Comparison of Head Injury Criteria Based on Real-World Accident Simulations under Visual Performance Solution (VPS)

Debasis Sahoo, François Coulongeat, Franz Fuerst and Giacomo Marini

Abstract In the present study an existing, improved in-house finite element head model is used to reconstruct 70 well-documented real-world head trauma cases for the development of robust model-based brain injury criteria under Visual Performance Solution (VPS, ESI group). A combined strain and strain rate parameter, named the brain injury score (BIS), has been proposed to predict AIS2+ brain injury accurately based on statistical analysis. Further head kinematic-based Head Injury Criteria (HIC), Brain Injury Criteria (BrIC), Universal Brain Injury Criterion (UBrIC) and Convolution of Impulse response for Brain Injury Criterion (CIBIC) are computed and tissue-level injury criteria maximum principal strain, von Mises stress and brain pressure are extracted from the simulation. The injury risk probability for each case was computed for different parameters and the delta percentage risk was calculated for comparison between these injury criteria. In addition six real-world head trauma cases were reconstructed to validate the prediction capability of BIS, HIC, BrIC, UBrIC and CIBIC. It was concluded that BIS predicts the AIS2+ brain injury more accurately when compared to the others. The HIC and BrIC typically over predict the brain injury risk.

Keywords Brain injury criteria, Finite element head model, Accident reconstruction, Statistical analysis, Injury correlation.

I. INTRODUCTION

With the advent of modern transportation and improved protective systems, the truth of how fragile the human head can be to mechanical insult is becoming clearer. Though the biological evolution of the human head provides certain protection, it is not capable of withstanding the high dynamic loading involved in severe road, sport and fall accidents. As a result of these extreme loadings, traumatic brain injury (TBI) remains one of the leading causes of mortality and prolonged disability, with serious social and economic consequences [1-4]. Around 2.5 million severe health-related issues are associated with TBI in the USA [1-2]. About 57,000 TBI-related deaths and 1·5 million hospital discharges are estimated to have occurred in 2012 in the EU [5]. Furthermore, 1.24 million people die each year because of road traffic accidents [6]. Based on the study conducted by the Center for Disease Control and Prevention (CDC), the associated TBI-related deaths due to road traffic accident stand at 25% between the years 2006 and 2010 [7]. The severity of TBI may range from mild (having concussion with brief loss of consciousness) to severe (an extended period of unconsciousness or memory loss after the injury). In 2019 CDC estimated that 75% of the 2.89 million TBI patients were diagnosed with mild TBI [8]. According to Abbreviated injury scale (AIS) code definition (code: 161002.2 or 161006.3) the injuries sustained by mild TBI patients can be between AIS2-3 [9]. The current study mainly focused on AIS 2+ head injury cases. Also in most of the vehicle and sport accidents, a concussion with brief loss of consciousness is the most diagnosed injury as reported in accident databases [10-11] and literatures [12-13].

In order to develop effective countermeasures aimed at mitigation of head injury, a means of predicting potential injury is of great importance. Based on head kinematics, one of the most popular criterion is the Head Injury Criteria (HIC), which has been adopted in automotive industries over the last decades [14]. The HIC is computed from the resultant linear acceleration at the centre of gravity of the dummy head [15]. National Highway Traffic Safety Administration (NHTSA) defined the current version of HIC as described in Equation 1[15]:

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$$HIC = \max_{(t_1,t_2)}\left\{(t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}\right\} \tag{1}$$

where *a(t) [m/s²]* is the resultant linear acceleration measured at the centre of gravity of the head, and t_1 and t_2 *[ms]* are chosen in order to maximise the HIC value. The maximum time duration (t_2-t_1) was set as 36 ms at first, but current standards use 15 ms [15] and corresponding HIC15 was used in the current study. The HIC15 value of 700 was estimated as a 5% risk of AIS4+ head injury. For adult pedestrians, a HIC15 value of 1000 has been proposed as an injury tolerance level for severe head injuries [16].

However, HIC is independent of the loading direction and is not based on a specific injury mechanism. This leads to poor injury correlation with real-world observation, as witnessed in several studies [17-20]. Furthermore, HIC is criticised for not taking into account rotational accelerations of the head [17]. The importance of head rotation as a mechanism for concussion injury was first hypothesised by Holbourn [21]. Further experimental studies on animals demonstrated that without any linear acceleration, head rotation alone can cause significant brain damage, such as diffuse axonal injury (DAI) and subdural hematoma [22-24]. To complement HIC, an angular velocity-based brain injury criterion (BrIC) was developed by NHTSA [25-26]. The formulation of BrIC is described by Equation 2:

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xC}}\right)^2 + \left(\frac{\omega_y}{\omega_{yC}}\right)^2 + \left(\frac{\omega_z}{\omega_{zC}}\right)^2} \tag{2}$$

where ω_x, ω_y, and ω_z are maximum angular velocities about X, Y, and Z axes respectively, and ω_{xC}, ω_{yC} and ω_{zC} are the critical angular velocities in their respective directions. Based on the cumulative strain damage measure, the critical angular velocity along X, Y and Z directions are 66.2, 59.1 and 44.25 rad/s respectively [26].

