Abstract Title: **Brain Injuries in Real World Accidents – A Multidisciplinary Investigation**

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BRAIN INJURIES IN REAL WORLD ACCIDENTS – A MULTIDISCIPLINARY INVESTIGATION

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ABSTRACT

A study of brain injury biomechanics has been conducted using detailed reconstruction of real world injury events. A total of nineteen head injury cases were identified in neurosurgery wards of two hospitals in Sweden. From these cases, nine were subjected to detailed reconstruction techniques to quantify the head loading causing the injuries. Output of the analyses included the kinematics of the head and contact loads. Reconstructions of vehicle and occupant dynamics were conducted primarily with computer simulation tools with some limited mechanical testing using vehicle components and Hybrid III dummies.

Results of the study indicate that computer simulation resources are maturing to the point where useful biomechanical information can be obtained through the reconstruction of injury events. The flexibility of the computer models, compared to mechanical dummy testing, is an attractive research approach. Objective evaluation procedures were identified that allowed the quality of the reconstruction to be assessed. Preliminary output of the brain injury research indicated considerable rotational motions of the head were involved in all the brain injuries investigated. Angular accelerations above 5000 rad/s^2 were always associated with brain injuries and no head injury was attributed to pure linear accelerations of the head..

Key words: Accident Reconstructions, Brains, Computer Programs, Injury Criteria

THERE ARE MANY injuries that arise in automobile collisions. Injuries to the central nervous system tend to be the most debilitating injuries in terms of severity and duration of symptoms. Kraus and McArthur (1996) report that, worldwide, the largest source of traumatic brain injury (TBI) is traffic accidents. The most common injury diagnosis in traffic accidents within Sweden is head injury without skull fracture and this constitutes 32% of all reported traffic injuries (n= 29172) according to the 1994-1995 statistics (SIKA 1997).

Reduction of the frequency and severity of brain injuries through the use of vehicle protective systems requires a better understanding of injury characteristics. The possible mechanisms of injury must be identified in terms of impact trauma and physiological consequences. Thresholds for injury should then be identified for the possible loading conditions (linear and angular head kinematics). With improved understanding of the injury mechanisms, the requirements for protective systems can be identified.

Publications listing the occurrence of severe human brain injuries can be grouped into categories representing cadaver studies and accident case studies. Cadaver studies provide information on mechanical damage to the head and brain for different loading conditions. Löwenhielm (1974) investigated bridging vein rupture due to angular head motions. More recent investigations into brain injuries with cadavers include more advanced measurement techniques (Hardy et al., 1997). However, no neurological impairment can be assessed in this type of testing. Case studies can be used to provide information on the neurological impairments associated with different injuries. Examples of these studies include studies of falls (Foust et al., 1977), head impacts in car interiors (McLean et al., 1996), and full scale reconstructions of head impacts (Bertrand et al., 1999). Injury type and severity can be correlated with parameters such as the direction of impact load applied to the head or presence of skull fractures.

The best potential information source for biomechanical response data for humans is the detailed reconstruction of injurious events and correlating reconstruction information to medical data for the subject. Until recently, this research option has not been fully exploited. Improved computer and test facilities now allow detailed studies of head and brain response to be conducted (Willinger et al., 2000, Bertrand et al 1999).

To investigate the potential of accident reconstruction as a source of biomechanical information, a multidisciplinary research consortium was assembled in an attempt to understand the cause, injury mechanisms, and threshold levels of traumatic head injuries in collisions. Research activities within the consortium were not limited to accident reconstruction activities. The medical treatment and pharmacological research also conducted within the larger project framework is not presented herein.

OBJECTIVES

The vision of the research consortium is to identify biomechanical brain injury mechanisms and their relevant thresholds based on quantified human response. This will lead to new or improved test methods as well as guidelines for countermeasures to protect against severe brain injuries. Working towards this vision, a pilot project was initiated with the objective to explore research methodologies to investigate injury mechanisms associated with severe brain injuries. Patients admitted to a neurosurgery ward provided a source of detailed medical information for different types of brain injuries. The goals of the pilot project included the investigation of accident reconstruction techniques for the vehicles and occupants, procedures to analyse the data, as well as the development of a head and brain injury database. The scope of the project was limited to reconstructing the kinematics and contact forces for the head. This information can then be used as input to subsequent research of injury mechanisms for brain tissue.

METHODOLOGY

SAMPLING CRITERIA: All head injuries investigated in the project were identified in the neurosurgery wards of Sahlgrenska University Hospital (Göteborg) or Lund University Hospital. Two surgeons, one for each hospital, were participants in the project and monitored patient admissions to their respective wards. The first criterion to be satisfied was that the patient was assessed with the Reaction Level Scale (RLS) and was diagnosed as RLS 3 or worse. This indicates significant brain trauma and warrants intensive medical intervention. Individuals dying before or shortly after arriving at the hospital were not included in the study as treatment records were required for the subsequent analyses. Upon identification of the patient, consent of the family was required before further investigation could be pursued.

The medical staff collected clinical information on the patients. This information consisted of radiology records from CAT and MRI scans, skeletal and soft tissue trauma, and general neurological response. The type and quantity of radiological information varied among the patients involved in the study. Although not fully discussed herein, this data source is crucial to the further investigations of brain injuries.

FIELD INVESTIGATIONS: Every case sampled in the project was subject to investigations of the site where the injury occurred and the motor vehicles involved. In most cases, a police report was available, describing the accident location, names and contact information for those involved (injured parties, witnesses, etc.), and vehicle specifics when applicable. Anecdotal information obtained from those present at the accident scene (police, ambulance, etc.) was important to understand the possible vehicle and occupant conditions prior to the impact. Post crash information was also important so that position of the occupant after the impact, potential head contact sources, and vehicle deformations due to the occupant extraction could be identified. This last point is important as vehicle occupant contact evidence is often destroyed during rescue procedures.

