Feasibility of using a novel instrumented human head surrogate to measure helmet, head and brain kinematics and intracranial pressure during multidirectional impact tests

Nicola Petrone [a,*], Gianluca Candiotto [a], Edoardo Marzella [a], Federico Uriati [a], Giovanni Carraro [a], Mikael Bäckström [b], Andrey Koptyug [b]

[a] Department of Industrial Engineering, University of Padova, Italy
[b] SportsTech Research Centre, Mid Sweden University, Sweden

ABSTRACT

Objectives: Aim of the work is to present the feasibility of using an Instrumented Human Head Surrogate (IHHS-1) during multidirectional impacts while wearing a modern ski helmet. The IHHS-1 is intended to provide reliable and repeatable data for the experimental validation of FE models and for the experimental evaluation of modern helmets designed to enhance the degree of protection against multidirectional impacts.

Design: The new IHHS-1 includes 9 triaxial MEMS accelerometers embedded in a silicone rubber brain, independently molded and presenting lobes separation and cerebellum, placed into an ABS skull filled with surrogate cerebrospinal fluid. A triaxial MEMS gyroscope is placed at the brain center of mass. Intracranial pressure can be detected by eight pressure sensors applied to the skull internal surface along a transversal plane located at the brain center of mass and two at the apex. Additional MEMS sensors positioned over the skull and the helmet allow comparison between outer and inner structure kinematics and surrogate CSF pressure behavior.

Methods: The IHHS-1 was mounted through a Hybrid III neck on a force platform and impacted with a striker connected to a pendulum tower, with the impact energies reaching 24J. Impact locations were aligned with the brain center of mass and located in the back (sagittal axis), right (90° from sagittal axis), back/right (45°), and front right (135°) locations. Following dynamic data were collected: values of the linear accelerations and angular velocities of the brain, skull and helmet; intracranial pressures inside the skull.

Results: Despite the relatively low intensity of impacts (HIC at skull max value 46), the skull rotational actions reached BrIC values of 0.33 and angular accelerations of 5216 rad/s^2, whereas brain angular acceleration resulted between 1,44 and 2,1 times lower with similar values of BrIC.

Conclusions: The IHHS-1 is a physical head surrogate that can produce repeatable data for the interpretation of inner structures behavior during multidirectional impacts with or without helmets of different characteristics.

1. Introduction

Traumatic Brain Injury (TBI) is one of the most severe outcomes of accidents in sports, crashes or blasts.[1] In winter sports, head injuries present high severity, despite their lower incidence with respect to knee and wrist injuries.[2]

Helmet manufacturers, regulatory institutions and scientists have been working towards the improvement of protective devices and surveillance methods to reduce the incidence of TBI. Compact recording systems help analyzing the collisions in active sports, supporting the improvements into injury prevention technologies and equipment.[3,4,5] The use of modern wearable devices[6] and video analysis also significantly contributed to the pool of available data. But linking the external sensor data to the brain injury mechanisms is an issue.

Laboratory testing of helmets, often extending the procedures established in international standards (ISO, EN, ASTM), is evolving

* Corresponding author.
E-mail address: nicola.petrone@unipd.it (N. Petrone).

towards multidirectional impacts and instrumented dummy heads able to evaluate the protection against complex cases.[7]

Together with cadaveric studies,[8,9] recent studies are carried out using Finite Element (FE) analyses. Several FE models have been developed over the years[10]: Wayne State University Head Injury Model (WSUHIM), TNO Head Finite Element Model, Strasbourg University Finite Element Head Model (SUFEHM), KTH models,[11] University College Dublin Brain Trauma Model (UCDBTM), Toyota's Total HUman Model for Safety (THUMS), the SIMulated Injury Monitor (SIMon), the Global Human Body Models Consortium mid-sized male full body model (GHBMC), the Dartmouth Scaled and Normalized Model (DSNM),[12] just to mention some.

All FE models share three issues to address: (i) the model geometry approximation and level of discretization; (ii) the assumptions on tissue mechanical characteristics and their homogeneity; and (iii) the validation against experimental data.

