop, a control drop was performed from 5cm in order to check for failure/injury. A force transducer was used under the lower pot in order to measure forces and moments, and high speed videos were recorded of the sample under impact.

The HBMs were prepared to match the specimens from the physical experiments, by removing all muscle and ligament elements which were excised by Christou [13]. The HBM specimens were then positioned in order to match the location of the physical specimens as observed in the high speed video. Kinematic data were extracted from the high speed videos using FalCon eXtra version 9.22.0000 (Gräfelfing-Locham, Germany) and used as the given boundary conditions for the the FE models.

The forces were then measured at the same locations corresponding to the physical experiments and used as the output comparison quantities. Only the 5cm drop tests were considered, as they should have the closest strain rate and deformation to the previous IVD investigation. This also eliminates using data from any failure tests, as failure was not implemented in the FSUs of any of the HBMs investigated. A figure comparing the experimental setup to the numerical setup can be seen in Figure 3.

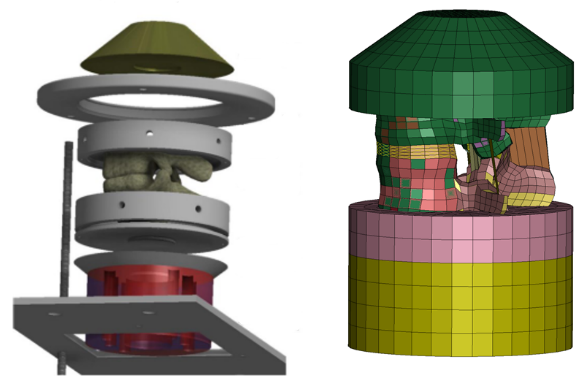

Fig. 3: Diagram of the functional spinal unit reference experiment from Christou [13] (Left) and the simulation of the reference experiment (Right)

3 Results

3.1 Results of the IVD Validation Study

Figure 4 shows the results of the IVD evaluation. The THUMS v3 and THUMS v5 show the most overlap to the experimental corridors. The THUMS v3 shows a response which cuts across the experimental mean values, while the THUMS v5 follows a similar trajectory at a higher force level than the experiments.

Table 2 shows the results of the CORA analysis of the HBMs, with C1 being the corridor score, V being the progression score, P being the phase score, G being the size score C2 the cross-correlation score, which is a weighted sum of V,P, and G, and C3 the total CORA score, which is a weighted sum of C1 and C2. A CORA rating of 1.0 signifies a perfect correlation, and a CORA rating of 0.0 means the curves are completely uncorrelated.

3.2 Results of the FSU Impact Investigations

When comparing the response for the various FSUs, corridors could not be constructed due to the small number of tests. But looking at the peak force value as well as the curve development, the THUMS v3 and GHBM have the closest response to the experiments. THUMS 3 has a peak 10% lower than the experiment, GHBM has a peak response 4% higher than the experiment, and all other models have a peak difference greater than 20%. The force-displacement response of the five HBM FSUs can be seen in Figure 5.

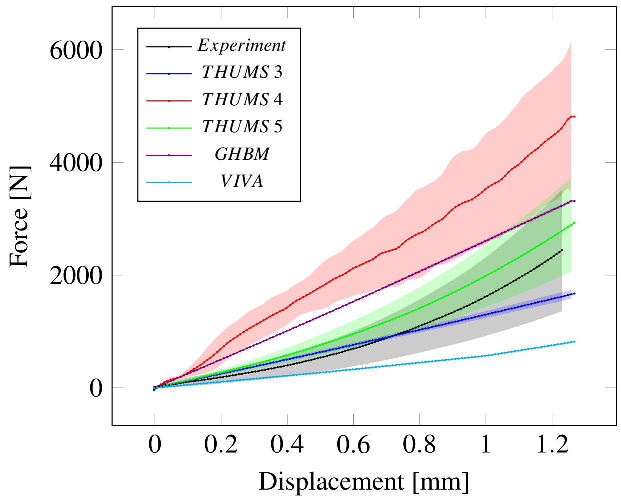

Fig. 4: Results comparing the IVD simulation results to the IVD reference experiment