CRASH RECONSTRUCTION: Analytical reconstructions were the primary focus for the study. Vehicle collision dynamics were quantified using momentum and energy principles. Commercial software (PC-Crash, WinCrash) as well as lumped mass models of the collision were selected for use in the study. Full scale crash tests were not used to recreate the impacts, although pertinent crash test data was identified as a supporting tool for the study. Finite element analysis was eliminated as a possible resource for analysing vehicle impacts due to the limited availability of vehicle models and long simulation solution times.

All motor vehicle impacts were reconstructed to identify the ΔV and pre-impact configurations. Cases that were selected for further occupant reconstruction required more detailed collision dynamics information. In these cases, spring / lumped-mass analytical models of vehicle collision were developed for each collision. These models provided acceleration-time histories (sinusoidal) for input into the occupant simulation models. Full scale test data was sought after to identify suitable crash pulse shapes for applicable cases.

The reconstruction of human motions during a dynamic event requires sophisticated models of the human body. The occupant motions were reconstructed with the use of MADYMO simulation software (TNO, The Netherlands). This program has a library of models representing the standard crash test dummies used in motor vehicle safety research. The Hybrid III and BIOSID dummy models were used for reconstructing vehicle occupant motions during crash conditions. As the size of the individuals can vary, scaling of vehicle occupant models was conducted using the MADYSCALE module for MADYMO. This tool scales the geometric, inertial, and stiffness properties of the computer dummy model.

Pedestrian injuries were reconstructed using the validated pedestrian model developed by Yang (1997). Liu (2001) has developed scaling procedures for the adult model to produce child pedestrian models.

The simulation of vehicle occupant kinematics required that the vehicle interior, safety equipment, occupant sitting position, and any compartment intrusions were represented in the model. All of these features are possible within the MADYMO modelling environment. The vehicle interiors were approximated using known dimensions for the applicable vehicles and safety equipment models from the MADYMO reference library.

Reconstruction of cases through mechanical tests is possible if a testing reference is identified. For this study of head injuries, the test reference was damage to vehicle components caused by direct head contact. Damaged components were saved and used as a template. Head contact dynamics were recreated using an instrumented Hybrid III head in the Chalmers crash test facility. The Hybrid III head was impacted into an identical, undamaged vehicle component and the resulting component damage was compared to the template.

RECONSTRUCTION QUALITY ASSESSMENT: An inherent shortcoming of accident reconstruction is that the analysis cannot be assessed by reference to a known solution. To understand the quality of the reconstruction, indirect methods to objectively assess the results were investigated. The first of these methods is the comparison of reconstructed head contact loads to published fracture loads for the skull. Clinical data for the patient will indicate if a bone fracture is present and available test data for the bone in question was used as a benchmark for the reconstruction results. A second tool that was applied to assess the validity of the computer reconstructions was a sensitivity analysis of the critical parameters. A two level factorial study was applied to relevant parameters used in the analysis (collision crash pulse, intrusion amount, head contact stiffness, etc.). The sensitivity study included the most likely values as well as the worst case for these selected parameters. The results of reconstructions in the sensitivity studies provided a range of "solutions". The characteristics of this range provided feedback on the reconstruction.

MATERIAL FOR ANALYSIS

Accident investigations of head injury cases covered the period from January 1998-July 1999. A total of nineteen cases were opened from the NIVA wards at Sahlgrenska (9) and

Lund (10). The average age of the injured was 27 years. The youngest was 7 and the oldest was 48. A summary of the cases is presented in Appendix A. Of the nineteen cases collected, nine were selected for further reconstruction to quantify the loading conditions to the head. These cases were selected because a clearly identified head contact surface was observed in or on the motor vehicle and the collision characteristics could be reconstructed with confidence. The nine cases that were further investigated represented a range of collision types. Three cases involved head impacts into unpadded rigid objects, three cases represented head contact to vehicle exteriors, and the remaining involved interior objects. A list of the reconstructed cases and the reconstruction approaches are presented in Table 1.

Table 1: Reconstructed Cases

Case Description	Injury and Injury Source	Reconstruction Method
Case C: Side Impact tram-car	EDH, contusions to left temporal lobe, fractured parietal bone (left), DAI in brainstem and corpus callosum Head contact to rigid surface on striking vehicle (street tram)	Computer Simulation, 50%ile male
Case D: Moped-Car	Contusion left temporal lobe, DAI left central lobe and corpus callosum, fracture occipital bone Head contact to rigid surface on striking vehicle (windshield frame)	Mechanical Test / Computer Simulation 50%ile male
Case E: Tree Impact	SDH right side Head contact to unpadded A-Pillar	Mechanical Test (50%ile male head and torso)/ Computer Simulation (Scaled female dummy)
Case G: Pedestrian (Child) Impact	SDH left frontal lobe, fracture left orbit Head contact to hood	Computer Simulation (scaled model)
Case J: Oblique Impact (car- building wall)	left parietal lobe SDH, bilateral temporal lobe contusions, bilateral subfrontal DAI and DAI left temporal lobe, fracture parietal bone Head contact to roll-bar (unpadded)	Computer Simulation 50%ile male
Case L: Tree Impact	SDH left side, contusion right frontal lobe, fractured right orbit Face contact with upper leg	Computer Simulation 50%ile male
Case N: Side Impact (car-truck)	bilateral frontal contusions, impressed fracture left frontal, skull base fracture Head contact to rigid surface on striking vehicle (truck grill)'	Computer Simulation 50%ile male
Case P: Pedestrian (Child) Impact	Bleeding left thalmus, DAI brain stem Head contact to hood	Computer Simulation (scaled model)
Case S: Car – Car	SDH, contusions temporal and frontal lobes Head contact with steering wheel	Computer Simulation 50%ile male

Note: SDH - Subdural Hematomae, DAI - Diffuse Axonal Injury

RECONSTRUCTION BACKGROUND

The preparation for reconstructing these accidents required the collection of supporting information, particularly for the occupant model. The reconstruction of occupant motions for comparison to clinical data on the injuries requires that a human response should be simulated. There were no reliable human simulation models available at the time of the study so the validated models for crash dummies were the best alternative. In order to compensate for the behaviour of the mechanical components in the dummy, some model parameters were modified to provide more human-like response. The changes were predominantly for the head contact stiffness which represents a metal skull and rubber skin in the original dummy model.

