Title: A Comparison of the Head Dynamic Response and Brain Tissue Deformation from Impacts Resulting in Concussion, Concussion with Persistent Post-Concussive Symptoms, and Subdural Hematoma

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<u>Structured Abstract</u>

Objective:

Concussions typically resolve within a few days however in a few cases the symptoms last for a month or longer and are termed persistent post-concussive symptoms (PPCS) with more serious brain trauma resulting in bleeds, such as subdural hematoma (SDH). Dynamic response and brain tissue deformation characteristics may provide a means of distinguishing between these three types of injuries.

Methods:

Reconstruction cases were recruited from sports medicine clinics and hospitals along with medical reports, video footage, and medical imaging. All subjects received a direct blow to the head resulting in head trauma symptoms, those that resolved in 9 days were termed concussions, those with symptoms longer than 18 months were PPCS and those presenting with subdural hematoma (SDH). An anthropometric dummy headform was dropped onto various impact surfaces using a monorail drop rig. Headform dynamic response data was collected and used as input into the University College Dublin Brain Trauma Model to obtain maximum principal strain and von Mises stress.

Results:

Both linear and rotational acceleration of the head increased in magnitude with an increase in injury severity (from concussion, to PPCS, and SDH). The PPCS group had peak resultant rotational accelerations similar to SDH and significantly higher than concussions. There were no significant differences for peak resultant linear accelerations between the two concussion groups however they were both significantly lower than the SDH group. Brain tissue deformation measures however, did not follow the same trend as dynamic response and resulted with SDH having the lowest values of stress and strain. PPCS had significantly higher values of strain than the SDH group, where both the concussion and PPCS groups had significantly higher stress values than the SDH group.

Conclusion:

This study supports the notion that there is a positive relationship between an increase in the dynamic response and the risk for more serious brain injury. Peak resultant linear acceleration may be more related to SDH meanwhile rotational acceleration may be more related to severity of concussion. Despite SDH being the more severe brain injury, on average this group

had the lowest values for stress and strain as compared to concussion and PPCS. Finite element analysis of the SDH injuries examined brain tissue values for the group of elements in the model than corresponded to the location of the bleed which may not be reflective of the highest values if the entire cerebrum was considered. More importantly, SDH injuries are vascular injuries and may not necessarily result in damage to the brain. In summary, this study found that the dynamic response of an impact is reflective of injury severity. Understanding the relationship between the dynamic response and the nature of the injury provides important information for developing strategies for injury prevention.

Definitions

Bulk Modulus – is a measure of the compressibility of a material in Pascal

Decay Constant – a rate constant that defines the diminishing effect of a constant load. Decay constant is described using s^{-1}

Linear Acceleration – characterizes translational motion and is measured in g as a factor of gravitational acceleration ($9.81 m/s^2$)

Maximum Principal Strain – is proportional to the largest magnitude of strain in the x, y, or z axes of a material.

Poisson's Ratio – is a measure of the deformability of a material to a load. It is calculated by taking the ratio of the change in length of a material to its change in thickness.

Rear boss is an impact location that is on the median point of the posterior intersection between the mid-sagittal and frontal planes.

Rotational Acceleration – characterizes rotational motion and is measured in radians/s^2

Shear Modulus – describes the viscoelastic (time-dependent) nature of a material in response to loading. Shear modulus is represented by two constants and measured in Pascal. G_0 characterizes the stored energy or the elastic portion of the material. G_∞ characterizes the amount of energy lost or dissipated as heat and is also known as the viscous portion

Strain – characterizes the amount of deformation of a material and is proportional to the ratio of a change in length of a material to its initial length

Stress – measured in Pascal and is proportional to the magnitude of a load over an area

Young's Modulus – measure of material stiffness and is characterized by the ratio of stress to strain

von Mises Stress – represents the three-dimensional state of stress in a material represented using a single value that summarizes the stress in the x, y, and z axes.