Many studies addressed the experimental characterization of head and brain tissues,[13] and others experimentally addressed impact kinematics[14] using either human subjects (mostly from cadavers and MRIs) or animal tests (pigs, bovines and rats). All FE models refer to the literature for the implementation of tissue properties and give evidence of the parameters adopted in the model.[10]

Given technical and ethical issues with cadaveric multidirectional impacts, many models were validated against available impact tests in terms of intracranial pressure[8] and acceleration dynamics.[9] Several FE studies achieved a good correlation between human cadaver data and FE simulations of intracranial pressures[11,15,16] but great attention is posed on damage mechanism involving axons (Diffuse Axon Injury, DAI)[17] correlated with angular rather than linear kinematics. Comparisons among simulation results of three validated models[18] also highlighted differences in the results of modeling in different brain regions.

FE simulations are however fundamental for studying brain injury mechanisms, considering the complexity of testing human cadavers or scaling animal testing to humans. Therefore, a validated instrumented physical model with the desired experimental repeatability can become an experimental cross-validation tool for FE models and allow investigating significant parameters during impacts. Currently, headforms used for impact tests are relatively simple and not representative of the human head outer and inner anatomy. Headforms in standards like EN 960 are hollow aluminum/magnesium shells with simplified shape, housing a triaxial accelerometer at the head Center of Mass (HCoM). Several works for helmet evaluation utilized the Hybrid III dummy head, mostly connected to the Hybrid III neck that, despite its limitations, presents different flexibility in flexion and extension; several studies were conducted using the NOCSAE headform, presenting more biofidelic shape, with nylon skull walls and a gel-filled cavity.[19] Instruments in dummy heads are typically single or multiple triaxial accelerometer disposed around the HCoM to compute linear and angular quantities; additional gyros at the HCoM are also common.

The number of studies devoted to the development of biofidelic human head surrogates for helmet analysis is quite limited. Zhang et al.[20] used a gel-filled ellipsoidal-shaped physical model. The shell cavity was filled with a gel, four pressure transducers were attached outside the shell and four were distributed into the brain simulant. Transducers recorded intracranial pressure responses, but the biofidelity of the model was poor. Zhu et al.,[21] used silicone gel (Sylgard® 527 A&B) for the brain tissue simulation: an egg-shaped skull/brain surrogate was exposed to blast overpressure in a shock tube. Pressures within the tube and the surrogate were recorded. Authors admitted that anatomical details of the human head were neglected. Another study, carried out by Taha et al.[22] investigated the effects of soccer heading on the brain. A hollow ABS skull was filled a with ultrasound gel 12. This solution ignored the relative movement between brain and skull and the influence of the cranial fluid between them. One triaxial accelerometer was placed inside the gel at the head CoM, assuming these accelerations represented the brain acceleration. In 2015, Awad et al.[23] developed a head surrogate while investigating blast-induced mild traumatic brain injuries. Four pressure transducers (frontal, occipital and temporal lobe, plus one between the two hemispheres) were embedded in the surrogate brain, while one accelerometer was attached to the brain surface. Authors studied the airdriven shock tube rather than the brain-skull complex, as it was by Zhu et al.[21]

An advanced human head surrogate was developed by Freitas et al.[24] for military helmets ballistic investigations. This human surrogate is based on refreshed human craniums (dehydrated human bone from donors, rehydrated in a Shellac solution) and surrogate materials representing head soft tissues such as the skin (5–7 mm of Perma-gel), dura (0.5 mm silicone membrane), and brain (Perma-gel mixed with iron). Sensors applied to the head surrogate measured intracranial pressure (four pressure sensors in the brain), skull strain (12 strain rosettes), and skull (triaxial accelerometer at the hard palate) and helmet accelerations. Together with the use of dehydrated human skulls, a limitation of the study was a brain surrogate not validated against experimental brain characteristics.

The Head Injury Criterion (HIC) is widely used to estimate the head injury risk.[25] The Brain Injury Criterion (BrIC), based on angular speed about x, y, z directions (x-sagittal forward direction, y-transverse left direction and z-longitudinal upwards direction[18]), was introduced in 2013 to overcome HIC limitations. Takhounts et al.[26] proposed the BrIC criterion using a maximal value of 1 corresponding to a 50% probability of AIS 4+. Angular accelerations were excluded from BrIC as not well correlating to physical parameters, but recent studies are consistently reporting angular acceleration values as well.[18]

Both HIC and BrIC consider the human head as a solid entity and assume that referring to the head HCoM linear acceleration and angular velocities is sufficient to evaluate fracture and brain injury risk. This assumption has proven to be weak in real-life scenarios.[27]

Aim of this work is to present and discuss the feasibility of using a novel Instrumented Human Head Surrogate (IHHS-1) developed in collaboration between Mid Sweden University, Östersund, Sweden and University of Padova, Italy, for the biofidelic impact investigation of helmets and the study of brain injury mechanisms.[28]

2. Methods

The Instrumented Human Head Surrogate (IHHS-1) geometry was obtained from open source MRI scans. Original topologies of skull and brain were simplified, a smoothing process was carried out and bottom part of the skull was flattened for connection with Hybrid-III neck. The brain sulci were neglected but anatomical separation between the hemispheres and cerebellum was preserved.

