The influence of personalisation of the Finite Element Head Model in predicting Traumatic Brain Injury (TBI)

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Abstract Finite Element Head Models (FEHMs) have emerged as a cost-effective tool for studying Traumatic Brain Injuries (TBIs) resulting from a fall. The ability to capture spatial injury location in terms of location Index (LI) and Overlap Index (OI) can enhance the usability of FEHMs to correlate FE predictions with CT injuries in real-world accidents. This work uses personalized FEHMs to predict injuries in a fall and correlate with clinical records spatially. Three real world fall scenarios were used to demonstrate the methodology. In these cases, OI and LI improved by 31.3%, 26.4%, and 27.7%, and by 23.2%, 22% and 27.3%, respectively on using the personalized FEHM. This study, thus, highlights the need for personalising FEHMs for brain injury predicton.

Keywords Finite Element Head Model, Head Personalisation, Spatial injury correlation, Location Index, Overlap Index.

I. INTRODUCTION

Post-injury CT/MRI scans are commonly used by clinicians to diagnose brain injury resulting from a fall [1]. Researchers use Finite Element Head Models (FEHMs) to understand injury mechanisms and use injury location and volume for validation against CT images[2-5]. Fahlstedt *et al.* (2015) correlated the injury pattern with clinical images by assessing the location index (LI) and overlap index (OI). Most of these studies are limited to two-dimensional comparisons of LI and OI at various sections of FEHM. This study uses 3D FEHM and carries out a spatial correlation with CT data. Further, the injury estimation from the FEHM depends on the size/geometry of the HM, therefore employing a 50th percentile or baseline model universally may yield erroneous outcomes [7],[8]. This is why it is important to use a personalised FEHM in such studies. This study investigates the effect of personalisation of the HM on the LI and the OI and presents a methodology for the reconstruction of falls. This methodology can enhance the usability of FEHMs for spatially correlating FE predictions with CT injuries in real-world accident scenarios, thereby reliably reconstructing the fall.

II. METHODS

This work studies the effect of personalising the FEHMs with regard to the location and extent of traumatic brain injury (TBI). Figure 1 shows the workflow used in this study. Data on three cases were collected from the JPN Apex Trauma Centre New Delhi (JPNATC), as shown in Table I.

These falls were reconstructed using the Hybrid-III male dummy model available in multibody dynamics software (MADYMO © 2021 Siemens Inc.). The H-III dummy was scaled using GEBOD according to the height and weight of the subjects. Iterations were carried out by changing the initial body orientation to match the point of head impact on the floor with the clinical record. Initial impact velocity and orientation of the head were extracted from the simulations and subsequently used in FE simulations to predict injuries in the head.

Simulations were done in LS-DYNA (© 2023 ANSYS, Inc). A baseline Head Model corresponding to the 50th percentile Indian male population [9], which was validated based on previous experimental studies [10-12], was used in this study. This model was personalised as per patient anthropometry, and the results were compared with those of the baseline model. For each subject, the head length (anterior-to-posterior), head width (left-to-right), and head height (vertex-to-gnathion) were measured as in earlier studies [7][13-14]. The scale factors were calculated by dividing the patient's head height h_s, head length l_s, and head width w_s by the baseline FE head height H_b, head length L_b, and head width W_b, respectively. The head model was scaled by these factors about three orthogonal dimensions of the head height, head length, and head width. Each simulation was conducted on LS-DYNA (© 2023 ANSYS, Inc) utilising 32 GB of RAM and an Intel Core i9 3.5 GHz processor for a duration of 10 ms, adequately capturing the head-ground collision. The FE head was impacted on concrete ground, and a coefficient of friction of 0.5 was used between the two.

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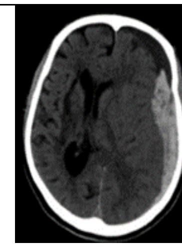
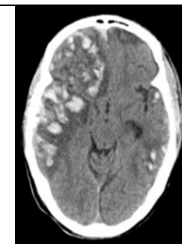
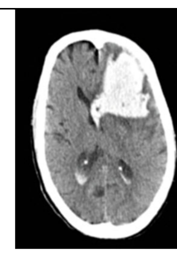
TABLE I
DETAILS OF THE PATIENTS AND THE ACCIDENTS