Introduction:

Concussion has been defined as short-term cognitive impairment often presenting with symptoms like headaches, dizziness, and nausea after mild head trauma.[24] While the majority of concussive symptoms resolve, some symptoms have been reported to persist and often lead to disability and depression having devastating effects on quality of life.[36,37] The long-term effects of concussion have been associated with chronic traumatic encephalopathy which is a progressive brain disease characterized by cognitive decline and emotional instability.[25,29] Due to the combined effects of the short- and long-term outcomes of concussion, this injury has been estimated to affect up to 3.8 million people annually costing $12 billion for hospitalization and treatment.[7,22]

The severity of a concussion is typically determined by the number, severity, and duration of presented symptoms.[3,36,37] Some patients have reported symptoms to resolve within 7-10 days[23], meanwhile other patients suffer from persistent post-concussive symptoms (PPCS) often having symptoms lasting from months to years.[1,19,23] Currently, it is not well understood why some patients who sustain head impacts have concussion with transient symptoms while other patients suffer from PPCS.

Concussion can be caused by an impact to the head as a result of participating in sports, motor vehicle, leisure, or work accidents.[19,36-38] The conditions surrounding the head impact plays a major role in the outcome of brain injury since this affects how energy from the impact is transmitted to the skull and brain tissues.[9,12,26] For example, high-energy impacts comprised of fast speeds and hard surfaces are more likely to result in skull fractures and subdural hematomas than concussion.[43] How the head is loaded during an injury event can be described using mechanical characteristics of the impact. These include details about the impacted/impacting surfaces, the mass and velocity of the two bodies colliding, and the impact location and angle on the head. Conditions describing the impact have been known to influence head dynamic response and the resulting trauma to the brain.[9,12,16,35,41] Dynamic response describes how the head moves in space after an impact and is measured using linear and rotational acceleration about three orthogonal axes of the head.[28,33] The amount of brain trauma can be described using engineering stress and strain variables as calculated from finite element analysis.[4,18,20,40,42]

Accident reconstruction in which the injury outcome is known provides an opportunity for researchers to study the link between measurable parameters of the impact and the resulting injury.[5,6,34] This approach involves obtaining a detailed description of the injurious event, reconstructing the event under controlled laboratory conditions, using physical or numerical surrogates to represent the human head, and analyzing the results of the reconstruction.[28,34] Injury reconstruction provides information regarding the head dynamic response and brain tissue deformation. As a result, research employing injury reconstruction has linked metrics such as peak linear and rotational acceleration and brain tissue stress and strain with the risk of brain injury. [5,6,18,20,34,43,44]

Past research examining concussive injury has primarily focused on head impacts resulting in injury and non- injury events.[31,44] This research was conducted using anthropometric dummy reconstructions of player-to-player helmeted head impacts in professional American Football where the results of the injured player were compared to the non-injured player for the same collision event.[31] The dynamic responses collected from the anthropometric dummy head were used as input into finite element models of the brain to examine the brain trauma associated with the impacts.[44] Overall, concussed players had higher dynamic response and brain tissue deformation results than non-injured players.[20,31,44] In comparison with more severe TBI outcomes of subdural hematoma and contusion, concussion is associated with lower values of dynamic response and brain tissue deformation.[6,20,43,44]

Examining different severities of concussive injuries such as those presenting with transient symptoms compared with persistent post-concussive symptoms has yet to be studied. Moreover, the link between concussive injury severity as defined by the appearance and persistence of neurocognitive signs and symptoms and the magnitude of brain trauma that is sustained has yet to be described. Therefore, the purpose of this present research was to use head dynamic response and brain tissue deformation to distinguish between groups of concussion with transient symptoms and those with persistent symptoms in comparison with more serious traumatic brain injuries resulting in subdural hematoma.