However, as BrIC does not consider angular acceleration, BrIC has regimes of applicability and cannot be extrapolated to moderate or longer duration events. Furthermore, BrIC was derived from animal data scaled to humans through computational modeling, which could lead to over predicting the risk of injury [19][27].

Recently two new kinematic based brain injury criteria were developed considering rotational acceleration. Universal Brain Injury Criterion (UBrIC) is based on deformation response from a second order system and uses the magnitudes of head angular velocity and acceleration to predict strain based brain injury indicators [28]. The formulation of UBrIC is described by Equation 3:

$$UBrIC = \left\{\sum_i \left[\omega_i^* + (\alpha_i^* - \omega_i^*)e^{-\frac{\alpha_i^*}{\omega_i^*}}\right]^r\right\}^{\frac{1}{r}} \tag{3}$$

Where ω_i^* and α_i^* are the directionally dependent (i = x, y, z) maximum magnitudes of head angular velocity and angular acceleration each normalized by a critical value (cr); $\omega_i^* = \omega_i/\omega_{icr}$ and $\alpha_i^* = \alpha_i/\alpha_{icr}$.The exponent r equals to two [28]. However, this criterion does not include translational kinematic parameters. Linear acceleration is important for resulting pressure gradients due to impact loading which leads to concussion [17].

Motion based brain injury criteria, Convolution of Impulse response for Brain Injury Criterion (CIBIC) [29] is described by Equation 4:

$$CIBIC = \left.\sqrt{\sum_{i=1}^{3}\left\{\int_0^t x_i(t-\tau)\alpha_i(\tau)d\tau\right\}^2}\right|_{max} \tag{4}$$

where i=1,2,3 represent the x, y and z axis and α_i is rotational acceleration. The other parameters are described in [29]. However, it was assumed that impact response of the brain tissue can be characterized by a standard linear solid. The development of robust injury criteria therefore remains a primary focus of research.

Brain tissue level response due to mechanical loading, rather than head kinematics, is the key to understanding brain injury mechanism [30]. With the progress of computational power and model resolution, finite element (FE) head models are now able to extract complex parameters, describing accurately the real injury mechanism. Validated high-quality FE models are therefore mandatory as such tissue-level studies are beyond the capability of conventional experimental methods [30]. Several widely recognised FE head models have been developed to investigate head injury mechanisms [31-36]. However, the influence of different material implementation, modeling techniques and software platforms (LS-DYNA, RADIOSS, ABAQUS, VPS) creates enormous challenges to bring harmony between these head models [37], thus, reducing the value of FE head models with a high biofidelic structure. Most FE head models are developed and validated under LS-DYNA platform, creating a scarcity of well-built models under VPS (Visual Performance Solution, ESI group), which is widely used by various car manufacturers [38].

Based on FE head models and head trauma simulation, brain pressure, von Mises stress and brain strain are the most common parameters used to predict brain injury [18][35][39]. Experimental studies emphasised brain strain due to relative motion between skull and brain as a suitable parameter to predict diffuse axonal injury (DAI) in case of mild or severe TBI [40-42]. However, a recent study that used strain as injury criterion predicted severe injury for some of the volunteer experiments who did not sustain injuries [27]. Biological material, such as the brain tissue, has time-dependent properties that could influence the failure characteristic of the material [43]. The bulk modulus of brain tissue is roughly five to six orders of magnitude larger than the shear modulus [44], which suggests that the brain tends to deform predominantly in shear for a given impact. A rapid elongation of the axon was shown as a leading cause of DAI [45]. Therefore, to develop a realistic injury criteria, both strain and strain rate are mandatory [17]. A combined strain and strain rate criterion for brain injury prediction should provide a better correlation with the occurrence of mild TBI.

In the current study, existing in-house improved Total Human Model for Safety (THUMS) v4 head model [46] is used for FE simulation with regard to head injury. Real-world head trauma cases (N=70) were reconstructed. Different parameters were investigated as potential brain injury predictors (AIS2+). An injury criterion based on combined strain and strain rate was developed and compared with other recognised injury criteria (head kinematics-based HIC, BrIC, UBrIC and CIBIC) and with mechanical parameters, such as maximum principal strain, von Mises stress and brain pressure. Statistical analysis was used to investigate the different injury predictors. In addition six real-world head trauma cases were reconstructed to validate the prediction capability of BIS, HIC, BrIC, UBrIC and CIBIC.

II. METHODS

The first section describes the existing THUMS head model along with the improvements implemented to enhance the biofidelity of the model. Furthermore, a short description of the model validation is presented. Following on from the methodology, the database used for the accident reconstruction is described. Finally, a statistical analysis of the results is given.