In all but three of the cases, the injured could be considered representative of a 50%ile male. The remaining individuals were a female and two young boys. The female was modelled using a scaled Hybrid III model using the MADYSCALE software. The children involved in the study were pedestrians that could be modelled using the procedures developed by Liu (2001).

Stiffness values and fracture loads for cranial and facial bones were investigated in a literature review. Some results of this review are illustrated in Figure 1. On the left, the figure shows that the facial bones have a much lower stiffness (slope of the curve) than the Hybrid III dummy head. On the right, the stiffness of the cranial bones is seen to be about the same as the dummy. However the dummy has a thicker elastic covering compared to the scalp and exhibits asymptotic behaviour after 5 mm of deflection, producing a lag in load response compared to a human exposed to the same impact. Additionally, human bones have a fracture threshold after which higher loads cannot be generated. The dummy head is designed to withstand substantially higher loads.

A notable gap in the description of biomechanical properties of skull bones was identified when estimation of damping properties was attempted. No damping factor was explicitly provided in any reviewed literature for any head impact configuration. Similarly, indirect calculations of damping values were not possible as detailed information of the skull deformation or energy dissipation was not provided.

The confidence in the simulation output was gauged by comparison of the contact loads predicted by the reconstruction to the fracture loads for different skull bones located in the literature, Table 2. This provides an objective measure of the reconstruction results. In some of the available literature, fracture loads are given in terms of grade of fracture (0-no fracture, 1-minimal detectable change, not clinically significant, 2- readily detectable fracture, clinically significant, 3 comminuted, and/or depressed fractures). If available, this graded fracture data may allow more representative fracture loads to be identified.

Summary of Simulation Results

Case	Injury Source	Head Injury Exterior/Fracture	dV/pre. imp. vel. km/h	Linear acc. g	Angular vel. change rad/s	Angular acc. rad/s^2	Contact Force N	HIC 36 ms
C	Head contact with rigid surface.	Bleeding from scalp front-temp left, small linear skull base fx, sinus maxillaris and zygomaticus fx.	Vehicle 1: piv=**35-45** Vehicle 2: piv=**25-35**	235<**280**<335 x: -110 y: 255 z: -160	**140** (x) x: 140 y: -104 z: -33	24902<**28400**<43015 x: 27800 y: -6500 z: 5700	13700<**18100**<18500 **fx** [4990-12390]	**7255**
E	Head contact with A-pillar.	6-7 cm longitudinal flesh wound at eyebrow height, nose fx, skull base fx.	Vehicle 1: dV=**45-50**	**320** x: -160 y: 270 z: 112			**fx** [2200-4100 (nose)]	**4245**
G	Head contact with hood.	Fx left orbita, visible injuries mostly on the left side of the head.	Vehicle 1: piv=**44-54**	**75** x: 12 y: 64 z: 49	**55** (x) x: 55 y: -10 z: 10	**7135** x: -6900 y: -1600 z: -1000	**3600** **fx** [930-2850]	**1150**
J	Contact with roll bar, parietal bone fx.	Fleshwounds rt temple region, fx and swelling rt temporoparietal.	Vehicle 1: piv=**110**	95<**180**<915 x: -50 y: -165 z: 70	**-75** (y) x: -35 y: -75 z: -20	10126<**26500**<85735 x: -24000 y: 3100 z: -11100	3100<**3100**<32800 **fx** [4990-12390]	**835**
L	Contact knees to cheek bones	Extensive facial fractures, right side	dV=**70 approx.**	105<**185**<655 x: -170 y: -45 z: 60	**-75** (y) x: 15 y: -75 z: -10	6234<**7100**<28335 x: -1400 y: -7000 z: 1500	1100<**4000**<12900 **fx** [4000-15000]	**1210**
N	Head contact with truck front.	Impression fx frontal lt, system of fx in skull base.	Vehicle 1: dV=**45,30,20** Vehicle 2: dV=**2**	195<**325**<425 x: -80 y: 315 z: 85	**115** (x) x: 115 y: -50 z: 40	15003<**30900**<69549 x: 30100 y: -2500 z: -7300	4800<**18000**<20100 **fx** [4990-12390]	**6640**
P	Head contact with hood.	Small wound on lower lip.	Vehicle 1: piv=**30-40**	**90** x: -35 y: -85 z: -45	**-60** (x) x: -60 y: 20 z: 10	**13000** x: -12500 y: 4700 z: -1300	**5500** **No fx** [930-2850]	**760**
S	Head contact with steering wheel	Mandible fx.	Vehicle 1: dV=**90** Vehicle 2: dV=**90**	**240** x: -230 y: -15 z: 65	**-55** (y) x: 15 y: -55 z: -15	**20400** x: -10900 y: -20200 z: -8600	**15800** **fx** [4460-6740]	**1875**

N.B. The peak acceleration components **do not** necessarily occur at the same point in time.
Values in **[ ]** indicates fracture forces found in literature. Values in **bold** indicates the most likely run.