Materials and Methods/Case Material:

A total of nine reconstructions were performed. Three patients with transient symptoms (called the "concussion" group), three patients with persistent post-concussive symptoms (PPCS), and three with subdural hematoma (SDH) were recruited from sports medicine clinics and hospitals as summarized in Table 1. Two cases in the SDH group also presented with contusion however only the results for SDH were used for comparison. This research used a physical reconstruction method combined with finite element analysis to examine the results of each group of brain injury.[34,44]

Subject Groups

Concussion Group

The concussion group included cases of patients suffering from concussion and whose symptoms resolved within 10 days.[23] Inclusion criteria required that patients had clear documentation of the duration of symptoms and details of the injury as noted by a physician. The event description from the medical report was matched to video footage of the injury that confirmed the impact location and surface. All cases were helmeted head impacts against the boards or ice as a result of participation in ice hockey. Injury data was provided by the Mayo Clinic Sports Medicine Center (SMC) in Rochester, MN, USA. A SMC athletic trainer and physician were present at all home games and identified each concussion case. Players were seen in the SMC for medical examination and informed consent was obtained. The medical reports and video footage of the game impacts were made available to guide the reconstructions. Valuable information for reconstruction includes impact location and orientation of the player's head and the impacting surfaces involved in the collision. To improve the accuracy of the reconstruction, the same helmet model as worn by the player at the time of impact was used for the reconstruction. The inbound velocity of the head prior to impact was estimated by digitizing the video footage.

Persistent Post-Concussive Symptoms (PPCS) Group

The persistent post-concussive symptom (PPCS) group was defined as concussion with symptoms lasting 6 months or more.[23] Inclusion criteria required that patients had documentation of the duration of symptoms and details of the impact event from a physician. The three cases for PPCS had symptoms that persisted for 23, 26 and 28 months and have not yet resolved (Table 1). These cases were recruited from the Ottawa General Hospital in Ottawa, Canada. Two cases were the result of non-helmeted falls and one case was a non-helmeted head impact against a steel panel since the subject walked into a street sign (case 6). For case 6, the impact velocity of 1.5 m/s was taken from the literature for average walking speed.[2,10] Documented medical reports provided the details for eligibility as well as information regarding head impact conditions used for reconstruction, such as impact location and orientation of the patient's body and head prior to impact.

Subdural Hematoma (SDH) Group

The subdural hematoma (SDH) group is comprised of non-fatal cases of brain contusions and subdural hematoma. Inclusion criteria required that patients presented with subdural hematoma without skull fracture and were injured as a result of an uncomplicated fall onto a rigid surface. These cases were the result of non-helmeted falls onto wood, concrete and ice. Patients were recruited from the Centre de Santé et de Services Sociaux (CSSS) Gatineau (Hull site), Gatineau, Canada, St. Michael's Hospital in Toronto, Canada, and the Beaumont Hospital in Dublin, Ireland where care was provided and information for reconstruction was also collected. Similar to the PPCS group, reconstruction parameters were obtained from medical reports and computed tomography (CT). The CT scans were used to verify the injury for eligibility in the SDH group and to verify the impact location on the head.

Since video footage was not available for the PPCS and SDH groups to estimate impact velocity, the computer simulation software Mathematical Dynamic Models (MADYMO) was used. MADYMO is software that has a database of human body models used to study pedestrian and vehicle accidents (TASS, 2004). In previous research, a MADYMO human body model was set-up in a manner guided by information determined from medical report forms to best simulate the head and body kinematics for fall incidents.[5,6,34] For the purpose of obtaining inbound head impact velocity in this study, a representative MADYMO human body model simulation was used to estimate the final head kinematics in the fall cases. The variable of interest from these simulations was inbound head velocity, which was then set as the inbound velocity for physical reconstruction. Since the exact impact scenario of each fall case was unknown, a variety of fall simulations were performed to obtain a range of possible head impact velocities for reconstruction. The ranges of velocities are presented in Table 2. The lowest head velocity values were chosen for physical reconstructions and analysis to represent the most conservative impact velocity associated with the injury event.

Laboratory Reconstruction

Physical Reconstruction

Once the impact variables such as location, velocity, head orientation and impact surfaces had been determined from medical report forms, video footage and MADYMO simulations, these variables were used as input to guide physical reconstruction. Head impact variables for reconstruction are listed in Table 2 for each case.