Case details	Injury history discharge summary	Witness testimonies, Details investigating the case	CT findings	CT image
Male, 61yo Height 166 cm Weight 65 kg Head length 173.4 Head width 139 Head height 181.2	Fall from 4th step of stairs. No loss of consciousness, vomiting, and ENT bleeding.	The patient was climbing the stairs when he fell backward from the 4th stair. The right leg is on the fourth step of the stair, whereas the left leg is aerial. Tread 22.8 cm, riser 20.32 cm, width 1.8 m.	Left front-temporal-parietal subdural haematoma 73.7 cc, 18.8 mm thick with 14 mm midline shift toward right.	
Male, 35 yo Height 170 cm Weight 68 kg Head length 184 Head width 147 Head height 195	Fall from the first floor under the influence of alcohol. Loss of consciousness. No vomiting, ENT bleed, or seizure.	Leaning backward on the railing for fresh air, fall asleep/ unconscious. And fell from 318 cm onto the ground, which is made of cement/concrete.	Right fronto-temporal contusion with midline shift to left side with left temporal contusion with subdural haematoma.	
Male, 45 yo Height 170 cm Weight 70 kg Head length 208 Head width 146 Head height 218	This case involved a 45-year-old male who lost his balance on a wet floor in Saket, Delhi, while getting down to the stairs, forward fall from the 4th step of the stairs.	This case involved a male who lost his balance on a wet floor in Saket, Delhi, while getting down to the stairs. He fell forwards from the 4th step of the stairs.	No skull fracture, Right Frontal hematoma of size 68.2 cc, midline shift of 4 mm.	

Computation of LI and OI

As shown in Fig. 2(a), below, the damage volume of the brain CT image was segmented in MIMICS (© Materialise, inc.) software adopting Hounsfield Unit (HU) range of 0–130 HU [15]. In Fig. 2(b), cumulative damage volume of the FE brain hemisphere was computed in HyperView (©Altair inc) using a Maximum Principal Strain (MPS) injury threshold of 0.19, indicating a 50% probability of mild traumatic brain injury (mTBI) [16]. Cumulative damage in the FE brain model was estimated by creating an envelope over the 10 ms duration of the simulation, as illustrated in Fig. 2(b). To compute the LI and OI, the FE model and the CT scan were scaled to fit inside an identical bounding box and superimposed (Fig. 2(c)). In Fig. 2(d), the damaged zone in the FE elements and the volume of patient injuries were depicted using the 3D scatter plot function in MATLAB (©MathWorks, Inc.). Finite Element brain length (l_1), as well as centroidal distance between FE and CT injury patterns (l_2), are shown in Fig. 2(d). The location index (LI) was defined as the ratio of the difference of FE brain length (l_1) and centroidal distance (l_2) between FE and CT injury patterns divided by the FE brain length in the 3D brain hemisphere. In Fig. 2(e), the intersecting elemental volume of FE model and patient brain was calculated in HyperView (© 2024 Altair inc). Overlap index (OI) was defined as the ratio of intersecting volume (v) of the FE and CT lesion volume divided by the mean of the FE (v_1) and CT haematoma (v_2) volumes (Fig. 2(e)). Maximum correlation between FE and CT injuries is achieved when both LI and OI are 1.0. The LI and OI of the baseline and personalised FE brain were computed to assess the impact of personalisation in FE simulations.