Finite Element Head Model

An improved biofidelic FE head model was developed by using the head of the 50th percentile male THUMS Version 4.02 [47] under VPS platform as basis. The original THUMS model was translated by ESI Group from the THUMS Version 4.02 LS-DYNA model developed by [36]. The basic geometry represents a 50th percentile adult male. The main anatomical details of the FE head model are presented in Fig. 1. The skull FE model is composed of parietal, occipital, frontal, temporal, ethnoid, sphenoid, nasal, vomer, lacrimal, palatine, maxilla, zygomatic and mandible bones. All the bones have the cortical bone modelled with shell elements and the inner spongy bone with mostly one layer of solid elements [36], as shown in Fig. 1. The sutures are modelled with solid elements and function as a connection between different cranial bones. Facial muscles, such as the masseter muscle and eye muscles, are represented by bar elements. The brain model consists of cerebrum, cerebellum, brainstem with distinct white and gray matter, cerebral spinal fluid (CSF) and sagittal sinus modelled with solid elements. Shell elements are used to represent dura matter, pia, arachnoid, meninx, falx and tentorium. Material models for different parts are available in literature [36] [48].

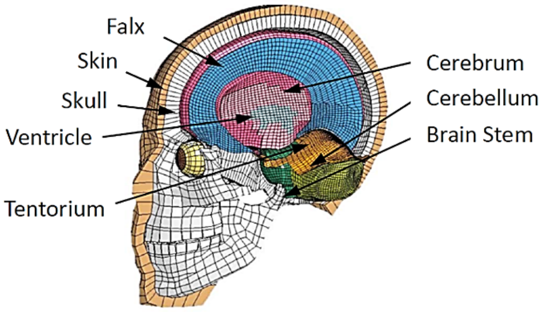

Fig. 1. Detail of the original THUMS v4 FE head model [36].

To improve the fracture response of the skull, mesh improvements were performed based on a convergence study conducted for different mesh configurations. A hyper-viscoelastic material model was implemented under VPS platform to improve the brain behaviour instead of a linear viscoelastic material model [36]. The material model 37 under VPS, which is a combination of Ogden law for hyperelasticity and a Prony series for viscoelasticity, was implemented. Separate material models for white and gray matter were assigned to the brain model as the white matter is stiffer than the gray matter. A second order Ogden law was implemented for hyperplastic part and the material validated with the experimental work of Franceschini [49]. The viscoelastic constants were obtained from the in vivo MRI data by [50]. The improved head model was validated against local brain motion data from Hardy [51-52], and intracranial pressure data from Nahum [53]. The model is also validated for strain distribution against experimental data from Gennarelli [22] in [54]. There are no bad hexa element in the brain. The brain is validated also for stability test described by [55] with hourglass energy less than 10% of internal energy by applying high linear and angular acceleration pulses in sagittal and coronal plane. More information about model validation and material models is given in [36] [46] [54].

Methodology of accident reconstruction and Accident Database

Comprehensive investigation of accidents is the foundation of accident reconstruction, which comprises several steps, as shown in Fig. 2. The first step is to collect accident cases to build a well-documented accident database. In the current study, the accident database consists of 70 cases from real-world head trauma cases and volunteer experimental studies. Twenty-three American football head impact events were collected from the reconstruction study reported by Newman [12-13], with corrections suggested by [56]. The injured cases in NFL are reported as the players having concussion with brief loss of consciousness [57-58]. According to AIS code definition (code: 161002.2 or 161006.3) the injuries can be between AIS2 and AIS3 [9]. There were 29 fall cases with AIS2+ injuries collected from Post's [59-60] reconstruction study. Four occupant accident cases were collected from [61]. Fourteen volunteer sled tests conducted by Naval Body Dynamics Lab (NBDL) were also used for the analysis [62]. In all of the accident cases, occurrence/non-occurrence AIS2+ brain injuries were reported. Linear and rotational acceleration at the head centre of gravity were reported in all cases, except for the seven fall cases from [60]. For the seven fall cases the impact surface was concrete. The material properties of concrete were obtained from [63]. The ranges of maximum resultant linear acceleration, resultant angular acceleration and resultant angular velocity for the database are 19-933 g, 1216-429876 rad/s2 and 12-104 rad/s respectively.

Two separate methods were implemented for the reconstruction of the 70 accidents. For the cases with available head accelerations data, the six accelerations were implemented at the head centre of gravity. The skull was modelled rigid in order to facilitate the implementation of 6 degree of freedom acceleration field. For the seven fall cases [60], the head with deformable skull was impacted to the respective impact surfaces after correcting the head orientation. All the simulations are simulated for the time duration available in the literature. This is between beginning and end of the head kinematics data reported in respective studies. Several mechanical parameters were extracted, such as maximum brain pressure, maximum von Mises stress, maximum principal strain and combination of principal strain and strain rate (named as BIS: Brain injury Score), to derive brain injury criteria. The maximum principal strain and strain rate are from the same tissue location (elements).The BIS is calculated by Equation 5.

$$BIS = a_1 \times \varepsilon + a_2 \times \dot{\varepsilon} \quad (5)$$

Where ε is the local brain strain and $\dot{\varepsilon}$ is the local brain strain rate. a_1 (0.6) and a_2 (0.4 s) are two injury criteria parameters. The distribution of the maximum MPS over the time was filtered with an averaging moving filter to reduce the influence of abnormal MPS peaks.