To reconstruct the head impacts, a 50th percentile adult male Hybrid III head and neckform (mass 6.08 ± 0.01kg) coupled with a monorail drop rig were used (Figure 1). A monorail drop rig system was chosen because head impacts were onto a stationary or immovable surface, such as a steel sign or concrete surface, respectively. The monorail drop rig used a sliding carriage situated on a rail to guide a fixed Hybrid III head and neckform during the drop. The Hybrid III headform was equipped with nine single-axis Endevco 7264C-2KTZ-2-300 accelerometers arranged in a 3-2-2-2 array to measure linear and rotational accelerations.[30] The resultant linear and rotational accelerations were recorded at 20 kHz and were filtered using a low-pass Butterworth filter at 1650 Hz.

University College Dublin Brain Trauma Model (UCDBTM)

The x, y, and z axes acceleration-time histories recorded using the Hybrid III head impacts were used as input into a finite element model of the human brain, the University College Dublin Brain Trauma Model (UCDBTM). This model was developed by Horgan & Gilchrist[14,15] and is composed of 26 000 elements comprising the skull, scalp, pia, falx, tentorium, cerebrospinal fluid (CSF), grey and white matter, cerebellum and brain stem. A sliding boundary condition between the skull and brain was accomplished by modeling the CSF using solid elements with low shear moduli.[15] The brain tissue material properties governing this model are reported in Tables 3 and 4.[14,15] The UCDBTM was validated by comparing brain model simulation responses against cadaver head impact experiments[11,27,39] as well as reconstructions of traumatic brain injuries.[5,34] Brain tissue deformation measures of maximum principal strain and von Mises stress were used to compare the three groups of brain injury reconstructions as these variables have been used in previous research to characterize brain injury.[4,5,18,20,43,44] An aspect-ratio check was performed on all elements of the brain model for each case simulation to identify erroneous elements that were overly distorted as a result of issues with software formulations. Element aspect-ratios exceeding a maximum elongation of 3 were reviewed. Afterwards, those with an aspect-ratio change greater than 1.0 were excluded from analysis for a total of 167 elements. For the concussion and PPCS cases, the brain tissue deformation results are reported as a peak stress or strain in the overall cerebrum of the brain model however, for the SDH cases the peak stress or strain were determined in the region of elements that are associated with the area of injury indicated by a CT scan. Figure 2 illustrates an example of the brain tissue analysis conducted for SDH cases. A computed tomography scan with a SDH is indicated with a red arrow (2A), and the associated group of elements in the brain finite element model corresponding with the region of injury is shown in red for a top view (2B).

Results:

A description of each injury event and the parameters used for reconstruction for each case is presented in Table 1 and 2 respectively. The dynamic response and brain tissue deformation results for each case are presented in Table 5 along with the mean and standard deviation for each injury group. One-way ANOVAs were used to compare the mean head accelerations and brain tissue deformations. Peak resultant linear acceleration ranged between 52-209 g for concussion, 53-266 g for PPCS, and 266-414 g for SDH. When comparing group means for peak linear acceleration, a significant difference between brain injury groups was found ($p=0.001$). On average, the SDH group had significantly higher linear accelerations (316 g) than the concussion (148 g) and PPCS groups (182 g), however the two concussion groups were not significantly different from each other ($p=0.676$).

The range of rotational acceleration for concussion, PPCS, and SDH are 2865 - 11700 rads/s^2, 4847 - 23 211 rads/s^2, and 14 044 - 30 799 rads/s^2 respectively. A significant difference was found for peak rotational acceleration amongst injury groups ($p=<0.001$). Both the PPCS (16 460 rads/s^2) and SDH (23 181 rad/s^2) groups had significantly higher rotational accelerations when compared to the concussion group ($p<0.05$), however these groups were not different from each other ($p=0.126$).