Figure 1: Skull Stiffness Definitions for Head Contacts

Table 2: Fracture Loads for Selected Cranial Bones (Summary from Appendix B)

Frontal Bone [N]	Temporo-Parietal Bones [N]	Occiput Bone [N]	Maxilla Bone [N]	Mandible [N]	Zygoma Bones [N]
2197-9880	1340-12390	6410	625-4150	1600-6740	505-2856

Objectives of the study included analysing the loads to the head with a subsequent comparison to the clinically observed injuries and symptoms. In addition, this analysis was compared to existing knowledge on brain injury mechanisms and thresholds. Suitable kinematics variables were identified for use in the study. The main parameters that were selected for analysis were: linear and angular head accelerations, linear and angular head velocities, skull contact loads, and the Head Injury Criterion (HIC). These data were selected as the main indicators of injury using the proposed brain injury mechanisms and thresholds put forward by previous researchers. These data are presented in Figure 2. The grey shaded area represents the loading conditions for bridging vein ruptures proposed by Löwenhielm (1974). The strain curves proposed by Marguiles (1992) represent local deformation of brain tissue and thus proposals for Diffuse Axonal Injury tolerance levels. Other proposed injury conditions (listed in Appendix B) are plotted for reference. The HIC values were recorded to facilitate comparison of the collected case information to the maximum legislated HIC criterion of 1000.

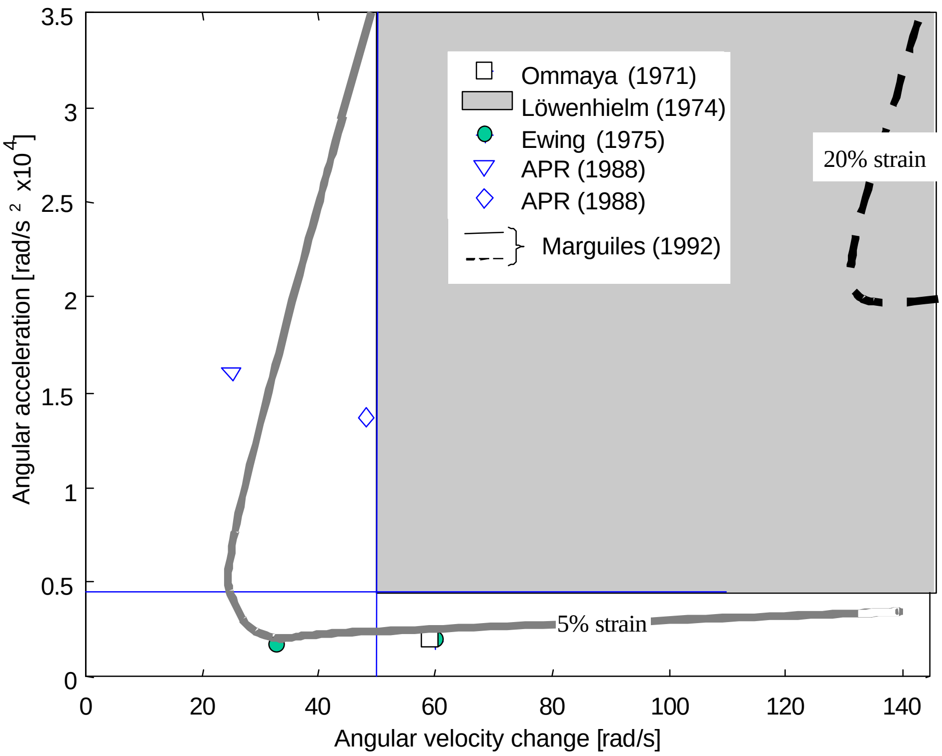

Figure 2: Reported Tolerance Limits From Previous Researchers

RESULTS

Appendix C lists the main computer simulation results found in the detailed analysis. The main criteria presented are the HIC value - representing the linear accelerations of the head - and the rotational motions of the head. The critical angular motions (representing the injurious motion) are presented as rotations about the x (lateral bending), y (flexion/extension), and z (rotation) axis of the head.

Computer reconstructions were conducted for essentially every case. Only a case with a moped passenger was not reconstructed using the MADYMO model. The occupant's body orientation and speed at impact were too difficult to define. In this case mechanical tests were conducted in order to duplicate the observed vehicle damage from the head contact. Otherwise, MADYMO reconstructions were conducted and are reported in Appendix C.

Mechanical tests were conducted as part of the reconstruction activities for cases D and E and are also presented in Appendix C. Reconstruction tests with variations to impact speed and head position prior to impact were conducted in an attempt to duplicate the damage observed in the collision vehicles. The mechanical tests tended to produce low HIC values and this could be attributed to the use of vehicle components instead of full vehicle assemblies. The vehicle components fixed to the test sled were more flexible since surrounding structures could not be totally accounted for in the test fixture.

The injury criterion proposed by Löwenhielm (1974) is used in Figure 3 as a reference to graphically present the results in Appendix C. This criteria includes rotational acceleration and the change in angular velocity for the head. In this plot, it is not the resultant, but the vector components of significant angular acceleration and velocity that are used. The type of angular motion is identified by the marker style so that frontal impact type loading (flexion-extension) cases are differentiated from the side impact (lateral bending) or torsional (rotation) cases. In cases where a sensitivity study was conducted, only the results from the default input values are plotted in the Figure 3. Two points are plotted for case J and represent two noticeable head motions observed during a crash simulation. It is notable that the calculated injury loading lies close to the grey area outlined by proposed bridging vein ruptures (Löwenhielm, 74) and within the 5-20% strain corridors calculated by Margulies and Thibault (1992). The HIC values in computer based reconstructions were in the range of 800 to 7300.