Skull and brain molds were 3D printed in ABS plus-P430 by FDM technology: the inner surface of skull was equipped with pressure transducers embedded in the skull. A sawtooth suture was introduced between two skull portions for sustaining shear loads and sealing cerebrospinal fluid (Fig. 1a).

Given the large variability in literature data about brain properties,[29] silicone rubber Platsil-Gel 00-20 A + B (Polyconform GmbH®) was adopted for the brain surrogate for the possibility of tuning its properties to the brain tissue.[29,30] The brain surrogate was molded in the "upside down" position in consecutive layers embedding sensors after corresponding layer was cured (Fig. 1b and c).
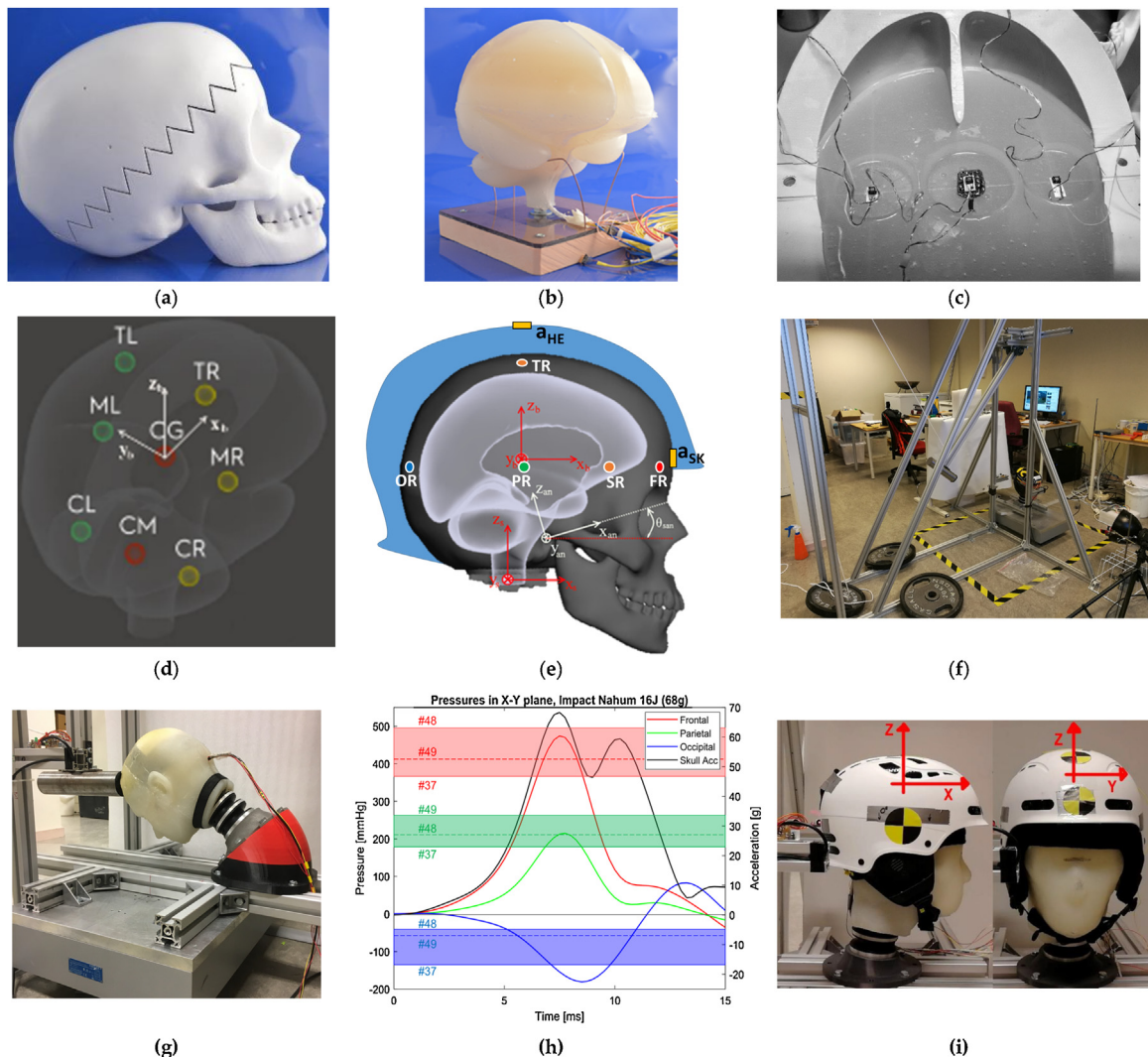
Fig. 1. (a) 3D ABS printed version of the simplified skull with the visible suture for insertion of the sensorized brain; (b) molded version of the simplified brain with lobe separation and cerebellum (sensor cables coming out from the brain stem); (c) example of sensor application in the brain during upside-down molding (MR, ML & CG); (d) location of 9 triaxial accelerometers in the brain; (e) location of Helmet and Skull triaxial accelerometers with respect to head and brain system of reference, location of right side pressure sensors at Frontal (*FR*), Sphenoid (*SR*), Parietal (*PR*), Occipital (*OR*) bones and at Top skull (*TR*); (f) impact pendulum and experimental setup; (g) head setup similar to Nahum et al.[8] experiments used for validation tests; (h) pressure signals from validation tests and comparison with pressure values from experiments #37, #48 and #49 (Ref. Nahum et al.[8]) scaled to the resultant peak acceleration of 68 g; (i) complete head with sensorized brain inside, outer skin and helmet under test, with helmet and head system of reference, in the BACK and RIGHT impact test configurations.

