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Validation Performance Comparison for Finite Element Models of the Human Brain

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Abstract

The objective of this study was to compare the performance of six validated brain finite element (FE) models to localized brain motion validation data in five experimental configurations. Model performance was measured using the objective metric CORA (CORrelation and Analysis), where higher ratings represent better correlation. The KTH model achieved the highest average CORA rating, and the ABM received the highest average rating among models robustly validated against five cadaver impacts in three directions. This technique can be more frequently employed to build better models and, when associated limitations are well understood, to compare inter-model performance under similar conditions.

Keywords

Brain model; head injury; validation; optimization; finite element model; CORA

Introduction

Each year, approximately 1.7 million people in the United States suffer from traumatic brain injury (TBI) (Faul *et al.* 2010). To increase the ability to prevent and mitigate these injuries, fundamental injury mechanisms need to be well-characterized and understood. One way to study the response of the brain under various loading conditions is through simulation using finite element (FE) models. Models with varying degrees of anatomical accuracy and complexity have been developed over the last several decades. Anatomical accuracy of the models varies with the number of elements, ranging from models employing a rather coarse mesh to more precise models containing almost two million elements. The constitutive models employed for brain tissue vary across FE models and include linear and quasi-linear viscoelastic, hyperelastic, and fully nonlinear Green-Rivlin models. There is also a wide range of material properties and parameters used throughout the literature. Reported values for shear relaxation moduli, for example, span orders of magnitude (Chatelin *et al.* 2010). Finally, models differ in their approach to representing the boundary condition at the brain-skull interface.

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Conflicts of Interest

No potential conflict of interest was reported by the authors.

Once an FE model has been developed, it must be validated against experimental data before it can reliably be used to predict response and injury. Brain models are commonly validated against experimental brain motion data and intracranial pressure (ICP) response. The finding that some brain injuries (e.g., diffuse axonal injury) are dependent on strain (Holbourn 1943, Gennarelli *et al.* 1972, Abel *et al.* 1978, Bain and Meaney 2000, King *et al.* 2003, Tse *et al.* 2014) reinforces the importance of validating models with displacement data in addition to ICP data.

While there are some experiments that are commonly used by researchers for model validation purposes, there is no standard for all brain FE models and it is difficult to compare results between models. Thus, there is a need to standardize validation series and quantitatively assess model performance using a robust objective rating method. A recent study (Deck and Willinger 2009) illustrates the need for a standardized performance metric and rating method for validation results. This study presented validation results for six brain models in three localized brain motion cadaver experiments. One limitation of this work is that the models were not labeled, so the reader does not know which model performed best in any given validation condition. Additionally, the study examined a reduced set of measured responses, excluding a large amount of validation data.

Due to limitations of previous rating methods, the current study quantifies error between experimental and predicted validation results using a suite of objective evaluation metrics known as CORA (CORrelation and Analysis) (Gehre *et al.* 2009). In an evaluation of objective rating methods (Vavalle *et al.* 2013), found CORA to be the most comprehensive metric of the three rating methods studied (Sprague and Geers, Cumulative Standard Deviation, and CORA). Additionally, it was shown that there was no strong correlation between the four metrics within CORA, indicating that each metric provides independent and unique information describing the error between model and experimental response.

The current study examined local brain response to five experimental impact tests used for validation. This study examined the following six brain FE models: the atlas-based brain model (ABM) (Miller *et al.* 2016), Simulated Injury Monitor (SIMon) (Takhounts *et al.* 2003), Global Human Body Models Consortium (GHBMC) head model (Mao *et al.* 2013), Total Human Model for Safety (THUMS) head model (Kimpura *et al.* 2006), Kungliga Tekniska Högskolan (KTH) model (Kleiven and von Holst 2002, Kleiven 2007), and the Dartmouth Head Injury Model (DHIM) (Ji *et al.* 2015). These six models were chosen based on model access and availability of validation results. Access to the ABM, SIMon, GHBMC, and THUMS models allowed direct simulation of the validation conditions in the current study. Results for three of the five validation cases were obtained from literature for the KTH model (Kleiven 2006, Giordano and Kleiven 2014) and for two of the five conditions for the DHIM model (Ji *et al.* 2015). Although there are other validated models in the literature, such as the University College Dublin Brain Trauma Model (UCDBTM) (Horgan and Gilchrist 2003) and the Strasbourg University Finite Element Head Model (SUFEHM) (Deck and Willinger 2008), they are not considered in the current study because displacement results for the impact conditions examined were not available.