Table 2: The results of the CORA analysis of the various simulations

	C1	C2	V	P	G	C3
THUMS 3	0.82	0.67	0.97	0.00	0.94	0.74
THUMS 4	0.01	0.49	0.97	0.00	0.33	0.25
THUMS 5	0.68	0.68	0.99	0.00	0.93	0.68
GHBM	0.06	0.53	0.97	0.00	0.47	0.29
ViVa	0.35	0.58	0.73	0.00	0.96	0.46

C1:Corridor Rating C2:Cross Correlation V: Progression P: Phase G: Size C3: CORA

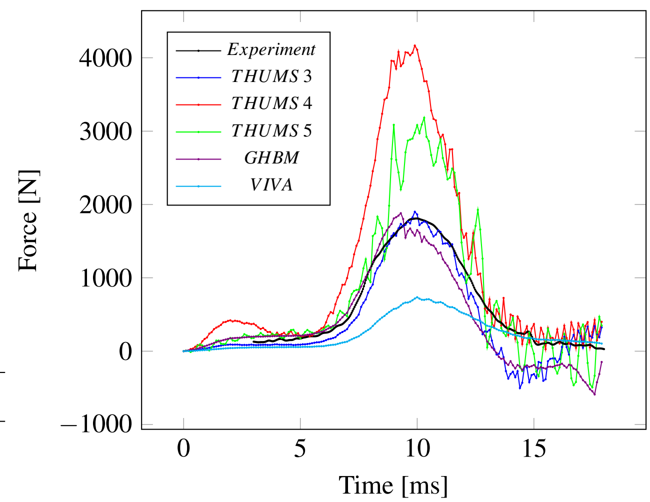

Fig. 5: A comparison of force-displacement response of the five FSU simulations compared against the experimental FSU results taken from literature [13]

Table 3: Strains and strain rates as reported in [13] and [14], and as measured in the THUMS 5 simulations

	IVD_{exp}	IVD_{sim}	FSU_{exp}	FSU_{sim}
ε_{peak}	15%	14.6%	10.5%	7.6%
$\dot{\varepsilon}_{peak}$	$1.0s^{-1}$	$1.16s^{-1}$	$48.07s^{-1}$	$36.41s^{-1}$

4 Discussion

4.1 Intervertebral Disc

During the IVD validation two models stood out as having the best CORA scores: the THUMS v3 with a total score of 0.74 and the THUMS v5 with a score of 0.68. In general, CORA scores greater than 0.58 are considered to be an adequate fit [15], and specifically for HBM applications CORA scores above 0.65 are considered to have good biofidelity [16]. A CORA score of 1.0 would be a perfect fit. Based on the results of the CORA study, as well as on qualitative analysis of the corridors, the THUMS v5 model was found to match the experimental results the closest. Both the THUMS v5 and THUMS v3 have high V scores, which measures how well the shape of each curve matches the reference data. This may be somewhat misleading, because, when looking at the response curves, the upward curvature seen in the experiment is captured only by the THUMS v5 and not by the THUMS v3, which has a linear response, as seen in Figure 4. This linear response also helps THUMS v3 to have a higher G score than the THUMS v5. The G score measures how well a sample curve's size matches the reference curve, as measured by comparing the respective areas under the curves. The linear THUMS v3 response intersects the reference experiment, yielding a smaller error in the size rating than the THUMS v5 response, which has a constant offset to the reference experiment. This linear response would be a poor indicator for injury prediction, as it would over-predict injury at IVD displacements less than 0.7mm but under-predict injury for IVD displacements greater than 0.7mm. It must be said that the constant offset seen in the THUMS v5 curve means its response is more conservative, which at lower levels of compression the THUMS v3 is not. These observations show potential limitations in the application of objective ratings such as CORA to HBM validity assessment.

The largest model differences seen for the IVD experiments can be attributed to the various modelling approaches used to construct IVDs. The vertebral geometries have no effects as no contact was seen anywhere between the vertebrae, which had their posterior elements removed. In THUMS v3, GHBM, and Viva, the vertebrae are all modelled as rigid, and as such have no influence on the compliance measured during the simulations. THUMS v4 and v5 have deformable vertebrae, but they are modelled with materials orders of magnitude stiffer than those of the IVD. In the simulation results this is reflected with vertebral displacements orders of magnitude smaller than the IVD displacements, at 15% strain in the IVD for the THUMS 5, compared to 0.008% strain in the vertebral bodies. Other modelling factors such as contact did not play a role in the IVD simulations as there was no contact observed between bony structures, which agrees well with the experiments.