The range of maximum principal strain ranged from 0.187 – 0.608, 0.207 -0.594, and 0.232 - 0.305 for concussion, PPCS, and SDH respectively. For von Mises stress, the values for concussion, PPCS and SDH were 4.8 - 16.4 kPa, 4.5 -19.5 kPa, and 14.2 - 23.1 kPa. On average, the SDH group (0.255) had statistically lower strain values than the PPCS group (0.459) and lower von Mises stress (8.2 kPa) than both the concussion (14.9 kPa) and the PPCS (15.4 kPa) groups however, concussion and PPCS were not different from each other for either variable (P>0.05).

Discussion:

This study examines the relationship between head impact characteristics and brain injury severity ranging from concussion, to PPCS and SDH. In general, head dynamic response values demonstrated a positive relationship with severity of injury where an increase in severity was reflected in an increase in response. More specifically, the peak resultant linear acceleration variable was able to distinguish the more severe outcomes such as SDH from the less severe concussive injuries (both the concussion and PPCS groups). The peak resultant rotational acceleration variable was able to distinguish between concussion groups with the higher severity PPCS group having similar values to the SDH group. Thus, the magnitude of rotational acceleration may be more related to severity of concussive injury. These findings are consistent with animal studies investigating the roles of linear and rotational acceleration on brain trauma outcome. Gennarelli et al.[8,9] has associated linear acceleration with focal injuries like hematomas and contusions and rotational acceleration with diffuse injuries like concussion. Using a gelatin model of the brain, Holburn[13] demonstrated the deformability of brain tissue to shear strain as a result of rotational motion, attributing rotational acceleration being more related to concussive injuries.

Past research employing finite element analysis have suggested that brain tissue deformation as described by tissue stress and strain may be better variables to predict severity of injury.[18,20,40] It is interesting to find that peak maximum principal strain and peak von Mises stress variables were not reflective of severity of brain injury as SDH had the lowest values of stress and strain with concussion and PPCS not having statistically different results. Finite element analysis of the SDH injuries examined stress and strain values in specific group of elements in the brain model that corresponded to the region of bleeding in the CT scan. As a result, these brain tissue values may not be reflective of the highest values if the entire cerebrum was considered. More importantly, SDH injuries are primarily lesions to vascular tissue therefore may not necessarily result in damaging stress and strain to the brain. The findings in the present study support the use of peak resultant head dynamic response variables to measure severity of brain injury. It should be noted that the sample size was very limited in this study and the results should be interpreted with caution.

In the past, high severity traumatic brain injuries resulting in bleeds and lesions were compared to lower severity impacts resulting in concussion or no concussion.[5,20,32,44] For these studies, peak variables of maximum principal strain and Von Mises stress have been identified as possible relevant variables to describe the relative risk of injury.[20,43,44] Since traumatic brain injuries such as SDH are the result of damage to blood vessels rather than trauma to the brain, it would be more appropriate to examine the amount of stress or strain experienced by vascular tissues for these types of injuries. Furthermore, to distinguish the subtle differences between concussion and PPCS, different brain deformation variables may be more effective in characterizing the injury. Lamy et al.[21] conducted experimental research on rats investigating rotational head injury combined with finite element analysis and suggested that a Von Mises stress-time metric may be better associated with histological data than peak Von Mises stress alone. This research only investigated the role of rotational acceleration and was specific to rat models of head injury.

All injury reconstructions presented herein were from direct blows to the head. All cases of concussion with transient symptoms were subjects who were helmeted and playing hockey, with the more severe PPCS and SDH cases from non-helmeted blows. Based on the cases chosen in this study, headgear seems to be effective against more serious brain injury however, that is not to say that PPCS and SDH do not occur with helmeted impacts. Additionally, how the head is impacted affects the head and brain response to impact. For instance, Kendall et al.[17] demonstrated that collision-, punch-, and fall-type impacts produced characteristic head and brain responses that influence the risk for injury. As more reconstruction research on concussion begins to fill the gap between the presence of concussive injury and SDH, future research examining the spectrum of concussion should consider identifying the appropriate brain tissue deformation variables to describe brain injury.