The objective of the current study was to present brain displacement validation results in five experimental configurations for six validated FE models and use an objective rating method to quantitatively compare model performance. The five experimental impact tests used for validation were: C755-T2 (occipital impact), C383-T1 (frontal impact), C383-T3 (frontal impact), C383-T4 (frontal impact), and C291-T1 (parietal impact) (Hardy *et al.* 2001, Hardy 2007). CORA (Gehre *et al.* 2009) was used to evaluate model performance and compare results between models and identify the FE brain model that performs best under the current conditions.

Methods

Validation against Localized Brain Displacements

Model validation results against brain motion data for six FE brain models were assessed and quantitatively compared. The following cadaver impact experiments were considered: C755-T2, C383-T1, C383-T3, C383-T4, and C291-T1 (Hardy *et al.* 2001, 2007). These five tests were selected because they vary in impact direction and magnitude (Table 1). Additionally, three of these tests (C755-T2, C383-T1, and C291-T1) are commonly used in brain model validation (Zhang *et al.* 2001, King *et al.* 2003, Kimpura *et al.* 2006, Kleiven 2006, Mao *et al.* 2006, Takhounts *et al.* 2008, Ji *et al.* 2015). In the cadaver impact experiments, local displacements were evaluated throughout the brain using a high-speed biplanar X-ray system to track the relative motion of implanted radio-opaque neutral density targets (NDTs) (Hardy *et al.* 2001). NDTs were placed in the cadaver brain in 2–3 vertical columns: one column in the anterior portion and 1–2 columns in the posterior portion of the brain (Fig. 1). Three-dimensional skull kinematics were collected with an accelerometer array affixed to the cadaver skull and were used to determine linear and angular velocities at the head center of gravity (CG) (Hardy *et al.* 2001).

The experimental conditions were simulated in LS-DYNA (MPP, Version 971, R7.1.2, LSTC, Livermore, CA) for the ABM, SIMon, GHBM, and THUMS models. Displacements in the FE models were compared to experimental data by evaluating local displacements at nodes closest to the physical location of each NDT. For the KTH and DHIM models, validation results available in the literature were digitized for comparison (Kleiven 2006, Giordano and Kleiven 2014, Ji *et al.* 2015).

FE Model Description and Comparison

Details of the constitutive models describing brain material for each of the six FE models can be found in Table 2 as well as other model characteristics. Additional details on development and FE properties for each model can be found in the respective references. The latest version of the ABM includes a recent update which is discussed in Appendix A.

Model Performance

To evaluate model performance, error between experimental and predicted NDT displacements was quantified using CORA (Gehre *et al.* 2009). CORA is a command line tool that evaluates the similarity of curves using two independent sub-methods: a corridor method and a cross correlation method. The corridor method takes into account

experimental variation by assessing the fit of a measured response with respect to corridors around an experimental or reference curve. The cross correlation method evaluates error associated with phase shift, size, and shape. The ratings from these sub-methods are combined to produce a CORA score ranging from '0' to '1' ('1' indicates a perfect match).

At each NDT, displacements are evaluated in the two in-plane coordinate directions. Displacements in the third coordinate direction were not considered because the in-plane motion was much greater than the out-of-plane motion and therefore were not reported by Hardy et al. (2007). Individual NDT CORA scores are obtained by averaging these two ratings at each NDT location. For each experimental condition, an overall CORA score (oCORA) is computed for each model by averaging the individual NDT CORA scores.

Results

The current study used CORA to examine the performance of six FE head models in five validation tests against local brain displacement data. Simulated displacements at each NDT were compared to experimental displacements in two directions. For the occipital impact (C755-T2), displacements were evaluated in the x- and z-directions at each of the 10 NDT locations for all models except the DHIM, where displacement results were only available for four NDT locations. This resulted in a total of 20 available displacement curves to evaluate performance – resulting in a total of 20 CORA scores per model in this configuration. NDT CORA scores for each of the models considered are shown in Fig. 3 by NDT location. The oCORA ratings for each model are displayed in Table 3.