The skin geometry was simplified to be compatible with the skull. Silicone rubber Platsil-Gel 25 A+B (Polyconform GmbH®) was used to mimic the skin properties.[30] The "skin mask" was tightly applied over the skull to complete the IHHS-1 and perform the impact tests.

Nine triaxial accelerometers (ADXL377, Analog Devices, ±200 g) were placed in the brain in order to capture its local kinematics during impacts (Fig. 1c and d). Two biaxial gyro chips (LPY4150AL-pitch and yaw, and LPR4150AL-pitch and roll, both ±1500 deg/s, ST Microelectronics) and one accelerometer were placed in the center of mass of the brain (BCoM). Two accelerometers (ML and MR) were placed 40 mm aside the BCoM, at about 20 mm from the side surface; two accelerometers (TL and TR) were positioned on the same coronal plane of BCoM, 15 mm from the top of the lobe surface. Three accelerometers (CL, CM and CR) were located in the cerebellum center of mass (CM) and 20 mm to its sides (CL and CR), to track its motion separately from the rest of the brain. Brain and neck axes were aligned with the Frankfort plane so the line between tragus and glabella resulted inclined of 15° (Fig. 1e).

Ten pressure sensors (MS5401-AM, TE Connectivity) were applied with sensor surface aligned with the skull inner surface. Eight sensors were located in the XY plane of the skull, symmetrically, in correspondence to Frontal, Sphenoid, Parietal and Occipital bones, two at the skull top above the brain lobes (Fig. 1e). SilOil M4.165/220.10, (Huber USA, Inc.Centrewest Ct., NC) was used as the Cerebral-Spinal-Fluid (CSF) surrogate: despite its higher viscosity than natural CSF, it was adopted for its dielectric behavior. The Pia-Arachnoid-Complex was simulated with a 7 mm thick layer of non-woven polyester fiber.

To capture skull kinematics, two triaxial accelerometers were placed at the euryion[8] and one at the frontal bone, together with two biaxial gyro chips placed at the skull apex. A triaxial accelerometer was added at the helmet apex for helmeted tests (Fig. 1e).

Validation tests were performed on the head-neck assembly after inclining 45° downward the X-axis to reproduce Nahum et al.[8] tests (Fig. 1g). The pendulum adopted a 5.6 kg impactor (Fig. 1f) similar to the one used by Nahum et al.,[8] with speed ranging up to 5.4 m/s measured with a laser photocell. The IHHS-1 assembled to