Conclusions:

This study supports the notion that there is a positive relationship between an increase in head dynamic response and the risk for more serious brain injury. However there was a difference in the character of the dynamic response between the three groups studied. Subdural hematomas had significantly greater peak resultant linear acceleration values than the two concussion groups however there was no difference between the two concussion groups for this measure. Peak resultant rotational acceleration did distinguish between concussion groups with the PPCS group having significantly higher peak rotational acceleration values. For brain tissue stress and strain, SDH had the lowest values as compared to concussion and PPCS groups. This is likely the result of examining brain tissue variables for a specific group of elements in the brain model as opposed to the entire cerebrum. More importantly, SDH injuries are lesions to vascular tissue that may not necessarily damage the brain. These findings suggest that severity of concussion may be more sensitive to rotational acceleration. This research also found that the peak head dynamic response variables are better able to distinguish different brain injury groups as compared to brain tissue deformation variables. Thus, understanding the relationship between the dynamic response and the nature of the injury provides important information for developing strategies for injury prevention.

Limitations:

Reconstruction serves as a promising method to investigate head injury however the tools used as in all studies have inherent limitations. The human body surrogates used in the reconstruction process are idealized representations of more complex geometries and do not account for the more compliant nature of soft tissues. The Hybrid III headform used to collect the head dynamic response data was a rigid steel headform covered with a vinyl layer to simulate the soft tissues of the scalp. Although this headform is commonly used in head impact research, it may be too rigid of an instrument to measure true the human head response due to blunt impacts. Similarly, the MADYMO human body models are composed of idealized ellipsoids used to represent the more complex geometries associated with the human body. Secondly, the geometry of the finite element model did not account for the individual differences for each subject in this study. The intracranial response variables examined in this research was specific to a single head impact event reconstructed from medical reports and do not take into account the state of brain deformation as a result of accumulated head injuries such as those with multiple concussions. Also, the material properties used to define the finite element model were based on both cadaver and animal studies and may not be reflective of the response of live human brain tissue to impact.

A total of nine cases were used for reconstruction with three cases representing each group. This small sample size is another limitation of this work. Future work would be to increase to sample size in each injury group to obtain a more robust data set.

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Disclosure:

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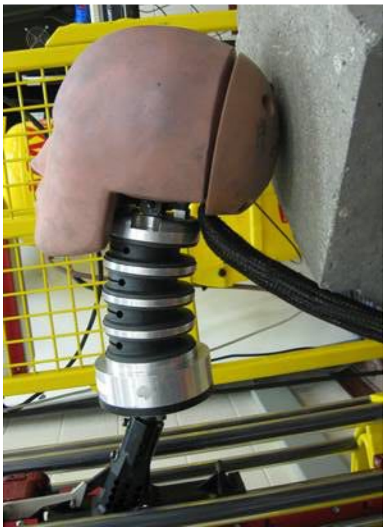
Figure Legends

Figure 1 Hybrid III head and neckform attached to a monorail drop rig with a concrete impact surface

Figure 2. The subset of finite elements in the UCDBTM (B) that are associated with the region of subdural hematoma as indicated by a CT scan (A).