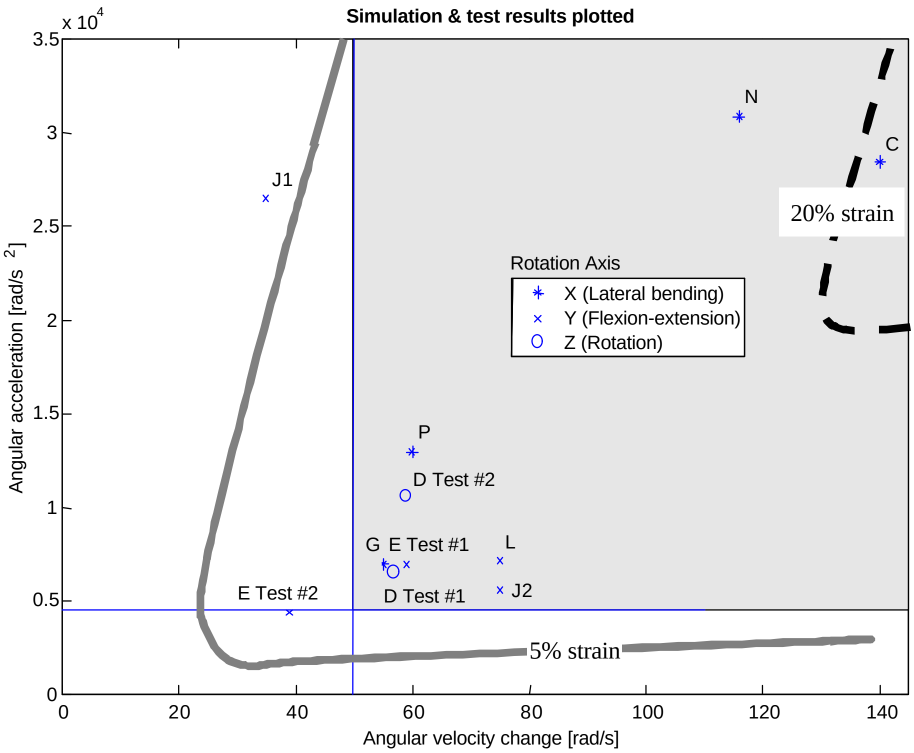

Figure 3: Simulation Results Plotted Referenced to Proposed Injury Thresholds (Points are identified from the information in Appendix C)

As described in the methodology section, sensitivity analyses were conducted for several cases. An example is Case L (frontal impact with a tree). In this case four parameters were investigated. Head stiffness was varied from the Hybrid III value to one found for cadavers reported in literature. Crash test data was scaled (in acceleration) to represent 70 km/h and 80 km/h crash speeds. Seatbelt slack was simulated from a reference level, close to the body, to one with 10% additional free play. Finally, the interior intrusion was varied from a maximum (dynamic) value of 30 cm to 35 cm. The results of this analysis is shown in Table 3. In this table, the percentage change in output (from the default value) due to the change in the input values is displayed.

The first four rows in Table 3 show the sensitivity of the output to changes to only one variable, while subsequent rows show the combined influence of the different variables. For example, row 12 (1+2+4) show the sensitivity of model output due changes in head stiffness, peak acceleration, and intrusion.

It is interesting to note the most sensitive output variable to a single change in the input was the change of HIC due the change in head contact properties. This was common for other cases studied. Changes to vehicle accelerations did not appreciably affect the results (less than 10%) and was also typical for the other cases. Intrusion and seatbelt slack were more influential on head response than vehicle accelerations, but were still less important than head properties. In all cases studied, isolated changes to input data produced the most significant changes in output data as opposed to interactions of different variables.

The linear acceleration did not change as dramatically as the HIC values for in the sensitivity study presented in Table 3. For example, changes in head stiffness caused a 22% increase in linear acceleration but a 520% increase in HIC. Seatbelt slack caused a decrease in linear acceleration but an increase in HIC. Since HIC is directly calculated from linear acceleration, only changes to the head's acceleration pulse shape could cause this behaviour.

Table 3: Sensitivity Analysis of Occupant Model (Case L) to Different Variables

	Linear Velocity	**Angular Velocity**	**Linear Acc.**	**Angular Acc.**	**Contact Force (Face-Knee**	**HIC**
Single Effects						
Head Properties (1)	22.15%	28.58%	188.04%	245.49%	249.62%	545.12%
Peak Acc. (2)	5.71%	6.01%	3.27%	4.41%	3.10%	7.73%
Seatbelt Slack (3)	9.89%	9.44%	-41.86%	2.32%	-39.22%	-44.58%
Intrusion (4)	-13.28%	-6.19%	-30.41%	9.89%	-10.94%	-31.36%
Combined Effects						
1+2	0.28%	0.26%	3.76%	1.39%	6.55%	25.46%
1+3	-0.63%	1.28%	-15.16%	-4.65%	-6.74%	-15.31%
1+4	-1.46%	1.61%	-67.35%	34.99%	9.56%	-213.51%
2+3	0.18%	-0.13%	-0.84%	0.85%	-1.95%	-0.76%
2+4	3.36%	3.55%	-4.03%	6.75%	0.07%	-36.22%
3+4	-20.84%	-22.58%	-16.05%	2.00%	-7.23%	-0.48%
1+2+3	0.35%	0.38%	-5.17%	-2.09%	-5.72%	-26.68%
1+2+4	-0.02%	0.09%	-0.21%	2.21%	1.77%	-4.92%
1+3+4	-14.34%	-11.05%	-59.55%	29.35%	1.09%	-31.46%
2+3+4	-1.21%	-1.74%	1.69%	-1.54%	0.67%	13.17%
1+2+3+4	-2.02%	-2.23%	-2.81%	-3.14%	-10.42%	2.75%

From a sensitivity analysis, like that discussed above, the reconstruction quality can be assessed by examining the influence of particular input data on output results. For example, the vehicle's acceleration pulse and intrusion levels determined from the vehicle dynamics reconstruction appear to be less influential than the influence of the head stiffness. Also the heads angular motions were less sensitive to variations to the input data than linear motions. This information then provides both feedback on areas to improve the reconstruction as well as a measure for the quality of the analysis. Reconstruction based data collection should be based on a range of possible scenarios since the true answer cannot be determined.