BACK – 24J   **RIGHT – 24J**
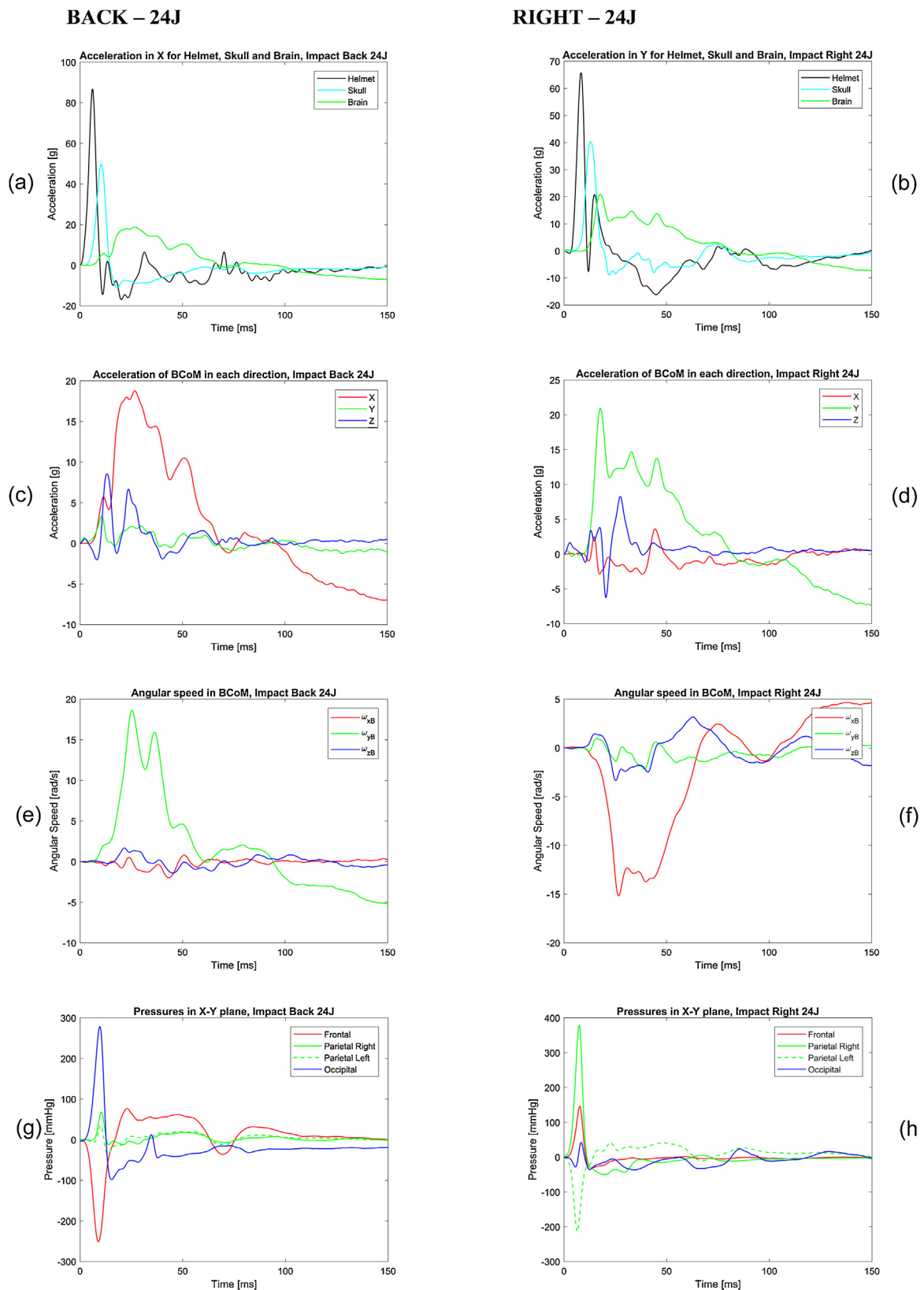
Fig. 2. Results of two multidirectional impacts. (a and b) Comparison of longitudinal accelerations x recorded on Helmet top (black), Skull front (cyan) and brain Center of Mass BCoM (green) for (a) Back Impact 24J and (b) Right Impact 24J. (c and d) Comparison of accelerations recorded in the three directions on the brain center of mass for (c) Back Impact 24J and (d) Right Impact 24J. (e and f) Comparison of angular speed recorded in the three directions at the brain center of mass for (e) Back Impact 24J and (f) Right Impact 24J. (g and h) Example of pressure signals measured at four of the pressure sensors placed internally in the skull at the plane corresponding to the XY plane of the brain, during (g) a Back Impact 24J and (h) a Right Impact 24J.

the Hybrid-III neck was mounted on a Kistler 9281 EA force platform for future data analysis and impacts occurred on the Back, the Right Side and the diagonal locations Back/Right and Front/Right, at respectively 45° and 135° incidence angle from sagittal x-axis. Front Impacts were avoided at this stage due to helmet's front lip conformation.