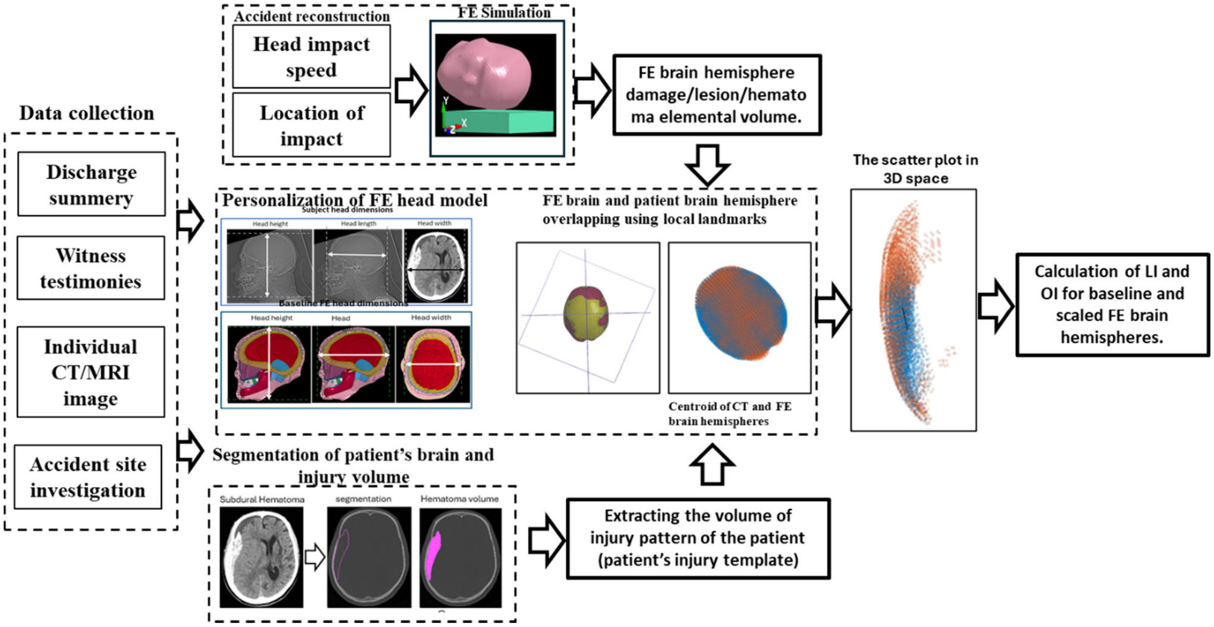


Fig. 1. Workflow of the injury pattern correlation in 3D brain hemisphere.

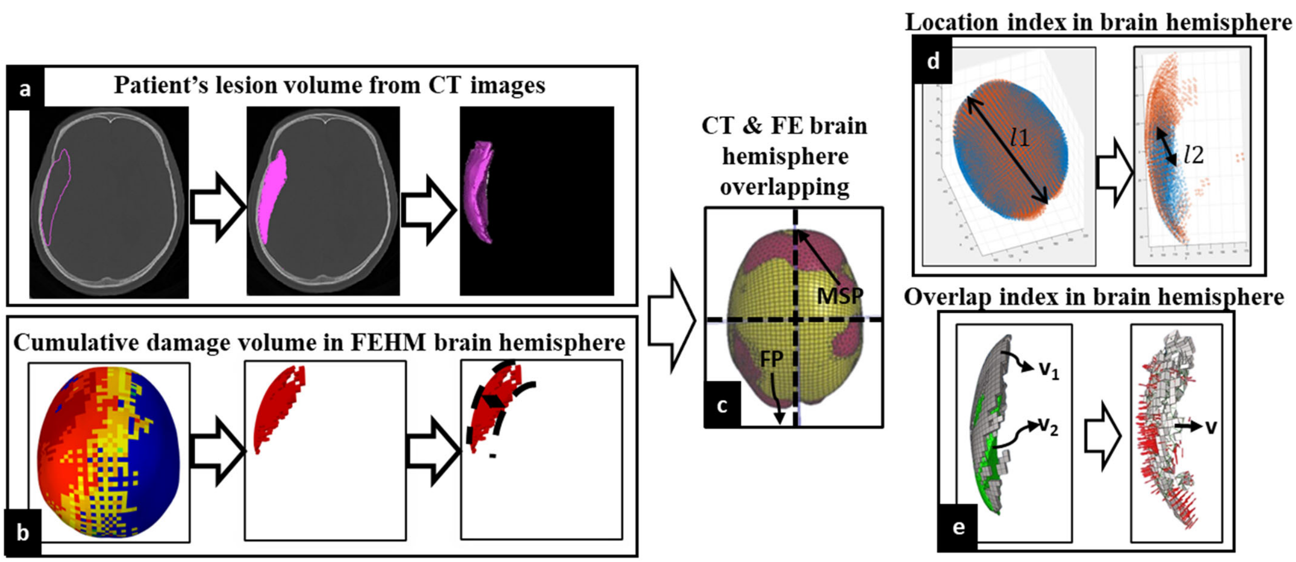


Fig. 2. (a) Patient lesion volume segmentation in MIMICS, (b) cumulative damage volume of FE brain hemisphere, (c) aligning CT & FE hemispheres, (d) Location index (LI) of brain hemisphere, (e) Overlap index (OI) of brain hemisphere.

III. RESULTS

The three accident cases for which data were available were used to demonstrate the methodology. The head impact speed and the orientation extracted from the MADYMO simulations are listed in Table II. The scaling factors used in the FE simulation in the next stage are shown in Table III for the three cases. The LI and OI of the baseline and scaled FEHM are presented in Table IV and Table V.