Another quantitative measure of the accuracy of the reconstruction was a comparison of head contact loads with fracture loads for relevant bones. Computer simulation of head impacts yielded contact loads for the head which could be compared to the clinical information (presence and severity of fractures) and fracture loads measured in cadaver testing (Table 2). In cases with softer impact surfaces to the head, the contact loads agreed quite well with published data such as Cases J and L (Appendix C). However, the reconstructions involving stiffer contacts were problematic and in particular Cases A and N (significant interior intrusion of rigid vehicle structures) resulted in higher predicted contact loads than could be substantiated with cadaver testing. This latter fact identifies the need to explicitly incorporate bone fracture in skull models if head impact is to be accurately simulated.

DISCUSSION

An improved understanding of brain injuries and their causes requires a database containing actual human injuries. Cadaveric or animal studies cannot provide all the information necessary to understand the mechanisms of brain tissue damage and the neurological consequences of this damage. Reconstructed injury events is the only identifiable source of this data if suitable reconstruction methods can be identified.

The collection of events producing significant brain injury has resulted in nineteen cases to date. Of these nineteen cases, nine have been further analysed through mathematical simulation or mechanical testing. The nine detailed analyses can be grouped into 1) side or oblique trauma, 2) frontal trauma, and 3) rotations about the vertical axis. The brain injuries were found both with and without skull fractures. All the cases involved direct head impact. Some cases involved head impacts with unpadded, stiff structures. In these latter cases, the modelling activities produced results with extremely high contact loads to the head, exceeding the limit for bone fracture reported in cadaver studies. Bone fractures were present in these cases and a biofidelic reconstruction would exhibit contact forces similar to those reported in Table 2.

Evaluation criteria for reconstructed cases are crucial if the data is to be interpreted properly. The use of cadaver based bone fracture loads is necessary to see if the head contacts, producing the brain injury, are reasonably modelled. There is considerable spread in published fracture data, but the information allows brackets to be placed on the possible solution range foe the reconstruction. Similarly, the sensitivity analysis provides feedback on the range for the solution for the reconstruction and can identify areas for focusing reconstruction activities. The problems associated with modelling the occupant were seen to be the most significant factor influencing the reconstructions. Vehicle crash dynamics were less influential on the reconstruction output and suggest that future research should first focus on describing human head impact response.

Objectives of this study included identifying methods to quantify the conditions causing brain injuries in individuals admitted to neurosurgery wards. The best candidate for further reconstruction activities is the use of computer simulation resources given further improvements to the biofidelity of the computer models. The difficulties in using mechanical tests to reconstruct the injury events were numerous. The biggest challenge for mechanical dummies is developing a humanlike response using conventional materials. Following this, difficulties in positioning the head prior to contact with the struck surface were encountered. For example, in Case E the driver head moved obliquely from the seating position, as well as vertically and this motion was difficult to replicate in a test environment. The use of vehicle components was also not satisfactory since the components were more flexible after being removed from the vehicle. Several mechanical tests with different configurations (speed, occupant position, etc.) were conducted, but conducting parameter studies in a crash lab for reconstruction analyses was not as efficient as computer simulation.

As described previously, a problem encountered with the reconstructions of the occupant crash response was placement of the occupant in the pre-crash position relative to the vehicle structures. Crash dummies, both mechanical and mathematical, are designed for standardised tests where minimal positioning of the body segments is involved. However, actual pre-crash motions of the occupant can be substantial and have a significant influence on occupant's crash response. This pre-crash positioning was particularly difficult in cases where the vehicle slid sideways prior to impact. Computer reconstructions of the pre-impact vehicle motions were attempted in order to "place" the occupant in the most likely orientation just prior to the crash loading. This process was not totally successful and considerable simulation of muscular activity must be implemented before this technique can be considered. The standard dummy model lacks natural joint motions for low-level acceleration loads encountered in braking or lateral sliding.

Reconstructions of pedestrian impacts undertaken in this study involved children. This was somewhat problematic as no validated child pedestrian models exist. The pedestrian models used were scaled versions of a validated adult model (Yang, 1997). Scaling factors were applied for the geometric as well as material properties (Liu 2001). Without a validation reference, there is some question about the accuracy of the reconstruction. A positive aspect of pursuing the reconstructions of these cases is that important biomechanical information has been collected. Due to sensitivities in the use of children in volunteer and cadaveric biomechanical research, the use of accident case studies is the only data source available for research.

The reconstruction methods for the vehicle's crash pulse relied on simple models of the crash event. The resulting descriptions of the global motions of the vehicle appeared to be sufficient input to the occupant reconstruction models. Crash test data such as from Buzeman-Jewkes (1998) provided some indication of dynamic intrusion levels and intrusion history when required in the analysis. Since only harmonic functions were used to represent the crash pulse, the true crash environment is not fully reproduced as input to occupant reconstructions. Only one reconstruction could take advantage of applicable crash test data.

None of the case vehicles investigated had crash recorder data. This type of data will become more available as more are installed in the vehicle population. Crash recorder analysis is still a new subject area and the utility to these types of research has not yet been exploited. It will simplify the vehicle reconstruction process and provide more accurate input data to occupant motion reconstructions.