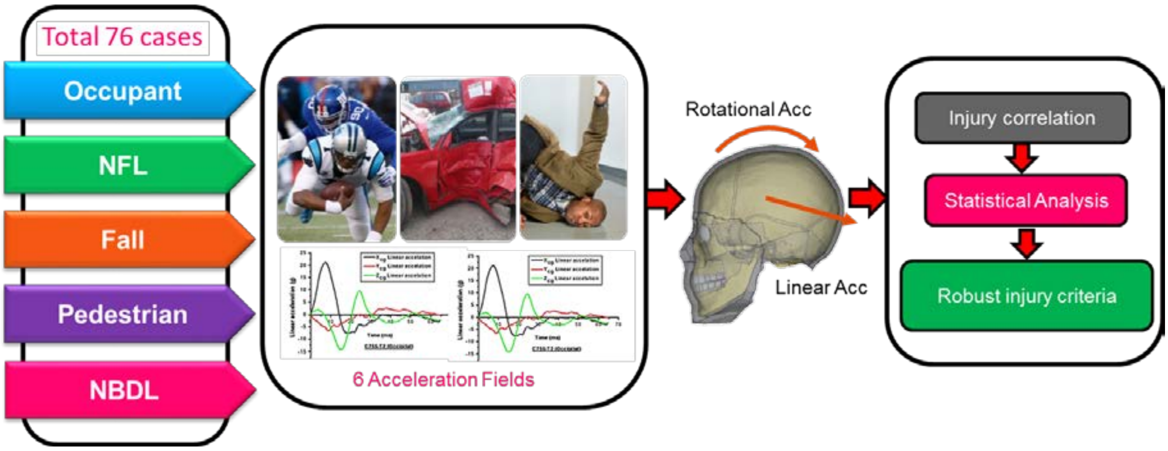

Fig. 2. Methodology for accident reconstruction. Reconstruction was performed for 70 accident cases to develop the criteria and 6 cases to validate the BIS.

Kinematics-based injury criteria HIC, BrIC, UBrIC and CIBIC were also computed for 70 accident cases, for comparison purposes based on Equations 1-4. Six occupant and pedestrian cases were collected from accident reconstructions based on the Audi Accident Research Unit accident database [11] in order to validate the prediction capability of BIS, HIC, BrIC, UBrIC and CIBIC. In-depth accident analysis was performed according to the methodology described in [64-65]. Similar methodology was used with numerus iteration to build the confidence on this reconstruction process. From this study the six accelerations were implemented at the head centre of gravity with a rigid skull to reconstruct the cases.

Statistical Analysis

The aim of the statistical analysis was to provide an objective mean for assessing the capability of different parameters to predict AIS2+ brain injury. Receiver operating characteristic (ROC) curves were plotted to evaluate the ability of the different candidate parameters to predict injury. To create the ROC curve, a binary classifier (with left censored injury (2) and without injury (0)) was used. The ROC plot expresses the performance of a binary classifier system as its discrimination threshold is varied. The curve is generated by plotting the true positive rate (sensitivity) against the false positive rate (fall-out, and can be calculated as 1 − specificity) for various thresholds as shown in Fig. 3. Area under the ROC (AUROC) curve (in solid red) is another measure of the test performance. The test is 100% accurate if the AUROC is 1 (because both the sensitivity and the specificity are 1.0, so there are no false positives and no false negatives). On the other hand, a test that cannot discriminate between normal and abnormal corresponds to a ROC curve that is the diagonal line from (0, 0) to (1, 1). The AUROC for this line is 0.5 (dashed blue line). As described in [66], AUROC is typically between 0.5 and 1.0. Hence, the candidate parameter that has the highest AUROC value and closest to 1 is considered the best parameter to predict injury. The Hosmer–Lemeshow (HL) test was performed using open source statistical code R [67] to test for goodness-of-fit for survival analysis [68]. This test assesses the extent to which the observed event rates match expected event rates in subgroups of the model population. The HL test specifically identifies subgroups as the deciles of fitted risk values and computes the chi-square distribution to get the probability value (P) (P values of 0.7–0.8 indicate acceptable discrimination, values of 0.8–0.9 to indicate excellent discrimination and values of ≥0.9 show outstanding discrimination) to test the fit of survival analysis according to Hosmer and Lemeshow [68]. Furthermore, the Akaike information criterion (AIC) and a log-likelihood analysis were used to show how closely the model predicts binary data. The statistical analysis was performed using the statistical code R [67].