A ski Helmet size XXL (Sweet Protection Igniter MIPS AB) was worn by the IHHS-1 on a synthetic cuff covering the skin. Impacts at 24J, with three repetitions per direction (Fig. 1i) were performed: higher energy impacts (44J) were sustained in previous comparative tests.[28] Data were simultaneously collected at 10 kHz per channel.

3. Results

The surrogate head validation was addressed with two complementary strategies: (i) adoption of biofidelic surrogate materials; (ii) full scale validation tests against cadaveric intracranial pressure patterns.

Material characterization required extensive test sessions for comparison with literature data, major focus being the brain tissue surrogate material and CerebroSpinalFluid surrogate: results of that work are collected in the Supplementary_Material_1. The silicone rubber showed an asymmetric tension-compression experimental behavior as the brain tissue: viscoelastic properties of the rubber showed moduli that were about two (tensile), three (compressive) and five times (shear) larger than experimental monotonic properties of the brain as reported by Jin et al.[29]

Full scale validation tests replicated the frontal bone impacts performed by Nahum et al.[8] to compare Frontal, Parietal and Occipital pressure signals with Nahum's work. Assuming the linear relation between pressure and acceleration,[8] literature values from three cadaver tests #37, #48, #49 were scaled to the surrogate recorded impact accelerations. Results of validation tests (see Supplementary_Material_1) are in Fig. 1h: surrogate pressure curve patterns replicate pressure curves reported in Nahum's paper in terms of pressure sign and values ratios from different sensors. Frontal and Parietal surrogate pressure values fall within Nahum's scaled range of values, Occipital values resulted higher than Nahum's, possibly due to the higher viscosity of CSF surrogate fluid. Results of the validation tests are also collected in Table 1.

The behavior of head surrogate IHHS-1 in protected impacts is appreciable from the analysis of Fig. 2 and Table 1: in Table 1, the mean values and standard deviations of three 24J energy impacts in the four test directions are reported. Fig. 2 shows the recorded curves in Back and Right side impact test.

During a 24J back Impact, the behavior of helmet, skull and brain in the impact x-direction is detailed in Fig. 2a: the peak delay of the skull and the brain acceleration with respect to the helmet can be clearly appreciated. The surrogate brain is showing a peak delayed of about 15 ms, synchronous with its angular velocity peak. Brain acceleration values are less than 50% of skull ones (Table 1).

Similar results are recorded in y-direction after a Right impact of 24J (Fig. 2b): coherently, the acceleration of helmet, skull and brain show a positive peak in y-direction, but brain CoM reveals a longer peak than skull, with a shorter delay. Complementary axes show minor values (Fig. 2c and d): resultant values of the four impact directions are collected in Table 1, together with the HIC values calculated at the skull and the brain CoM.

With respect to angular kinematics, angular speed components as recorded at the Brain CoM during Back and Right impacts are presented in Fig. 2e and f, respectively. The intracranial pressure curves are presented in Fig. 2g and h for Back and Right impacts: as expected,[8] positive and negative pressure peaks occur in sensors aligned with the loading direction, respectively, at impact or

opposite side. Peak pressure values with helmet never reach peak values of unprotected head impacts as in Nahum's validation tests.

In Table 1, computed values of HIC for skull (HICs) and brain (HICb) are reported for the four impact conditions. From angular speeds measured at the skull and brain center of mass, the computed BrIC values of four configurations can be compared. Finally, peak values of resultant angular accelerations recorded during the tests are presented for skull and brain.

4. Discussion

IHHS-1 is a synthetic surrogate head constructed using 3D printing. Made of ABS in the skull, silicone rubber in brain and skin, its major limitation is the use of homogenous synthetic material for simulating hard and soft tissue behavior, as well for the CSF; furthermore, topologies of complex biological structures are simplified, whereas some others were omitted in this first version of IHHS.

On the other hand, IHHS-1 is stable, reproducible and it can be shared among laboratories: this is one of its main intended values. Its morphological biofidelity is higher than EN or ASTM headforms and of HIII dummy heads: previous tests confirmed its ability to give overall comparable results with respect to HIII headform.[28] Compared to analog experiences by Freitas et al.,[24] a slightly lower skull biofidelity and a much higher sustainability of additive technology may result a preferable compromise with respect to dehydrated bone.

