【研究速報】

# Re-analysis of monkey head impact experiments to clarify traumatic brain injury kinematics and thresholds

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Abstract

A series of 43 traumatic head impact experiments on non-human primates carried out in the past were simulated with a validated finite element model of the specimens. From these simulations, brain tissue response and head accelerations were extracted. Based on these accelerations, existing global head injury criteria (HIC, BRIC, GAMBIT and RIC) were calculated. Correlation between the local brain tissue mechanical parameters, the global head injury criteria and the injuries scored in the experiments were analyzed. Based on this analysis, global head injury criteria that best correlate with concussion score for saggital impacts were identified and injury risk functions for brain tissue that can be used for human FE models are proposed.

## 1. Introduction

Traumatic Brain Injuries (TBIs) are one of the major public health problems in all parts of the World. The consequences following these injuries are serious and frequently present throughout life. Many of these injuries are caused by a combination of rotational and linear accelerations of the head in traffic accidents.

To develop effective countermeasures in head impacts, it is essential to understand TBI mechanisms and establish associated thresholds. With this purpose, experiments comprising animals, used as human surrogates, are deemed essential and historically, head impact experiments on non-human primates (thereafter called monkeys) have been carried out [1)-4)]. Some of these experimental results have been scaled to suit humans and were used in the development of the head injury criterion [5)], currently in use in FMVSS208 regulation for motor vehicles. This head injury criterion has been used for decades, but is still criticised for not considering many factors that are important to brain injury. Such factors include the impact direction and area of contact, stiffness of the impacting surface, and rotational accelerations induced by oblique impacts or when the torso is restrained. Therefore, alternative or complementary criteria that consider rotational acceleration of the head have been proposed [6)-8)] in combination with brain tissue injury criteria, for human head finite element (FE) models [7)]. The FE models are currently undergoing validation with reconstructions of real-life sports and traffic accidents, as well as scaled animal injury data. Unfortunately, the accuracy of the methods used to capture head kinematics and detailed brain injury location and severity from real-life events has limitations. The existing criteria also fail to capture the head-neck kinematics that causes the brain injuries.

The aims at developing improved TBI criteria that account for injurious head-neck kinematics and associated limits that will, when properly applied, reduce the number of brain injuries due to closed head

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impacts. This will be facilitated by numerical reconstruction of past head trauma experiments using monkeys.

## 2. Methods

An FE model of the head and neck of a macaque specimen was created, validated and applied to simulate case-by-case 19 occipital and 24 frontal [9),10)] head trauma experiments previously conducted at the Japan Automobile Research Institute (JARI) in the past [3), 4)]. The reported experimental injuries included subdural hematoma, subarachnoid hematoma, contusions and concussions. In the present study, occurence of concussion was evaluated based on measurements of physiological changes right after impact, according to a definition in use at the time of the experiments as explained in [10)]. Based on such criterion, 9 occipital and 10 frontal impacts produced concussion. Figure 1 shows a scheme of the experimental layout of impacts selected for this study.

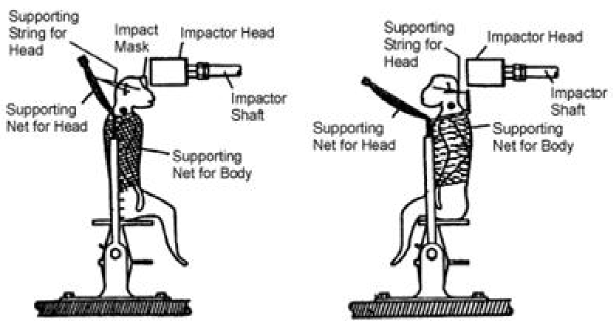
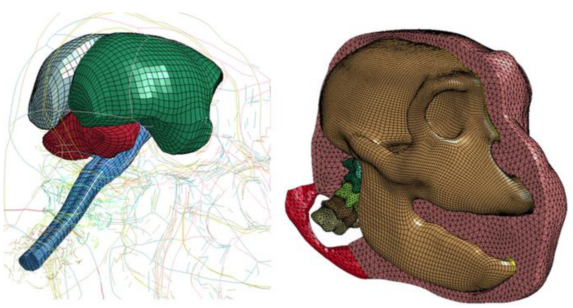



Figure 1 Scheme of frontal (left) and occipital (right) head trauma experiments



(a) Brain (b) skull and flesh

Figure 2 Images of the monkey FE model

The geometry of the monkey head-neck FE model (Figure 2) was developed based on medical images, and material models and material properties were implemented according to Table 1. The model was validated at the tissue level with experimental compression data from coupons of monkey scalp [11)] and brain tissue [12)], at the component level with quasi-static head compression test data [13)], and for head kinematics with full-scale head impact experiments [3)].

Table 1 Monkey FE model material properties

| | Material model | Material properties |
|---|---|---|
| Scalp and neck flesh | Fu Chang Foam | Experimental stress-strain curves |
| Skull bone | Piecewise linear plasticity | E = 6.48 GPa<br>US = 92.4 |
| Cerebrum, corpus callosum, cerebellum | General viscoelastic | G0 = 10.3 kPa<br>G1 = 3.7 kPa<br>tau= 100 s-1 |
| Brainstem | General viscoelastic | G0 = 18.5 kPa<br>G1 = 6.7 kPa<br>tau= 100 s-1 |
| E=Young Modulus, US=Ultimate strength, G0=Short term modulus, G1=Long term modulus, tau=decay constant | | |

To define the setup of the simulations, the velocity of the impactor just before the impact, the stiffness of the rubber block, and the maximum stroke of the impactor were set case by case according to the recorded data in the experiments. The results from the simulations were processed to extract head translational and rotational accelerations, and peak values for Von Mises Stress (VMS) and Maximum Principal Strain (MPS) at the cerebrum and the brainstem. The acceleration curves were used to calculate some of the existing injury criteria such as HIC[5)], GAMBIT [6)], BRIC [7)] and RIC [8)] as explained in [10)] for each simulated impact.