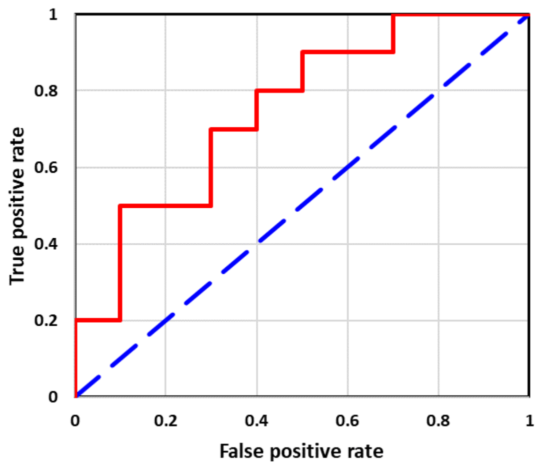

Fig. 3. Receiver operating characteristic curve

An injury risk curve for the different candidate parameters is generated through survival analysis of binary injured and non-injured data, assuming a Weibull distribution. The survival analysis was carried out using open source statistical code R [67]. This method involves fitting of a regression model between a number of possible injury predictors. The probability of brain AIS2+ injury is defined by Equation 6:

$$P\ (x) = 1 - e^{-\left(\frac{x}{b}\right)^{a}} \tag{6}$$

where a is the shape parameter and b is the scale parameter that characterise the Weibull distribution [69].

For each investigated setup, the injury risk based on the different mechanical and head kinematics parameters was computed. Then, the delta percentage risk was calculated for comparison between these injury criteria. The delta analysis represent the error in prediction capability of a metric by calculating difference in occurred injury (from literature) and predicted injury based on injury risk function for each metric. The parameter with the lower number of prediction error is the best suitable metric. ISO [70] recommends using confidence interval width as a measure of quality for the probability density function. The normalised confidence interval size (NCIS) [71] was computed. It is defined as the ratio of the width of the confidence interval to the magnitude of the predictor variable/stimulus from the chosen model at a specific risk level. A lower NCIS magnitude is associated with a tighter confidence interval at the chosen probability level.

III. RESULTS

Head trauma simulations of 70 well-documented accident cases were conducted using the improved THUMS v4 FE head model under VPS platform. Different tissue level parameters, such as maximum principal strain, von Mises stress, brain pressure and combined strain and strain rate parameter BIS, and head kinematics based HIC, BrIC, UBrIC and CIBIC were extracted for each reconstructed case. Artificial high strains have not been observed during the later stage of simulations in any of the investigated cases. VPS available standard mesh quality checks did not highlight any possible problem of the mesh (100% hexahedron element). The results in terms of the occurrence and non-occurrence of injury were plotted for all potential parameters. In Fig. 4 the distribution for BIS is reported: the red columns represent the cases with AIS2+ brain injury and the blue columns represent the cases without brain injury. The smooth histogram, with a relatively small discontinuity, indicates a good sensitivity of the BIS as injury criterion. The ranges of strain and strain rate for injured cases are 0.22-1.6 and 42-3000 /s respectively.

Survival analysis of binary injured and non-injured data with Weibull distribution was conducted to extract the injury risk curve for the different parameters. For BIS the weighing coefficients a_1 and a_2 are optimized to get the best correlation with the database. Fig. 5 shows the BIS injury risk curve to predict AIS2+ brain injury: the white circles represent the non-injured cases, while the cases with injury occurrence are represented by black circles. The 50% risk of AIS2+ brain injury is reported in Table I for each tissue-level and head kinematics based (HIC, BrIC, UBrIC and CIBIC) parameter. The 95% confidence interval was also extracted for all parameters and values are reported in Table I. Furthermore, the NCIS at 50% injury risk was computed and reported. It is observed that BIS has the smallest NCIS value, demonstrating the robust correlation to the injury sustained. The AUROC, HL-P, AIC and log-likelihood statistic test were performed for all tissue-level and kinematics-based parameters, as shown in Table I. It can be observed that BIS has the highest AUROC, HL p-value and log-likelihood of 0.99, 0.94 and -6.9 respectively, and lowest AIC value of 17.9, and presents the smallest confidence interval thus indicating a robust correlation with the observed injuries. Although, MPS and von Mises stress show good AUROC value, the HL p-value was below 0.8. CIBIC presented the lowest AUROC and HL p-value of 0.69 and 0.5, respectively. BrIC has the highest AIC value of 85.2 and lowest log-likelihood value of -40.6.