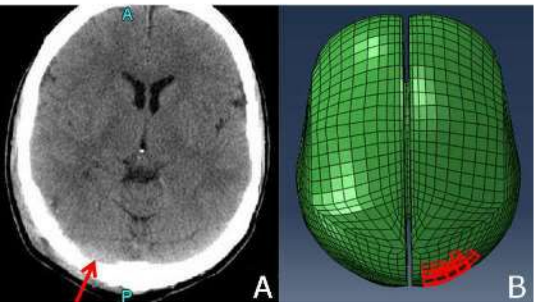

A
P
A
B

Table 1 Description of head injury events

Case No.	Injury Group	Age(y) /Sex	Height/ Weight	Event Description	Outcome/ Symptom Duration
1	Concussion	18/Male	N/A	Skating forwards, tripped and fell backwards, hit back of helmet on ice. No record of previous head injury.	8 days
2	Concussion	16/Male	1.73m/ 74kg	Attempted to body check, got pulled into the boards and hit chin. No record of previous head injury.	9 days
3	Concussion	18/Male	1.52m/ 75kg	Body checked by another player and hit left cheek on the boards. Had 3 previous concussions.	6 days
4	PPCS*	59/Female	1.67m/ 95kg	Walking, slipped backwards on ice and hit back of head. No record of previous head injury.	26 months
5	PPCS*	52/Female	N/A/ 75kg	Standing on skates and fell backwards on ice and hit back region of head. No record of previous head injury.	23 months
6	PPCS*	48/Male	N/A	Was in a parking lot and walked into a street sign. No record of previous head injury.	28 months
7	TBI**	54/Female	N/A	Was playing curling, slipped and fell backwards, hit back of head. No record of previous head injury.	Contusion, SDH†
8	TBI**	45/Male	N/A	Standing on wooden dock, slipped and hit back region of head on dock. No record of previous head injury.	SDH†
9	TBI**	52/Male	N/A	Slipped and fell on ice covered pavement and head on curb. No record of previous head injury.	Contusion, SDH†

* PPCS = persistent post-concussive symptoms

** TBI= traumatic brain injury

† SDH=subdural hematoma

Table 2: Reconstruction parameters for each head injury case

Case No.	Injury Classification	Surface	Impact velocity (m/s)	Impact Location
1	Concussion	Ice	5.9	Rear
2	Concussion	Pine wood	3.6	Front Chin
3	Concussion	Pine wood	3.7	Left Side
4	PPCS*	Concrete	3.9 - 4.69 - 5.2	Rear
5	PPCS*	Ice	4.1 – 5.87	Rear
6	PPCS*	Steel	1.5	Left Side
7	SDH**	Concrete	3.7 – 4.21 – 5.76	Rear
8	SDH**	Pine wood	4.8 -5.0 – 6.2	Rear
9	SDH**	Concrete	3.8 - 6.0	Rear Boss

* PPCS= persistent post-concussive symptoms

** SDH = subdural hematoma

Table 3: Brain tissue characteristics as defined in the University College Dublin Brain Trauma Model

Material	Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio
Scalp	16.7	1000	0.42
Trabecular bone	1000	1300	0.24
Cortical bone	15 000	2000	0.22
Pia	11.5	1130	0.45
Dura	31.5	1130	0.45
Falx/Tentorium	31.5	1140	0.45
CSF	-	1000	0.5
White matter	Hyperelastic	1060	0.499997
Grey matter	Hyperelastic	1060	0.499998

Table 4: Brain tissue material properties for the University College Dublin Brain Trauma Model

Material	Shear Modulus (kPa)		Bulk Modulus (GPa)	Decay Constant (s^{-1})
	G_0	G_∞		
Cerebellum	10	2.0	2.19	80
Grey Matter	10	2.0	2.19	80
White Matter	12.5	2.5	2.19	80
Brain Stem	22.5	4.5	2.19	80

Table 5: Individual case and mean and 1 standard deviation (SD) of peak resultant linear (g) and rotational acceleration (rad/s^2) and peak maximum principal strain and von Mises stress (kPa) for head injuries resulting in concussion, PPCS, and SDH.

Case No.	Injury Group	Peak Linear Acceleration (g)	Peak Rotational Acceleration (rad/s^2)	Peak Maximum Principal Strain	Peak von Mises Stress (kPa)
1	Concussion	187	11700	0.608	20.6
2	Concussion	209	9767	0.487	17.8
3	Concussion	52	2865	0.187	6.2
	Mean (SD)	149 (74)	8111 (4056)	0.428 (0.2)	14.9 (6.6)
4	PPCS	266	23211	0.594	19.2
5	PPCS	227	21323	0.577	19.5
6	PPCS	53	4847	0.207	7.4
	Mean (SD)	182 (98)	16 460 (8765)	0.459 (0.2)	15.4 (6.0)
7	SDH	268	14044	0.228	7.3
8	SDH	414	30799	0.305	10.4
9	SDH	266	24700	0.232	6.9
	Mean (SD)	316 (74)	23 181 (7354)	0.255 (0.043)	8.2 (1.7)