The sensitivity analyses conducted indicate that the final reconstruction results were much more sensitive to the occupant characteristics than the vehicle dynamics. A priority must be placed on developing more biofidelic occupant models that are suitable for reconstruction use. Ongoing FEM studies of human biomechanics can produce some of the important input data for simpler occupant models and provide the flexible research tool necessary to understand human response in real world injury events. It can be argued that the increased use of crash recorders in vehicles will improve reconstruction activities and provide the critical crash pulse information that could only be approximated in current reconstruction activities.

The reconstruction results indicate significant angular motions of the head for all the cases studied. No case could be considered a truly linear loading of the head and identifies a limitation of using only a linear acceleration based injury criterion, HIC, to indicate head injuries. The plots of angular acceleration vs change in angular velocity showed that the criteria of Löwenhielm, (1974) and Margulies and Thibault (1992) appear to provide a good basis for the development of injury assessment criteria. One clinical result of the study was that early use of MRI scans was important to identify tissue injuries since CAT images could not identify injuries such as DAI. Consistent radiological assessments is important so that all patients are diagnosed from identical procedures. There were cases in this study where, in the absence of MRI information, less injury details were provided. This will affect research results when further analyses of specific injuries types and affected brain areas are pursued.

The current study has not gone beyond the load and kinematics response of the head. This information is important for developing test procedures where transducers cannot be expected to record more than acceleration, force, and displacement. Further investigations of brain injury must include the response of brain tissue and requires an additional reconstruction step. This type of analysis is the next phase of research and will use the head response data as the input to a brain response model.

CONCLUSIONS AND RECOMMENDATIONS

The initiation of the crash reconstructions in the project has provided important information for head injury research. It has extended the current state-of-the-art by attempting the reconstruction of vehicle and occupant biomechanics in a collision. There is considerable value in linking technical reconstructions with the detailed medical information. This link is the critical information that the study provides actual human injury data with quantified loading conditions.

Materials and methods have been identified that not only provide the reconstruction results for an injury event, but also an evaluation of the reconstruction validity. The head contact loads, compared to published head fracture criteria, and sensitivity analyses were found to provide important feedback for assessing the results. Material is also being collected that will allow better simulation of human head contacts with different surfaces. Published information for head impacts is available, but not in a form applicable for integration into this current stage of the project. Continued investigations of available test data will lead to more human-like simulation tools for automotive designers.

The vision of the research consortium is to investigate the relationship between violence to the head (biomechanical loading) and injury. To date, the analysed cases all exhibited significant angular motions and suggest that future head injury criteria should incorporate these parameters. Present regulations are based on the assumption that serious head injuries can be predicted by the linear accelerations of the head. All the head injury events that were analysed in detail exhibited angular motions with minimum angular accelerations of 5000-6000 rad/s^2. As a tool for developing the safety equipment of vehicles, the HIC value has limited utility when interpreted in the absence of other head dynamic information. It is thus necessary to continue collecting cases with severe brain injuries to increase our understanding of the conditions producing brain injury. It is important to increase the data for combined rotational and linear motions of the head. Attempts to identify real world injuries caused by purely linear loading, if they can be identified, should also be encouraged. The identification of these linear injuries would allow us to objectively evaluate all loading conditions leading to brain injuries.

Further reconstruction of the cases will be extended to investigate the brain tissue response. These reconstruction activities will allow the actual injury mechanisms to be investigated and will require further analysis of the radiological data.

Data collection within the current project proceeded reasonably well. The assembled multidisciplinary team, representing universities, hospitals, and the automotive industry has created a unique and useable database. The number of cases collected to date is still low and thus limits the conclusions that can be drawn from the current database. Continued case studies and contributions to the database will soon allow more definitive conclusions to be drawn and lead to improved vehicle safety.

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Appendix A: Case Listing for Accident Reconstruction Project

Case	Type	Injury	Vehicle 1	Vehicle 2
A	Car-Car (Side Swipe)	Driver, Vehicle 1	CO* (1 occupant)	Van (4 occupants)
B	Car-Car (Oblique)	Driver, Vehicle 1	SU (5 occupants)	CO (1 occupant)
C	Car-Tram (Side Impact)	Driver, Vehicle 1	SU (1 occupant)	Train
D	Moped-Car (Intersection)	Passenger, Vehicle 1	Moped (2 occupants)	SU (1 occupant)
E	Car-Tree (Off Road)	Driver, Vehicle 1	SU (1 occupant)	Tree
F	Horse Fall	Rider		
G	Pedestrian – Car	Pedestrian	CO (1 occupant)	
H	Car-Tree (Off Road)	Front Passenger	SU (4 occupants)	Tree
I	Car-Truck	Driver, Vehicle 1	SU (1 occupant)	Truck (1 occupant)
J	Car-Wall	Driver	Kit Car	
K	Amusement Ride Fall	Rider	Amusement Ride	
L	Car-Tree	Front Passenger	CO (2 occupants)	Tree
M	Car – Off road Rollover	Driver	CO (2 occupants)	Roadside
N	Car-Truck (Side Impact)	Driver, Vehicle 1	SU (1 occupant)	Truck (1 occupant)
O	Car-Pedestrian	Pedestrian	CO (2 occupants)	
P	Car-Pedestrian	Pedestrian	CO (2 occupants)	
Q	Car-Truck (Side Impact)	Driver, Vehicle 1	CO (1 occupant)	Truck (1 occupant)
R	Car-Truck (Offset Frontal)	Driver, Vehicle 1	CO (1 occupant)	Truck (1 occupant)
S	Car-Car (Offset Frontal)	Driver, Vehicle 1	CO (1 occupant)	CO