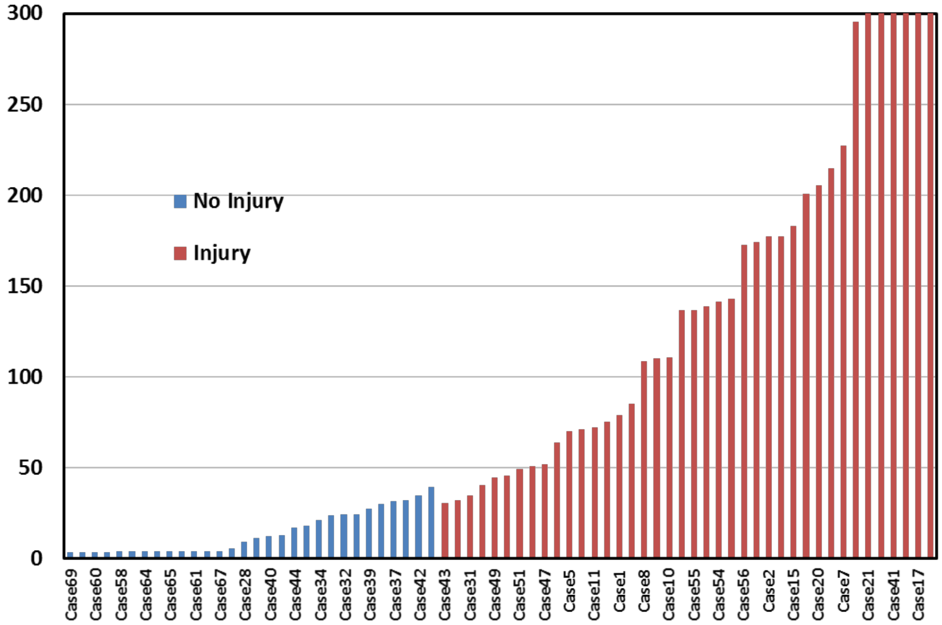

Fig. 4. Brain Injury Score computed for all head injury simulations. In blue are the cases without injury (30 cases), and in red are the setups (40 cases) where an AIS2+ brain injury occurred.

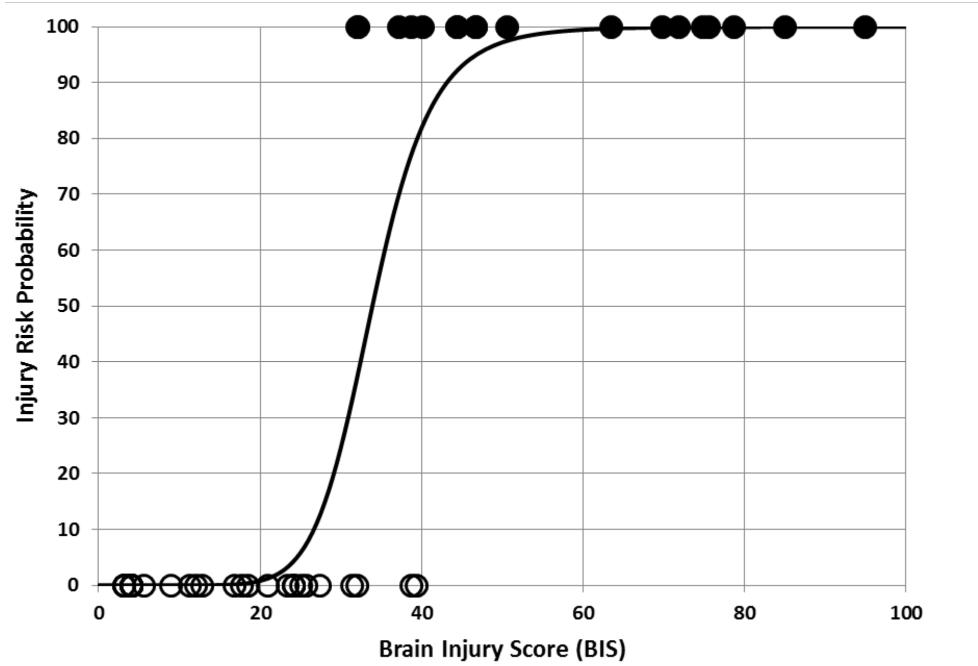

Fig. 5. Injury risk curve to predict the AIS2+ brain injury by considering BIS as injury predictor. The BIS values above 80 are having 100 percent injury risk. The points after BIS 100 are not shown.

TABLE I
COMPARISON OF RESULTS FROM SURVIVAL ANALYSIS FOR DIFFERENT INTRACEREBRAL MECHANICAL PARAMETERS COMPUTED FOR THE 70 ACCIDENT CASES TO PREDICT DAI

Predictor	Threshold (50% Risk)	Lower limit of 95% confidence interval (50% Risk)	Upper limit of 95% confidence interval (50% Risk)	NCIS $_{50\%risk}$	AUROC	HL p- value	AIC	Log-Likelihood
BIS	34.44	30.01	39.51	27%	0.99	0.94	17.9	-6.9
BrIC	0.59	0.48	0.72	41%	0.75	0.52	85.2	-40.6
HIC	265.2	188	375	70%	0.85	0.53	37.6	-16.8
MPS	0.32	0.26	0.39	56%	0.95	0.66	40.6	-18.3
Pressure	247499 Pa	206573 Pa	296532 Pa	42%	0.84	0.58	43.3	-19.6
VM stress	16890 Pa	13666 Pa	20876 Pa	45%	0.94	0.75	39.5	-17.8
UBrIC	0.41	0.32	0.52	48%	0.72	0.54	33.91	-14.9
CIBIC	0.62	0.49	0.78	46%	0.69	0.5	64.98	-30.5

The injury risk probability predicted by the different tissue-level and kinematics-based (HIC, BrIC, UBriC, CIBIC) criteria was computed for each case. Then the relative percentage difference (Δ) between the predicted risk and the sustained risk from literature was computed for all head trauma cases. Three different categories are defined to cluster the cases depending on the Δ value and are reported in Fig. 6: less than 25% (green), more than 50% and between 25% (blue), and 50% difference (red). The BIS has the highest number of cases with relative error below 25%. HIC has a smaller number of cases (35) with more than 50% difference than BrIC (40), UBrIC (44) and CIBIC (45). From the 63 cases (with less than 25% Δ) for BIS, only one case is above 20% and more than 50 cases have Δ equal to zero. The kinematics criteria show the smallest sensitivity of all the predictors.