There are, however, geometric as well as material differences in the modelling of the IVDs. In Figure 1 the geometric differences can be seen, and they are described in greater detail in Table 1. Two models, the GHBM and the VIVA, model the IVD using load-displacement curves to define stiffness with respect to the various modes of deformation. This approach is flexible, as only the curve-stiffness values must be changed to vary the model response; for example keeping the flexion and extension stiffnesses constant while changing the compressive stiffness. However, the point at which the forces and moments interact is rigidly fixed, which means the instantaneous center of rotation (ICR) cannot translate as it does in reality. Gertzbein et al. [17] described the ICR as translating anteriorly and cranially, and then posteriorly and caudally when going from extension to flexion, using experiments performed ex vivo. Aiyangar et al. [18] found that for in vivo lumbar spines the ICR translated posteriorly when going from flexion to upright, with large variations in caudal/cranial movement depending on the applied load. The three THUMS-family models all have solid meshed IVDs, but all with different geometries, mesh densities, and material models. The material models likely account for the majority of the variation between THUMS models, as geometric differences as measured by the IVD cross sectional areas vary less than 5% between models, which is much smaller than the -65% to +109% differences seen in the peak force response. A notable difference which can be seen in Figure 1 is that the nucleus of the THUMS 5 model covers 35% of the total IVD area compared with $\tilde{2}0\%$ disk area for THUMS 3 and THUMS 4. The THUMS 5 model has the finest meshed IVD of the models tested, which suggests that the IVD meshes are not converged. As HBMs are used for crash applications where the models' element size rather reflects the time step needs from application in full-scale simulation, this mesh coarseness could be seen as a feature, rather than an issue. THUMS 5 also uses a hyperelasitc material model for its nucleus, which perhaps helps to contribute to the convex curvature seen in the THUMS 5 average curve in Figure 4. THUMS 5 is the only model which captures the convex curvature present in the experimental results.

4.2 Functional Spine Unit

According to the hierarchical organization of this study, the FSU experiments are the next logical step to testing the HBMs for validation. When compared with the IVD alone, the FSU has more complex range of motion considerations, as the ligaments and posterior elements add restrictions to the otherwise relatively unconstrained IVD. Additionally, the drop tower setup generates higher strain rates as well as specimen failure, when compared to what was observed in the IVD cases. The FSU experiments used in this study can be thought of as pilot for future studies to be complemented with a numerical sensitivity study in order to further develop the boundary and loading conditions of subsequent experiments. The results from the FSU show a large spread between the peak force values of the various simulation models and the experiments. One explanation could be due to how strain hardening is implemented for the HBMs. The strain rate for the IVD experiments is in the order of $1s^{-1}$ while the FSU experiments exhibited strain rates approaching $40s^{-1}$, as seen in Table 3. Separate studies by Race et al. and Newell et al. have shown that strain rate only affects stiffnesses up to approximately $1s^{-1}$ [19] [14]. However, the material models in the HBMs might not be able to capture this type of behaviour, as their relation to the strain rate is predetermined, and usually monotonic, as is typical for most viscoelastic material models [20].

The FSU modelling shows the THUMS v4 HBM to have the stiffest response, as seen in Figure 5. THUMS 4 was also observed in the IVD comparison to have the stiffest response; this suggests that for the THUMS 4 model, the IVD is the largest contributor to its overall stiffness. The GHBM model, which had the second stiffest response in the IVD investigation, has the second softest response for the FSU study, which is the largest intra-model difference between the experiments. This difference brings the GHBM much closer to the experimental curve for the FSU than for the IVD experiment. As the curves defining the GHBM behavior are the same for both the IVD loading and the FSU loading, and no contact occurs which would stiffen the response, it can be inferred that the curves may have been defined in order to achieve good results on the FSU level rather than the IVD level. An interesting characteristic in the GHBM response is the jump that occurs at the peak of the GHBM curve in Figure 5. This might be due to how the curves which define the IVD stiffness interact with each other. The peak is where the transition from loading to unloading occurs and the model might be interpreting it as the transition from compression to tension, and thus applying the behavior defined in the tension curve instead of the unloading behavior defined in the compression curve, As the displacements extracted from the video are in the XZ plane; this means that there is also shear involved at this transition point.