For the C383-T1 frontal impact, displacements were again evaluated in the x- and z-directions. For this case, however, there were 12 implanted NDTs, resulting in 24 displacement curves, and a total of 24 CORA scores per model in this configuration. Displacements were evaluated at each of the 12 NDT locations for all models except the DHIM, where displacement results were only available for four NDT locations, and KTH with the Mooney-Rivlin material model (Giordano and Kleiven 2014), where results were available for 10 NDT locations. These scores are displayed by NDT location in Fig. 4 and the oCORA rating for each model is displayed in Table 3.

For the parietal impact (C291-T1), displacements are evaluated in the y- and z-directions. There were 3 NDT columns in this experiment - 2 in the left hemisphere and 1 in the right hemisphere. Since (Hardy *et al.* 2001) did not report results for all fifteen implanted NDTs, performance was evaluated at the twelve NDT locations where data was available. For the ABM, SIMon, GHBM, and THUMS models, performance was evaluated at all twelve of these NDT locations. Results for only 9 of these locations, however, were reported in the literature for the KTH models (Fig. 5).

The final two conditions (C383-T3 and C383-T4) were both frontal impacts and displacements were evaluated in the x- and z-directions with twelve implanted NDTs for both experimental conditions. Results for these 2 impact configurations were only obtained and compared for the ABM, SIMon, GHBM, and THUMS models since results were not published for either the KTH or DHIM models. For the C383-T3 case, results for the

posterior NDTs 1–4 were not reported, so the remaining 8 NDT locations were used to evaluate performance in this impact configuration (Fig. 6). CORA scores were computed at all twelve NDT locations for the C383-T4 case and are displayed in Fig. 7 by NDT location. The oCORA ratings per model were computed for the C383-T3 and C383-T4 (Table 3).

Discussion

CORA, which is becoming a more widely used metric, was developed to assess FE model validity and assesses the similarity of two curves by evaluating the error in shape, magnitude, and phase. CORA is similar to the coefficient of determination, r^2 , in that a higher rating is better, and 1 is a perfect match, but a CORA score of 0.45 is not comparable to an r^2 value of 0.45 (Fig. 8). There is a weak linear correlation between CORA and r^2 , but we can see that high r^2 values indicated a very high correlation (0.7), correspond to lower CORA scores (0.5).

Fig. 9 shows examples of predicted NDT responses that achieve CORA ratings classified as ‘poor,’ ‘moderate,’ and ‘good.’ This figure demonstrates how CORA is able to evaluate and score curves based on magnitude as well as curve shape. The ‘moderate’ and ‘good’ curves achieve better CORA scores than the ‘poor’ curve because the displacement magnitudes are much closer to the experimental value. And the ‘good’ curve scores better than the ‘moderate’ curve because the shape more closely resembles the experimental trace.

Table 4 displays a summary of previous validation work conducted for each model. All of the models considered in the current study have previously been validated against at least two of the cases considered; and three of the models (ABM, SIMon, KTH) have been validated against three of the same conditions. A complete comparison of all 5 experimental impact conditions was only possible between the ABM, SIMon, GHBMCM, and THUMS models due to the limitation of published validation results for the KTH and DHIM models. Complete results for the first KTH model (with Mooney-Rivlin material formulation) were obtained from (Kleiven 2006) for the C755-T2 and C383-T1 conditions, but results for only 2 of the 3 NDT columns were reported for the C291-T1 condition. Results for the second KTH model (with Ogden material formulation) were obtained from (Giordano and Kleiven 2014). Once again, complete NDT results were reported for the C755-T2 case, while results for 2 NDTs were omitted for the C383-T1 and results for the entire right NDT column were omitted for the C291-T1 case. Additionally, only the first 50 ms of the response was reported, which is a significant omission for the C383-T1 and C291-T1 conditions which had durations of 120 ms and 100 ms, respectively. Data for the C291-T1 case were not available for the DHIM model, while results for the C755-T2 and C383-T1 cases were obtained from (Ji *et al.* 2015). The published results for this model are limited, however, with data for only 4 NDTs available in both cases.