* SU=Sub-Compact Vehicle, CO=Compact Vehicle

Appendix B: Selected Tolerance Levels

Table B.1 Fracture Loads for Selected Cranial Bones

Frontal Bone [N]	Temporo-Parietal Bones [N]	Occiput Bone [N]	Maxilla Bone [N]	Mandible [N]	Zygoma Bones [N]
4450-7610[1]	3120-8500[1]	6410[1]	1148[1]	1600-3100[1]	1259-2297[1]
7340-11260[1] (padded impactor)	4990-12390[2]		2010-4150[3]	820-3400[4] (lateral)	930-2120[1] (Arch)
4140-9880[1]	1340-5920[1]		625-1980[4]	1890-4000[4]	930-2850[1]
3552-8972[5]	1399-4885[6]			4460-6740[7]	505-2856[6]
2197-7287[6]					
2563-6335[8]					

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Table B.2: Proposed Thresholds Rotational Motion Causing Brain Injuries

Reference	**a** [rad/s^2]	**w** [rad/s]	Model
Ommaya (1967)	7500	N/A	Primates
Ommaya (1971)	1800	60-70	Primates
Lowehiem (1974)	4500	50-70	Cadaver/math model
Ewing (1975)	1700	32	Volunteers
APR (1988)	16000	25	Volunteer Boxers
APR (1988)	13600	48	Volunteer Boxers

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Appendix C: Reconstruction Results

Table C.1 Results for Computer Simulation Activities

Summary of Simulation Results

Case	Injury Source	Head Injury Exterior/Fracture	dV/pre. imp. vel. km/h	Linear acc. g	Angular vel. change rad/s	Angular acc. rad/s^2	Contact Force N	HIC 36 ms	Runs
C	Head contact with rigid surface.	Bleeding from scalp front-temp left, small linear skull base fx, sinus maxillaris and zygomaticus fx.	Vehicle 1: piv=**35-45** Vehicle 2: piv=**25-35**	235<**280**<335 x: -110 y: 255 z: -160	**140** (x) x: 140 y: -104 z: -33	24902<**28400**<43015 x: 27800 y: -6500 z: 5700	13700<**18100**<18500 fx [4990-12390]	**7255**	n=32 p=5
E	Head contact with A-pillar.	6-7 cm longitudinal flesh wound at eyebrow height, nose fx, skull base fx.	Vehicle 1: dV=**45-50**	**320** x: -160 y: 270 z: 112			fx [2200-4100 (nose)]	**4245**	n=1 p=0
G	Head contact with hood.	Fx left orbita, visible injuries mostly on the left side of the head.	Vehicle 1: piv=**44-54**	**75** x: 12 y: 64 z: 49	**55** (x) x: 55 y: -10 z: 10	**7135** x: -6900 y: -1600 z: -1000	**3600** fx [930-2650]	**1150**	n=1 p=0
J	Contact with roll bar, parietal bone fx.	Fleshwounds rt temple region, fx and swelling rt temporoparietal.	Vehicle 1: piv=**110**	95<**180**<915 x: -50 y: -165 z: 70	**-75** (y) x: -35 y: -75 z: -20	10126<**26500**<85735 x: -24000 y: 3100 z: -11100	3100<**3100**<32800 fx [4990-12390]	**835**	n=8 p=3
L	Contact knees to cheek bones	Extensive facial fractures, right side	dV=**70 approx.**	105<**185**<655 x: -170 y: -45 z: 60	**-75** (y) x: 15 y: -76 z: -10	6234<**7100**<28335 x: -1400 y: -7000 z: 1500	1100<**4000**<12900 fx [4000-15000]	**1210**	n=16 p=4
N	Head contact with truck front.	Impression fx frontal lt, system of fx in skull base.	Vehicle 1: dV=**45,30,20** Vehicle 2: dV=**2**	195<**325**<425 x: -80 y: 316 z: 85	**115** (x) x: 115 y: -50 z: 40	15003<**30900**<69649 x: 30100 y: -2500 z: -7300	4800<**18000**<20100 fx [4990-12390]	**6640**	n=16 p=4
P	Head contact with hood.	Small wound on lower lip.	Vehicle 1: piv=**30-40**	**90** x: -35 y: -85 z: -45	**-60** (x) x: -60 y: 20 z: 10	**13000** x: -12500 y: 4700 z: -1300	**5500** **No fx** [930-2850]	**760**	n=1 p=0
S	Head contact with steering wheel	Mandible fx.	Vehicle 1: dV=**90** Vehicle 2: dV=**90**	**240** x: -230 y: -15 z: 65	**-55** (y) x: 15 y: -55 z: -15	**20400** x: -10900 y: -20200 z: -9600	**15800** fx [4460-6740]	**1875**	n=3 p=1

N.B. The peak acceleration components **do not** necessarily occur at the same point in time.
Values in [ ] indicates fracture forces found in literature. Values in **bold** indicates the most likely run.

The information provided in Appendix C is linear acceleration, angular velocity change for the main head loading, angular acceleration, head contact loads, and HIC value. For all the kinematics values, the resultant (first boldface value) and vector components are presented for the most likely result. The resultant is presented as a range when a sensitivity study was conducted. The range is the upper and lower values calculated in the entire parameter study.

The contact forces are presented as a boldface number for the most likely result. A range is presented for cases where parameter studies were conducted. The notation “fx” and “No fx” indicate if a fracture was clinically diagnosed. The numbers in square brackets represent the fracture loads measured in cadaver testing of the bones under observation (Appendix B). This last parameter is an indicator of the validity of the simulation results.

Table C.2 Summary of Mechanical Tests

Case	Injury Source	Linear acc. g (axis)	Angular vel. rad/s (axis)	Angular acc. rad/s^2 (axis)	HIC 36 ms
D	Head Contact with windshield frame	-85 (x)	57 (z) 59 (z)	6500 (z) 10500 (z)	750 715 140
E	Head Contact with A-pillar	100, 90 x: 100, 85 z: 30, 60	59 (y) 39 (y)	7000 (y) 4400 (y)	270 200