The larger oscillations seen in the THUMS v5 model appear to be numerical in nature, as the THUMS v5 has a hyperelastic nucleus. The hyperlastic material model is known to be more representative of the behaviour of the nucleus compared with an elastic material model [21]). This nearly incompressible behaviour in itself would not generate these sorts of high frequency peaks, but the explicit enforcement of the energy functional which lies behind this physical behavior might be unstable under very dynamic loads.

FSUs have posterior elements which connect to form the facet joints. Facet joints can be thought of as stiffening structures. It is therefore unsurprising that the IVD results are softer than the FSU results when compared to the peak forces of reference experiments. The IVD simulations are on average 12% stiffer than the peak experimental results, whereas the FSU simulations are on average 58% stiffer, as seen by comparing Figure 2 to Figure 5. Not all of the stiffening comes from the facet joints; strain-rate dependencies of the IVD also add a stiffening contribution. In models which do not have strain rate dependent materials, however all of the stiffening must come from the facet joints. The model with the best FSU response in terms of percent difference in peak force, THUMS v3, has no strain-rate dependency. If the THUMS 3 had a strain rate dependent disc model, it would be expected to be even stiffer in the FSU simulations

Another source of stiffening could be the modelling of the facet joints themselves. In the HBMs the facet joints are mainly modelled via a simple contact, and this contact force might be increasing the output force artificially, by simply causing the vertebrae to collide into one another instead of providing a rotational motion to further load the IVD. This contact is the main explanation of why the THUMS v5 has a 76% higher peak force when compared to the experiment in the FSU load case, but only a 9% higher peak force than the experiment for the IVD load case. It should be noted that the effects of contact are exacerbated by the chosen modelling strategy of using prescribed motions as boundary conditions instead of modelling the entire experimental setup. The prescribed displacement boundary conditions continue on their set path no matter if there is facet joint contact or not. Modelling the FSU experiments using gravity and contacts between the potting and the impactor instead of displacement boundary conditions could have avoided this issue and should be considered in future simulations.

Looking at which models are stiffest and softest, there are discrepancies between the IVD simulations and the FSU simulations. The THUMS v4 model is always the stiffest, and the ViVa model is always the softest, but THUMS v3, THUMS v5, and GHBM show no consistent pattern between the various experimental levels. This suggests that the modelling deficiencies described above play a role in this kind of bi-level validation.

For the IVD experiments, corridors could be constructed which allow for the validation of the FE models. For the FSU experiments, there were not enough data to construct corridors, and so no validation at this level could be achieved. More data is needed at the FSU level in order to allow more comprehensive comparisons between the HBMs, and to help filter out the influence of the IVD on the FSU.

As the FSU and IVD experiments where performed on different specimens, using different test setups, there is also systemic variability which affects the comparison across levels. In the best case scenario, all experiments would have been carried out on the same set of specimens, on both the IVD and FSU, using the same test setup.

5 Conclusions

A set of simulations was carried out to compare the behaviour of the IVDs and the FSUs of the lumbar spine of several Human Body Models in a hierarchical, two-level approach. The first level simulated results from a materials testing machine compressing IVDs. The THUMS v5 model was found to match the experimental data best. This is likely due to the THUMS v5 having the finest IVD mesh, and the most advanced material modelling than the other HBMs used. The second simulation study compared the same HBMs to experimental data concerning impact loading of lumbar FSUs in a drop tower environment. For these simulations the GHBM and THUMS v3 models matched the experimental results closest. Differences in the model ranking between IVD and FSU experiments shows the need for hierarchical validation. Overall, THUMS v5 is seen as the best compromise at the two presented levels of validation. The commonly used rating method, CORA, proved useful in response comparison, but also showed limitations. The study highlighted the importance of experimentalists and simulation specialists working together in representing validation experiments in a numerical environment. The observations from this study can be used to design the next set of experiments on FSUs as well as extending the described validation approach.

Acknowledgements

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