The reduced set of available responses for the KTH and DHIM models limits the ability to compare overall performance of these models to the remaining models, although comparison within individual tests is still possible. Table 3 shows which model performed best in each condition (by comparing oCORA ratings) and indicates that different models perform better under different experimental conditions, with no single model consistently performing best.

In general, most models demonstrated better agreement with experimental data in the C755-T2, C383-T1, and C383-T4 conditions and larger discrepancies in the C291-T1 and C383-T3 cases. This is illustrated by Figs. 4–8 which show higher oCORA ratings for the first 3 cases than the remaining conditions. It can also be seen by examining the individual displacement results for each model (Appendix B). In general, better agreement between experimental data and model response is observed in conditions with lower duration and lower severity. For example, the relatively high oCORA scores in the C755-T2 case are likely due to the low duration (60 ms) and low severity (22 g's). Similarly, lower oCORA ratings in general for the C291-T1 impact can be explained by the high impact severity (162 g's). Additionally, there is consistency between models in locations of relative good and poor performance. For example, all models achieve relatively high NDT CORA scores at a1, p3 and p6 in the C383-T1 frontal impact (Fig. 4). Additionally, there are consistently low NDT CORA scores in the C291-T1 parietal impact (Fig. 5) at a4 in the y-direction and at pL3 in the z-direction.

The discrepancies in performance for different impact magnitudes may indicate more complex material formulations and increased anatomical accuracy are needed to better match the time-dependent properties. To evaluate the predictive capabilities of a model, it is important to look at its performance over a range of loading conditions, as was done in the current study. From the results of the current investigation, we can conclude that the ABM is the most useful model in terms of predicting local displacements over a range of load cases, although not all models were able to be fully evaluated. The field must still make large improvements before being able to accurately predict the local response, but it is encouraging that we have observed several models that predict displacement magnitudes similar to the experimental response and correctly capture the shape of the response at various locations throughout the brain.

To quantify performance of a brain model in all impact conditions, oCORA scores in each available case were averaged to get an average rating. From Table 3 we see that the KTH model (with a Mooney-Rivlin material formulation) achieves the highest average score. This model was only tested in 3 of the 5 impact conditions, however, which must be taken into consideration when comparing overall performance. Of the models subject to the most rigorous validation conditions (ABM, SIMon, GHBMC, and THUMS), the ABM achieves the best average rating, which suggests the ABM demonstrates the strongest ability to predict local brain deformations under a range of impact severities and directions.

Limitations

Limitations of the current study exist due to potential experimental physiological response limitations present in all cadaver testing – including those conducted by Hardy et al. (2001, 2007). These effects were mitigated by perfusing the specimens with artificial cerebrospinal fluid (aCSF) and conducting the tests in an inverted configuration, which allowed the evacuation of gasses from the intracranial space (Hardy *et al.* 2001). There is also an inherent limitation in using cadavers, arising from delays post-mortem before testing begins and the fact that most specimens are in the elderly population. Hardy et al. reported that efforts were made to minimize the time between death and testing for all specimens and

typically ranged from 5 to 10 days (Hardy *et al.* 2001). These are accepted weaknesses, however, because using cadavers is the best available method to characterize brain response for high-rate loading. It is also possible that the density of the NDTs did not exactly match the density of the surrounding brain tissue, which could affect the local brain response. Despite these limitations, this is the most commonly referenced and used dataset reported in the literature and in many ways is the current ‘gold standard’ for higher velocity impacts to the brain describing large brain deformation in the load regimes associated with higher velocity head impact. Additionally, it should be noted that while a model may perform slightly better than another in predicting displacement at particular NDT markers, this does not necessarily mean it will be better at predicting injury in live humans. We do know, however, that strain is a function of the spatial derivatives of the displacements and it has been suggested that axonal injury is related to distortional strain (Bain and Meaney 2000), so validation against local displacement of brain tissue is relevant for injury prediction (Kleiven and Hardy 2002).