The experimental setup adopted for the impact tests is not an ISO or EN standard test one, where the dummy head equipped with triaxial accelerometers is dropped against an instrumented anvil. Chosen pendulum setup is able to replicate similar conditions as adopted by Nahum et al.[8] and used for several FE models validations. In this study, the surrogate head was connected to the Hybrid-III neck and fixed to a force platform, impacted in line with the brain center of mass in four directions in order to produce rotational multidirectional impacts with respect to the neck connection pin, preventing the risk of damaging brain and skull sensor cables during free head drop tests. Resultant angular velocities reaching values of 1059 dps were obtained with impacts energy of 24J, thus approaching mild levels of severity as expressed also by BrIC values. Interestingly, the four direction of impact give very similar values of BrIC at the skull (BrICs = 0.29–0.33) and at the brain (BrICb = 0.24–0.33): despite similar angular speeds, skull angular accelerations are up to 2,1 times those in the brain, opening new insights in the analysis of simulation and field data.[18]

Due to its large number of sensors, IHHS-1 can give insight in the local transient behavior of the brain and of CSF pressure during multidirectional impacts. In particular, it may (i) allow deeper validation of FE models with larger data repeatability (FE simulations of tests using exact topology and material properties of the physical model allow cross-validation and further biofidelic improvements) and (ii) give insights in the experimental evaluation of emerging technologies for protection against multidirectional impacts. Comparison of experimental results acquired with IHHS-1 and FE simulations would allow for validation of the topology simplifications and for the selection of biofidelic synthetic materials.

5. Conclusions

The instrumented human head surrogate IHHS-1, developed with the highest emphasis on biofidelity, was validated in terms of intracranial pressure experimental data and underwent multidirectional impacts with severity expressed by BrIC values at the skull ranging from 0,29 to 0,33. The large number of accelerometers and pressure sensors installed in the brain, cerebellum and skull

Table 1
Complete list of results from validation tests (ref. to Nahum et al.[8]) and multiple directions impacts: Back, Back-Right, Right, Front-Right.