TABLE II
HEAD IMPACT SPEED AND ORIENTATION FROM MADYMO SIMULATIONS

Cases	Patient details	Height (cm)	Weight (kg)	Estimated head impact speed (m/s)	Head impact location (azimuth and elevation angles) in degree
Case_1	M, 61	166	65	6.4	73°, 67°
Case_2	M, 35	170	68	7.7	-56°, 74°
Case_3	M, 45	170	70	5.3	-37°, 39°

TABLE III
MEASUREMENTS OF PATIENT, BASELINE, AND SCALED FE HEAD MODEL

Cases	Head model	Head height (in mm) HH	Head width (in mm) HW	Head length (in mm) HL	Scale factors	Brain volume (in cc)
Case_1	Patient head	181.2	139.2	173.4	--	1069.5
	Baseline FE head	201.8	156	192.5	--	1369
	Scaled FE head	181	140.5	172	0.9(HH) 0.89(HL) 0.9(HW)	1008
Case_2	Patient head	195	147	184	--	1362
	Baseline FE head	201.8	156	192.5	--	1369
	Scaled FE head	194	148	187	0.96(HH) 0.95(HL) 0.95(HW)	1291
Case_3	Patient head	218	146	208	--	1489
	Baseline FE head	201.8	156	192.5	--	1369
	Scaled head	216	146	208.5	1.08(HH) 1.08(HL) 0.93(HW)	1420

TABLE IV
EFFECT OF PERSONALISATION ON LOCATION INDEX (LI)

Cases	Baseline/scaled FE Head Model	Centroid of 3D injury pattern	FE Brain length L_1 (mm)	Distance between centroids of the patient and FE injury pattern L_2 (mm)	LI	Improvement in LI (%)
Case_1	CT head	-6.42, 102.2, 1.93	--	--	--	23.2
	Baseline head	-24.1, 139.0, 25.3	150.5	47.1	0.69	
	Scaled HM	11.6, 103.9, 9.8	132.22	19.7	0.85	
Case_2	CT head	-42.9, 73.1, -21.4	--	--	--	22
	Baseline head	14.9, 62.4, -2.1	150.5	62	0.59	
	Scaled HM	-73.3, 69.7, -48	145.36	40.5	0.72	
Case_3	CT head	-43.7, 123.9, -49.8	--	--	--	27.3
	Baseline head	-8.3, 134.4, 25.2	150.5	83.6	0.44	
	Scaled HM	-34.6, 121.1, -37.7	153.7	66.2	0.56	

TABLE V
EFFECT OF PERSONALISATION OF OVERLAP INDEX (OI)

Cases	Baseline/scaled FE Head Model	Volume of Damage (FE model) V_1 (cc)	Volume of injury (CT scan) V_2 (cc)	Intersecting Volume of CT and FE injury patterns (v) (cc)	OI	Improvement in OI (%)
Case_1	Baseline head	34.24	73.7	8.029	0.15	31.3
	scaled	56.4		12.8	0.197	
Case_2	Baseline head	44	197.8	10.5	0.087	26.4
	Scaled	72.75		15.45	0.11	
Case_3	Baseline head	55.3	68.2	8.2	0.13	27.7
	Scaled	71.4		11.6	0.166	

IV. DISCUSSION

This study introduces a framework to correlate the spatial FE injury pattern with the patient's brain injury. Location index and Overlap index were calculated in three accident scenarios. OI was improved by 31.3%, 26.4%, and 27.7% when the FEHM was adjusted to align with the patient's cranial anthropometry. LI was improved by 23.2%, 22% and 27.3% in the three cases when the FEHM was scaled to correspond with the patient's head model. The improvement in LI after personalisation of the head model indicates that the spatial proximity of the FE damage pattern is better aligned with the patient's injury for the personalised model. The OI denotes the intersection volume of HM with respect to the clinical injury pattern; an increase in OI after personalisation indicates an improved and robust association between personalised HM and clinical injury. The LI and OI are still not close to 1, indicating there is room for further improvement. This can possibly be achieved by the use of better injury criterion, or better personalisation method, or patient-specific HM.

This study highlights the need for personalising FEHMs for spatial injury correlation, as scaling the model to the patient's cranial dimensions improved injury correlation. In spatial correlation, OI exhibits more sensitivity and demonstrates trends consistent with other injury pattern correlation studies conducted on 2D sections [6],[16]. Scaling (to match the patient's head anthropometry) influences trauma-induced pressure and stresses in the brain, altering the volume and thickness of the injury.

While the study highlights the need for personalisation of FEHMs in injury prevention, it is a preliminary investigation and further investigations are warranted. The kinematics of the accident reconstruction may be affected by multiple parameters [17], and investigations into additional parameters may be warranted. Further, this study uses passive human body models and muscle forces during the fall are ignored. The injury volume is a time-dependent phenomenon [18-19]; hence, the cases examined in this investigation involved CT images acquired within six hours of the accidents. It should also be noted that this paper only investigates scaling for personalisation of the FEHMs. Therefore, other methods of personalisation also need to be explored. The study uses MPS as the injury criterion. Injury prediction and the effect of personalisation should also be investigated for other injury criteria, such as the Cumulative Strain Damage Measure (CSDM), Organ Injury Score (OIS), Military Combat Incapacitation Scale (MCIS), and New Injury Severity Score (NISS).

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