We recognize that models are created for different purposes and with different assumptions. Some of the models evaluated in this study were created with skull geometry and/or a head/neck primarily for the automotive environment, whereas others were created with close attention to anatomic detail for comprehensive investigation of brain injury mechanisms. The developers of all FE models of the brain need to make decisions about included anatomy, template geometry, mesh quality, element size, complexity, mechanics, boundary conditions, software and hardware computing platforms, among other choices. Choices made may be prioritized differently depending on the intended purpose of the model. In that sense comparing different models can be misleading. The results of the current study should not be interpreted to mean that these techniques automatically demonstrate which is the ‘best’ model but rather which best predicts brain motion based on the current experimental validation data available. However, we do intend to demonstrate these techniques can be employed during model development to build better models and that this framework can be used during model development or to assess model performance, and, when the associated limitations are well understood, to compare performance of models under similar conditions.

Conclusion

The current study quantitatively examined validation results from 6 existing brain FE models using localized displacement data. CORA was used to quantify error between experimental and model responses by incorporating measures of corridor fit and differences associated with curve size, shape, and phase shift. An advantage of CORA over other objective rating methods is its use of independent sub-methods, which has been shown to compensate for the disadvantages of either method alone (Gehre *et al.* 2009). This method allows detailed comparison of the response at specific NDT locations as well as overall response by impact configuration. Additionally, CORA ratings from different validation conditions were averaged to obtain a total rating for each brain model. Results from the current investigation indicate that the KTH model (with a Mooney-Rivlin material definition) performs the best when considering the average scores from available validation data for each model. When considering performance of all five tests, however, the ABM achieves the best average score. Comparison of total ratings should only be performed between models that have been tested

under the same validation conditions. Furthermore, models that have been validated in a greater number of configurations should be considered more rigorously tested.

Well-validated brain FE models are powerful tools for studying brain injury and improve the ability to prevent and mitigate TBI. As new brain models are developed, objective rating and comparison are vital to establish validation standards and allow comparison between models. Models should be validated against additional displacement tests (Hardy *et al.* 2001, Hardy 2007) in the future as well as against strain data from live humans obtained by magnetic resonance elastography (MRE) studies (Sabet *et al.* 2008). Injury prediction capabilities will continue to increase as brain models are improved and validated against more experimental data and further correlated with real world injuries (Urban *et al.* 2012, 2015).

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Appendix A. ABM Update

The original ABM FE model (Miller *et al.* 2016) has a volume of 1,639 mL, which is somewhat larger than the average reported by (Allen *et al.* 2002). This enlarged volume is expected because the ICBM average brain templates are slightly larger than average due to differences in brain shape and size (Toga and Mazziotta 2002). To better approximate the average brain, the model was uniformly scaled by a factor of 0.9195, by comparing the desired brain volume and the original volume using volume scaling ($\sqrt[3]{1,274/1,639} = 0.9195$). This results in a volume of 1,256 mL for the new scaled model. A Kelvin-Maxwell linear viscoelastic material model (*MAT_061 in LS-DYNA) is used for brain tissue. The shear relaxation is characterized by:

$$G(t) = G_{\infty} + (G_0 - G_{\infty}) * e^{-\beta t} \quad (1)$$

where G_{∞} is the infinite shear modulus, G_0 is the initial shear modulus, and β is the decay constant. (Miller *et al.* 2016) presented a methodology to identify brain material parameters using optimal Latin hypercube sampling (OLHS) and optimization against three cadaver impact experiments (C755-T2, C383-T1, and C291-T1) with the original (unscaled) ABM. In the current study, the parameters have been re-optimized using the same technique, but additional scaling was applied to the ABM to match reported cadaveric head dimensions for each experimental configuration. The global scaling method, presented by (Mertz *et al.* 1989), was used to calculate the scale factor for each condition, as it has previously been determined to be important for model validation as described by (Ji *et al.* 2015) and (Horgan and Gilchrist 2003). Additionally, the set of parameters in the current OLHS was modified from (Miller *et al.* 2016). Brain density and bulk modulus were not varied in the revised optimization and were instead set equal to 1,040 kg/m³ and 2.19 GPa, respectively. These parameters were prescribed because it was observed in the previous study that no strong relationship exists between these values and model performance. Unlike the values for brain shear parameters, which vary widely throughout the literature, values for density and bulk modulus are generally consistent between models and from material testing, which is how the parameter values were determined. The final change to the new optimization was a modification to the falx model by removing the thermal model and the addition of falx

thickness and stiffness as parameters to the OLHS. It was determined that the thermal model was unnecessary and pretension in the falx was instead modeled with an increased elastic modulus. The new parameters and ranges sampled in the new optimization are displayed in Table A1. The validation results presented for the ABM in the current study and used for model comparison were obtained using the average (1,256 mL) ABM with material parameters determined from the test-specific material optimization described above.