	IHHS1	NAHUM 16J VALIDATION TESTS		BACK 24J Theta = 0 deg		BACKRIGHT 24J Theta = 45 deg		RIGHT 24J Theta = 90 deg		FRONTRIGHT 24J Theta = 135 deg	
		Mean	STD Dev	Mean	STD Dev	Mean	STD Dev	Mean	STD Dev	Mean	STD Dev
Impactor	Mass [kg]	6,22	0	6,22	0	6,22	0	6,22	0	6,22	0
	Speed [m/s]	2,263	0,004	2,768	0,006	2,762	0,005	2,772	0,004	2,770	0,004
	Energy [J]	15,93	0,12	23,82	0,21	23,72	0,18	23,89	0,13	23,86	0,15
Helmet	acc_x [g]	-	-	70,39	15,24	47,80	5,64	10,18	4,52	−53,42	8,95
	acc_y [g]	-	-	−8,71	4,82	48,66	3,56	60,90	4,33	35,13	1,91
	acc_z [g]	-	-	−32,67	17,48	−27,88	7,30	−15,78	23,08	−11,71	3,49
	acc_R [g]	-	-	**70,81**	15,21	**68,42**	6,13	**62,07**	4,03	**64,94**	8,45
Skull	acc_x [g]	−11,99	5,54	**29,28**	9,17	15,94	0,90	0,96	15,27	−40,05	5,44
	acc_y [g]	10,05	1,34	−7,08	3,90	**24,21**	1,71	**42,61**	2,11	**63,15**	3,26
	acc_z [g]	67,66	0,95	−33,43	2,98	−23,43	2,27	−6,69	0,63	12,46	1,01
	acc_R [g]	68,30	0,80	**39,93**	10,67	**35,13**	2,28	**49,68**	6,26	**73,63**	5,59
	HICs	56,92	4,07	30,29	2,80	20,29	1,19	31,90	5,32	46,24	1,77
	ω_x [rad/s]	3,94	2,82	−3,42	0,82	−12,77	1,31	−17,95	3,64	−10,04	3,02
	ω_y [rad/s]	−14,35	3,50	15,06	1,16	8,62	0,50	−0,31	4,13	−10,08	1,13
	ω_z [rad/s]	1,18	0,45	0,17	1,37	6,45	0,86	4,12	0,36	−10,07	0,77
	ω_R [rad/s]	**14,47**	3,54	**15,28**	1,03	**15,68**	1,37	**16,41**	1,89	**16,35**	3,35
	ω_R [dps]	829,06	202,64	875,58	58,82	898,66	78,26	1059,14	214,86	936,88	192,13
	BrICs	0,27	0,06	0,29	0,02	0,29	0,02	0,29	0,06	0,33	0,04
	α_R [rad/s²]	6270,18	1975,29	3880,34	337,87	3630,92	595,67	5216,39	1639,48	4842,45	2005,1
Brain	acc_x [g]	−21,78	1,63	**18,66**	0,13	12,07	0,24	3,55	0,39	−12,67	0,45
	acc_y [g]	4,41	1,96	3,13	0,41	**13,40**	0,46	**22,31**	1,22	**13,07**	1,04
	acc_z [g]	−38,57	3,16	8,69	1,14	7,74	1,20	8,46	0,20	4,14	0,13
	acc_R [g]	**38,77**	3,28	**19,59**	0,52	**17,45**	2,48	**23,01**	1,38	**16,81**	0,76
	HICb	15,74	0,49	19,11	0,66	22,92	0,65	24,06	0,67	13,59	1,10
	ω_x [rad/s]	−0,40	1,53	0,24	1,94	−9,97	0,53	−14,55	0,55	−10,44	0,17
	ω_y [rad/s]	−14,74	0,97	18,30	0,51	11,54	0,27	−2,30	0,12	−9,40	0,17
	ω_z [rad/s]	−1,98	0,17	0,68	1,96	−4,89	0,50	−3,54	0,22	5,93	0,42
	ω_R [rad/s]	**14,88**	0,95	**18,33**	0,52	**14,99**	0,30	**14,23**	0,00	**14,25**	0,11
	ω_R [dps]	852,75	54,62	1050,42	30,03	858,72	17,04	854,55	26,08	816,24	6,14
	BrICb	0,27	0,02	0,33	0,01	0,28	0,00	0,24	0,01	0,27	0,01
	α_R [rad/s²]	3390,22	294,17	2547,90	78,58	2506,46	250,18	2541,31	138,48	2305,49	58,45
Pressure	P_Frontal Left [mmHg]	475,41	12,48	−275,90	30,44	−220,00	25,47	−38,23	3,89	196,05	12,81
	P_Frontal Right [mmHg]	460,00	10,36	−266,17	30,65	−145,55	19,64	143,86	8,04	278,67	17,45
	P_Sphenoid Left [mmHg]	349,48	10,96	−156,98	13,88	−212,17	23,22	−154,86	13,15	72,73	7,15
	P_Sphenoid Right [mmHg]	363,21	8,69	−161,92	18,36	−26,22	5,05	292,62	17,47	308,40	20,38
	P_Parietal Left [mmHg]	223,96	6,36	50,71	30,20	−142,58	15,24	−207,70	16,93	−115,85	7,38
	P_Parietal Right [mmHg]	201,19	3,08	60,82	16,17	231,57	26,37	370,18	21,80	228,15	16,14
	P_Occipital Left [mmHg]	−152,56	24,34	291,41	51,37	181,02	27,16	15,17	57,62	−178,51	2,09
	P_Occipital Right [mmHg]	−157,30	25,38	290,07	49,79	178,21	26,56	12,84	55,17	−178,22	2,50
	P_Top Left [mmHg]	539,67	2,25	478,92	47,87	414,33	28,10	297,53	9,76	228,02	3,10
	P_Top Right [mmHg]	557,53	6,64	458,46	44,43	240,91	20,94	128,80	6,18	−189,85	8,43

enabled a deeper insight into brain/skull dynamic interactions. The IHHS-1 will enhance the possibility of validating numerical FE models of the head and will open the possibility of comparing experimentally the performance of emerging protection technologies against multidirectional impacts.

Practical implications

The instrumented human head surrogate IHHS-1 can be reproduced in different laboratories and used for impact tests after characterization of surrogate materials and applications of sensors in well known locations.

Finite element models of the brain injury mechanism can find in the IHHS-1 a cross-validation tool to give higher reliability to model outputs.

Multidirectional impacts tests with helmets in different impact conditions will allow the evaluation of rotational actions transmitted to the brain.

Future developments of the IHHS-1 will enable the embedding of strain sensors directed as axons disposition inside the brain. Additional efforts will be devoted to choosing better synthetic surrogate of CSF fluid with adequate viscosity.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jsams.2019.05.015.

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