In addition six occupant and pedestrian cases coming from the AARU were reconstructed to validate the prediction capability of BIS, HIC, BrIC, UBrIC and CIBIC. The results are reported in Table II. The BIS was the best injury predictor in these cases the whereas BrIC, HIC, UBrIC and CIBIC over predicted the brain injury outcome in several cases.

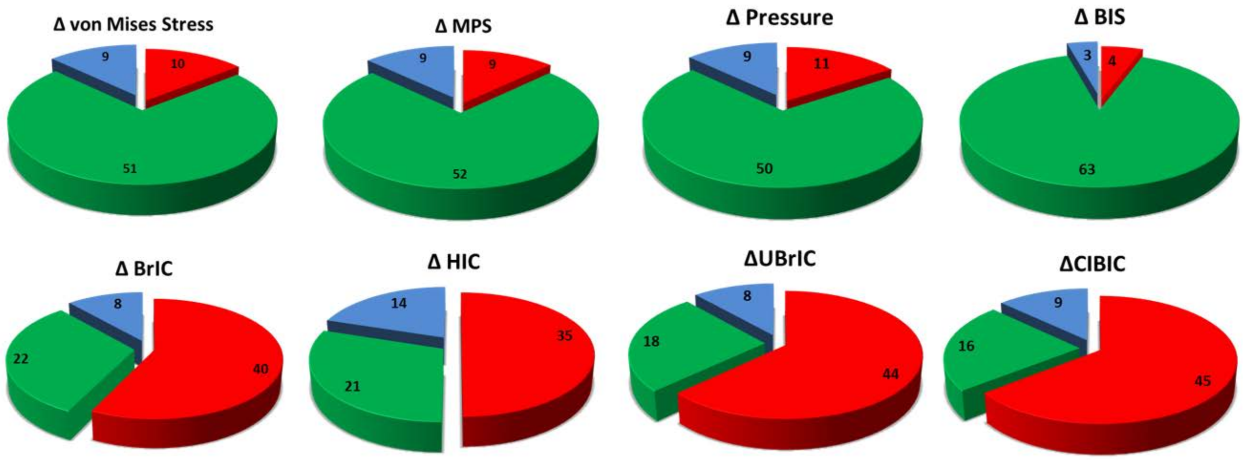

Fig. 6. Comparison of Δ percentage risk for different parameters.

TABLE II
COMPARISON OF INJURY PREDICTION CAPABILITY OF PARAMETERS

Cases	Injury sustained (AIS2+)	BIS (AIS2+)	BrIC (AIS2+)	HIC (AIS2+)	UBrIC	CIBIC
Audi load case1	0	0	0.37	0	0.16	0.14
Audi load case2	0	0.04	0.52	0.24	0.19	0.17
Audi load case3	1	1	1	0.95	0.74	0.76
Audi load case4	1	1	1	1	0.61	0.67
Audi load case5	1	1	1	0.9	0.72	0.74
Audi load case6	0	0.16	1	0.40	0.47	0.44

IV. Discussion

The principal objective of this study was to compare different brain tissue-based and global head kinematics-based injury criteria for well-documented real-world head trauma cases. The improved THUMS v4 model was used to simulate all the accident cases and several tissue-based criteria, such as brain pressure, von Mises stress, maximum principal strain and combined strain and strain rate criteria (BIS), were computed under VPS platform. Similarly, global head kinematics-based HIC, BrIC, UBrIC and CIBIC were calculated based on Equations 1, 2, 3 and 4 respectively, by using the imposed six field head acceleration data obtained from the literature (no data coming from improved THUMS v4 are used for the computation) at the head centre of gravity. As shown in the Results section, when plotting cases with and without injury occurrence, BIS shows a smooth transition from non-injured to injured cases with minimal discrepancy. Based on the survival analysis of all tissue-based and head kinematics-based parameters, BIS has, on average, the narrowest 95% confidence corridor (NCIS= 27%), which indicates that BIS presents the highest correlation with the injury sustained in the simulated trauma cases.

The statistical analysis performed for the different brain tissue-based and head kinematics-based criteria showed that BIS has the highest AUROC (0.99), HL p-value (0.94) and log-likelihood (-6.9) and lowest AIC value. AROC is a principled way of deciding hierarchy between candidate metrics [71]. The combination of these four statistical analyses represents a generalised and robust method [69-72]. von Mises stress and MPS proved equally good for AUROC test, but von Mises stress has higher HL p-value than MPS, which is in accordance with [18][73]. CIBIC had the lowest value of AUROC and HL p-value. BrIC had lowest log-likelihood value.