Based on the extracted results, first, the relationship between the global head injury criteria and the experimental concussion was evaluated. Second, injury risk curves as a function of brain tissue injury measurements were developed by carrying out a survival analysis. Third, linear regression between the global head injury criteria and the brain tissue injury measurements was conducted followed by the criteria being ranked by magnitude of correlation coefficient.

## 3. Results and discussion

The analysis of the experimental results obtained and the symptoms observed in the original experiments was performed by physicians [4]. They focused on the concussion output as measured by physiological changes and their possible correlation to pathological observations; including studies of hemorrhages, contusions and circulatory disturbances. Based on the presence of pathology in the brainstem and spinal cord, it was suggested that the changes that took place in these regions were responsible for the concussions [4]. In the simulations of both occipital and frontal impacts (Figure 3), the highest brain tissue strains occurred during the impact in the contrecoup region of the cerebrum (frontal region for occipital impacts and occipital region for frontal impacts) and in the brainstem between the pons and the foramen magnum. This latter is consistent with the hypothesis suggested in the past: concussions occured due to physical stress to the brainstem.

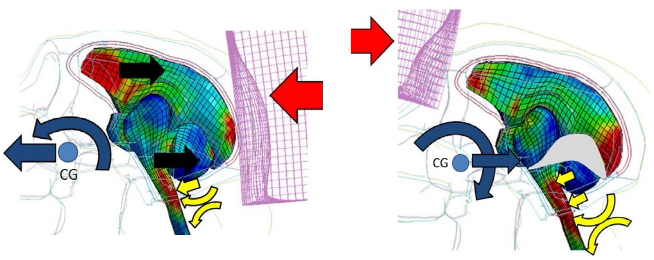



Figure 3 Brain kinematics in simulated occipital and frontal impact.

Local brain tissue values (VMS and MPS) at different regions (Cerebrum, Corpus Callosum, Brainstem, Cerebellum) obtained from the simulations were used to draw concussive injury risk curves as a function of the local brain measurements. Figure 4, shows one of those concussion injury risk curves as a function of MPS in the brainstem from the combined impacts simulations (Full results in (10)). According to this curve a 50% probability of concussion was found to correspond with a MPS of 0.23 in the brainstem. Assuming that tissue thresholds are the same for monkeys and humans, and considering the concussive injury mechanism proposed based on the simulation and the experimental output, these results can be used to interpret results obtained with human finite element models without scaling.

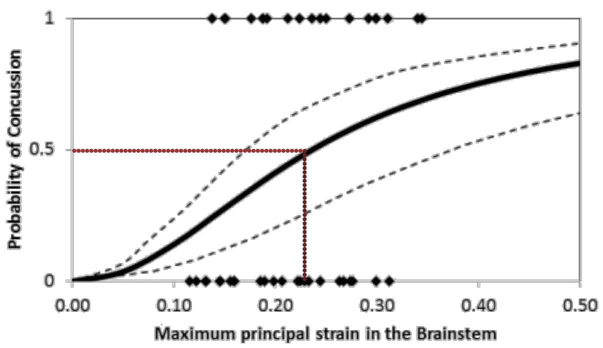



Figure 4 Concussion risk curve as a function of brainstem MPS for combined frontal and occipital impacts

Results from applying linear regression to global head injury criteria and brain tissue criteria from the simulations of combined impacts are presented in Table II. The results show that GAMBIT provided the highest correlation (0.84) to MPS in the brainstem, followed by BRIC (0.82), RIC (0.77) and HIC (0.48). All the global head injury criteria showed significantly higher values for the cases that scored concussion compared to those that did not.

Table 2 Correlation coefficients (R2) between head kinematics and brain tissue criteria for all simulated impacts (n=43)

| | Cerebrum | | Brainstem | |
|---|---|---|---|---|
| | VMS | MPS | VMS | MPS |
| HIC | 0.65 | 0.50 | 0.44 | 0.48 |
| BRIC | 0.36 | 0.18 | 0.82 | 0.82 |
| RIC | 0.18 | 0.06 | 0.79 | 0.77 |
| GAMBIT | 0.51 | 0.30 | 0.81 | 0.84 |

It appears that GAMBIT is a good candidate to predict concussion initiated from brainstem injury. However, GAMBIT does not offer the facility to identify the underlying injury causation defined in the simulated experiments, since it is limited to global head accelerations without considering the head-neck kinematics producing the injuries.

## 4. Conclusions

An original monkey head-neck FE model has been developed from medical images of a macaque primate specimen, validated based on literature data, and used to simulate series of head trauma saggital impact experiments conducted in the past.

Based on the simulations of both frontal and occipital impacts, it was observed that head-neck kinematics resulting in concussion could not be explained if the brainstem and the neck were not considered.

Risk curves for concussion as a function of brain tissue mechanical strain measurements have been developed. The proposed values, assuming similarity principles between monkeys and humans, can be used as reference values for studies with human FE brain models, provided that these have similar brain material properties to the monkey FE model.

Existing global head injury criteria show good statistical correlation with both injury occurrence and strains in the brainstem. However, these criteria fail to capture the head-neck and brain kinematics as observed in the simulations. Unless conceptual improvements are introduced to consider the relative head-neck motion, for instance, all currently available criteria should be used carefully and this limitation must be taken into account.

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