Table A1

Comparison of Brain FE Models

Brain Shear Parameters			Falx Parameters	
G_0 (kPa)	G_∞ (kPa)	β (s^{-1})	E (MPa)	t (mm)
0.407 – 49	0.233 – 23.285	0.06 – 400	11 – 172	0.41 – 3

Appendix B. NDT Displacement Results

Displacement results for each of the five impact conditions are shown below for the six FE models considered.

Figure B1. Comparison of experimental displacement results with model-estimated results in an occipital impact (C755-T2).

Figure B2.

Comparison of experimental displacement results with model-estimated results in a frontal impact (C383-T1).

Figure B3.

Comparison of experimental displacement results with model-estimated results in a parietal impact (C291-T1).

Figure B4. Comparison of experimental displacement results with model-estimated results in a frontal impact (C383-T3).

Figure B5.

Comparison of experimental displacement results with model-estimated results in a frontal impact (C383-T4).

Figure 1.
NDTs in experiment C383-T1 (Hardy 2007).

Figure 2.
Brain models compared in the current study. (von Holst and Kleiven 2014) (Ji *et al.* 2014).

Figure 3.

X and Z CORA scores for the 10 NDTs in the occipital (C755-T2) impact (a – anterior, p – posterior).

Figure 4. X and Z CORA scores for the 12 NDTs in the frontal (C383-T1) impact (a – anterior, p – posterior).

Figure 5.

Y and Z CORA scores for the NDTs in the parietal (C291-T1) impact (a – anterior, p – posterior, L – left, R – right).

Figure 6. X and Z CORA scores for the 12 NDTs in the frontal (C383-T3) impact (a – anterior, p – posterior).

Figure 7.

X and Z CORA scores for the 12 NDTs in the frontal (C383-T4) impact (a – anterior, p – posterior).

Figure 8.
Relationship between CORA and r^2 .

Figure 9.
Examples of NDT displacement curves that obtain 'poor,' 'moderate,' and 'good' CORA ratings.

Table 1

Summary of Experimental Test Conditions.

C755-T2		C383-T1	C291-T1	C383-T3	C383-T4

occipital		frontal	parietal (R)	frontal	frontal
Impact Location					
Impact Type		acceleration	deceleration	deceleration	deceleration
Peak G		22	63	58	100
Delta V (m/s)		1.90	3.91	3.13	2.89
NDTs		2 columns of 5 (R hemisphere)	2 columns of 6 (R hemisphere)	2 columns of 5 (2 in L hemisphere, 1 in R hemisphere)	2 columns of 6 (R hemisphere)
Duration (ms)		59.5	118	120	120