Furthermore, the relative error of AIS2+ brain injury predicted by the different tissue-level and kinematics-based criteria was computed for all head trauma cases. The BIS had the lowest rate of error. Interestingly, the CIBIC has the highest number of cases (45 from 70, followed by UBrIC (44), BrIC (40)) showing a relative error larger than 50%. However, all the tissue-based criteria (except brain pressure) show better correlation with the sustained injury than the global head kinematics criteria, which is in accordance with previous studies [18][35][73]. Based on six AARU accident reconstructions, the BIS prediction of Injury was well validated. The BrIC and HIC mostly over-predicted the injury for the six AARU cases (as reported in Table II), which was also confirmed by [19][27][74]. This may be due to the assumption used for the development of BrIC risk function that the AIS4+ injury sustained by animals can be scaled to humans under equivalent loading condition. The other AIS severity levels were derived using the ratios of HIC values for 50% risk at different severity levels [26]. This method indicates that rotational and translational motion-induced brain injuries would scale proportionally across injury severity, but it has no proof in the literature [27]. Similarly, the lesser ability of HIC to predict brain injury than tissue-based criteria is due to the lack of rotational motion in the formulation, which is an important factor to produce brain injury [42]. HIC was derived from the correlation of skull fracture and no further brain injury mechanism was considered in the criteria. Studies have found that there can be brain injury (DAI) without the occurrence of skull fracture [17]. UBrIC and CIBIC also over predicted the sustained injury for the six AARU cases.

The accuracy of the head trauma simulation was based on the correct extraction of head accelerations during accidents and well-documented accident reports. All the trauma cases were collected from published data and have been rigorously used by many biomechanics studies [18][27][35][73-74] and corrected through the last decades [13][56]. Nevertheless, the confidence of the injury risk is influenced by the sample size. In this study, 70 head trauma cases were investigated, which is reasonable when compared to other studies [18][33] and further

6 head-trauma cases were used to validate the injury risk function. The shape of the probability density function is greatly influenced by the ratio of injured/non-injured data [67]. In the current study 40 out of 70 cases presented an AIS2+ injury. According to [75] equal size group (equal number of injury and non-injury cases) is desirable for robust statistical analysis, maximization of the statistical power of the analysis. Therefore, the ratio of injured to non-injured cases was reasonable when compared with similar studies [25][26][33][73]. However, a good distribution of the data could increase the robustness of injury risk function. The ranges of maximum resultant linear acceleration, resultant angular acceleration and resultant angular velocity for the database (70 cases) are 19-933 g, 1054-429876 rad/s2 and 12-104 rad/s respectively. Based on kinematics values considering peak linear acceleration, for most of the fall cases (50-933.7g) and football cases (32-123g) are well within the range of occupant cases (19-680 g). Similarly for rotational acceleration most of the fall cases (2779-55602 rad/s2) and football cases (1953-9563 rad/s2) are well within the range of occupant cases (1054-30787 rad/s2). Among the 70 cases 40 cases are having AIS2+ injury for the brain. The method of using mixed injury data coming from different accident scenarios (sports, fall, road accidents and volunteer tests) and database were previously reported by several studies [26][28][30][73] to develop injury criteria.

The improved head model was validated with available literature data [46] which included the validation of the local brain motion, impactor force response and local internal pressure. Although there was a good agreement between the response predicted by the improved head model and the experiments, further validation is needed to increase the confidence in the model. The model is not validated against strain rate due to lack of experimental data. Nevertheless, the model is improved for strain rate dependent visco-elastic Ogden law based on in-vivo experiments [50]. However, the accurate prediction of the brain injury reported for 6 real accident cases suggests that the brain model and proposed method can be used to assess mild TBI. Also, the assumption of isotropic material response is not realistic. The inclusion of the axonal fibers direction of the brain matter could further improve the ability of the model to predict local injuries of the tissue. Furthermore, the modelling of additional physiological structures such as the bridging vein would also allow the possibility to predict additional injury mechanisms such as subdural haematoma.

The BIS is based on the improved THUMS v4 head model described in the current study. No other FE head model is tested for BIS. However, the concept of combination of strain and strain rate (BIS) may give the highest correlation for the accident database by using other model and the weighing coefficients (a1, a2) need to be tuned for the respective model.

V. CONCLUSIONS

An in-house improved head model was used to simulate 70 well-documented head trauma cases under VPS platform. Several brain tissue-level and global head kinematics parameters were computed from the simulation results. A brief comparison of all criteria was conducted to demonstrate the capability of different potential parameters to predict AIS2+ brain injury. Combined brain strain and local strain rate criteria (BIS) showed the highest correlation for all statistical tests, and hence resulted in the best parameter to predict AIS2+ brain injury. HIC, BrIC, UBrIC and CIBIC showed poor correlation with tissue-based injury criteria and BrIC mostly over-predicted the injury for the six AARU cases. This study is a constructive step toward the building of high-quality head models and robust brain injury criteria under VPS platform.

VI. ACKNOWLEDGEMENTS

The authors would like to acknowledge AUDI AG for funding and the Audi Accident Research Unit for providing the data for the accident reconstructions.

VII. REFERENCES

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