Peak G – peak acceleration, Delta V – change in velocity, R – right, L – left

Table 2

Comparison of Brain FE Models

	#elements/#nodes	Brain Mass (kg)	Brain Material Model	Brain Shear Parameters
ABM	2,122,232/2,034,724	1.31	Viscoelastic	$G_0 = 4.06$ kPa, $G_{\infty} = 0.447$ kPa, $\beta = 44.14$ s ⁻¹
SIMon	45,875/42,500	1.10	Viscoelastic	$G_0 = 1.66$ kPa, $G_{\infty} = 0.928$ kPa, $\beta = 16.95$ s ⁻¹
GHBMC	234,954/189,784	1.19	Viscoelastic	Gray: $G_0 = 6$ kPa, $G_{\infty} = 1.2$ kPa, $\beta = 12.5$ s ⁻¹ White: $G_0 = 7.5$ kPa, $G_{\infty} = 1.5$ kPa, $\beta = 12.5$ s ⁻¹
THUMS	49,598/37,759	1.14	Viscoelastic	Gray: $G_0 = 10$ kPa, $G_{\infty} = 5$ kPa, $\beta = 0.06$ s ⁻¹ White: $G_0 = 12.5$ kPa, $G_{\infty} = 6.125$ kPa, $\beta = 0.06$ s ⁻¹
KTH (2006)	18,416/19,350	1.48	Hyperelastic (Mooney-Rivlin)	$G_1 = 1628$ Pa, $G_2 = 930$ Pa $\beta_1 = 125$ s ⁻¹ , $\beta_2 = 6.67$ s ⁻¹
KTH (2014)	21,345/16,906	1.48	Hyperelastic (Ogden)	$\mu_1 = 53.8$ Pa, $\alpha_1 = 10.1$ $\mu_2 = -120.4$ Pa, $\alpha_2 = -12.9$ $G_1 = 320$ kPa, $\beta_1 = 10^6$ s ⁻¹ $G_2 = 78$ kPa, $\beta_2 = 10^5$ s ⁻¹ $G_3 = 6.2$ kPa, $\beta_3 = 10^4$ s ⁻¹ $G_4 = 8$ kPa, $\beta_4 = 10^3$ s ⁻¹ $G_5 = 0.10$ kPa, $\beta_5 = 10^2$ s ⁻¹ $G_6 = 3$ kPa, $\beta_6 = 10^1$ s ⁻¹
DHIM	115,228/101,420	1.58	Hyperelastic (Ogden)	$\mu_1 = 271.7$ Pa, $\alpha_1 = 10.1$ $\mu_2 = 776.6$ Pa, $\alpha_2 = -12.9$ $g_1 = 7.69\text{e-}1$, $\beta_1 = 10^6$ s ⁻¹ $g_2 = 1.86\text{e-}1$, $\beta_2 = 10^5$ s ⁻¹ $g_3 = 1.48\text{e-}2$, $\beta_3 = 10^4$ s ⁻¹ $g_4 = 1.90\text{e-}2$, $\beta_4 = 10^3$ s ⁻¹ $g_5 = 2.56\text{e-}3$, $\beta_5 = 10^2$ s ⁻¹ $g_6 = 7.04\text{e-}3$, $\beta_6 = 10^1$ s ⁻¹

Table 3

Overall CORA (oCORA) scores for each model in the 5 experimental configurations. Bolded values indicate the model with the highest score for the given test condition.

	C755-T2	C383-T1	C291-T1	C383-T3	C383-T4	Available Test Ave.	5 Test Ave.	Std. Dev.	Rank	Ave. Rank
ABM	0.449	0.393	0.385	0.306	0.347	0.376	0.376	0.053	2, 4, 3, 1, 3	2.60
SIMon	0.340	0.412	0.388	0.209	0.423	0.354	0.354	0.087	6, 2, 2, 3, 1	2.80
GHBMC	0.433	0.352	0.221	0.232	0.378	0.323	0.323	0.093	3, 5, 6, 2, 2	3.60
THUMS	0.313	0.306	0.246	0.186	0.251	0.260	0.260	0.052	7, 6, 5, 4, 4	5.20
KTH (M-R)	0.475	0.407	0.358	-	-	0.413	-	0.059	1, 3, 4, NA, NA	NA
KTH (Ogden)	0.390	0.256	0.389	-	-	0.345	-	0.077	4, 7, 1, NA, NA	NA
DHIM	0.390	0.440	-	-	-	0.415	-	0.035	4, 1, NA, NA, NA	NA

*** Note: oCORA model ratings were computed from available NDT data

Table 4

Summary of previous model validation

	C755-T2	C383-T1	C291-T1	C383-T3	C383-T4	References
ABM	✓	✓	✓			Miller et al. (2016) *
SIMon	✓	✓	✓			Takhounts et al. (2008)
GHBM	✓			✓		Mao et al. (2013)
THUMS	✓	✓				Kimpara et al. (2006)
KTH	✓	✓	✓			Kleiven and Hardy (2002) Kleiven (2006) Giordano and Kleiven (2014)
DHIM	✓	✓				Zhao et al. (2014) Ji et al. (2014a, b)

* material properties have since been updated