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The use of accident reconstruction for the analysis of traumatic brain injury due to head impacts arising from falls

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Brain injury is the leading cause of death in those aged under 45 years in both Europe and the USA. The objective of this research is to reconstruct and analyse real world cases of accidental head injury, thereby providing accurate data which can be used subsequently to develop clinical tolerance levels associated with particular traumatic injuries and brain lesions. This paper looks at using numerical modelling techniques, namely multibody body dynamics and finite element methods, to reconstruct two real-life accident cases arising from falls. Preliminary results show the levels of acceleration of the head and deformation of brain tissue correspond well to those found by other researchers, suggesting that this method is suitable for modeling head-injury accidents.

KeyWords: Impact biomechanics, falls, accident reconstruction, head injury, multibody dynamics.

1. Introduction

Mechanical impact is the leading cause of injury, death and disability in people aged under 45 in the USA, Europe and increasingly so in Third World countries [1]. Costs of hospitalisation, care and rehabilitation of head injured people are estimated to be as high as \$33 billion per year in the USA [2]. Much recent research has focused on the biomechanics of traumatic head injury, an objective of which is to correlate clinical dysfunction with mechanical impact conditions, with a view to reducing or eliminating the mechanisms that cause damage. There exist many causes of neurotrauma: accidents, falls, assaults and injuries occurring during occupational, recreational and sporting activities. While Road Traffic Accidents tend to be the leading cause of injury related death, falls tend to be the leading cause of non-fatal hospitalisation [3, 4]. In Ireland, falls are the single greatest cause of hospital admissions for both males and females across most age groups, with head injuries occurring in approximately a quarter of all fall admissions [4]. Falls are selected as the accidents of interest in this present study due to their lower levels of uncertainty regarding initial conditions, and due to the tendency of falls to result in focal, as opposed to diffuse, head trauma.

Research into the biomechanics of traumatic brain injury concentrates on four main areas. These are mechanisms of brain injury, response of brain tissue to impact, tolerance limits of tissue to injury and the development of injury assessment technology. The majority of literature on tolerance limits of the head to impact, and

the development of severity indices for head impact have resulted from research conducted on animals and cadavers. While both these forms of research have their advantages, the most important of which is that they can be subjected to rigorous experimentation, issues are often raised as to whether they can accurately represent the processes of human head injury. Results obtained from testing on animals must be scaled to values more representative of humans and it is very difficult to establish accurate scaling laws for this purpose. On the other hand, cadavers lack the response characteristics of living humans, and some injuries cannot be experimentally reproduced. Recently, efforts have been made to examine head injury patterns resulting from real-life accidents rather than animals or cadavers. This type of research has focussed on two main areas, namely the examination of the pattern of brain injury in fatalities, and the reconstruction of real-life accidents using either mechanical or computational models of the human body or head. While there is a degree of uncertainty regarding the exact circumstances of a real life accident, the value of obtaining information from real life cases of head injury is very important. A particular area of injury biomechanics that has developed significantly with the improvement of computational resources is that of numerical models for the analysis of injury mechanisms. It is now possible to analyse the dynamic response of the human body under various loading conditions using multibody models of the human body, and other similar techniques. More detailed analysis of tissue deformation and response to various inputs is available through the use of finite element methods. It must be noted, however, that these resources are only as good as the biomechanical data with which they are developed.

A number of studies have been carried out investigating and reconstructing real life accidents. Auer *et al* [5] carried out numerical reconstructions of 25 fatal pedestrian accidents in an attempt to establish tolerance limits of head impact. They produced tolerance curves for acute subdural haematoma, subarachnoid haematoma and contusions. Willinger *et al* [6] used real life motorcycle accident cases from the COST 327 Action database for their study. The damage to 13 helmets was replicated by carrying out drop tests of instrumented helmets at TRL UK. This data was used as input for a finite element head model in order to predict injury criteria. This led to the following proposals for injury criteria: Intracerebral Von Mises stress of about 20 kPa for concussion, strain energy in the CSF layer of 4 J for subdural haematoma and a Tsai-Wu criterion for skull fracture. Thomson and Lövsund [7] carried out detailed accident reconstruction for nine head injury cases using computer simulation techniques. Their study indicated that computer simulation resources have developed to such a level that useful biomechanical information can now be obtained through the reconstruction of injury events. This claim is also backed by O'Riordain [8], who used numerical reconstruction to model real life falling accidents.

The overall aim of this research is to reconstruct a number of real life falling accidents using numerical techniques in order to establish injury criteria for specific types of brain lesion. Firstly, the accidents are modeled using multibody dynamics software to recreate the overall movement of the body during the accident. Next, the output from the multibody dynamics simulation, in the form of velocities, accelerations and forces, is then used as input for the University College Dublin Brain Trauma Model (UCDBTM) [9, 10]. The UCDBTM, which is a 3D finite element model of the head, is able to simulate the effect of the overall head movement on the cranial contents, so the local deformation parameters within the brain tissue can be examined and compared to the clinical results observed.

2. Methodology

Real life cases of falls resulting in head injury are selected by Ireland's National Department of Neurosurgery at Beaumont Hospital, Dublin. Cases are screened to narrow the selection to relatively simple falls, in order to facilitate modelling of the accidents. Clinical assessments of each case are provided by the hospital, together with CT scans. The accident site is examined to determine the layout of the environment, the height of the fall, and the type of surface onto which the person fell. Informed consent is obtained from patients and witnesses, with the approval of the Ethics Committee of Beaumont Hospital.

Accident reconstruction is carried out using MADYMO(TM) (MATHematical DYNAMIC MOdels) [11] multibody dynamics software. MADYMO has a database of dummy models, which makes it very suitable for reconstructing accidents involving humans. For these analyses, the pedestrian models, which have been validated extensively against full body pedestrian tests, were used, with altered head-ground contact characteristics. It was found that the values for the forces and accelerations experienced by the head of the pedestrian model were very high in comparison to values cited in the literature. From previous related research [8] it was determined that the head response curve determined by Yoganandan *et al* [12] was the most suitable for this analysis since it was independent of the head impact location. It should be noted that the MADYMO head contact characteristics were based on tests performed using the EEVC headform. It was found that the simulations using the Yoganandan *et al* response curves, which were obtained from experiments with actual cadaver heads, gave more realistic predictions of accelerations and forces. Consequently, it is this latter force-penetration response that is assumed in the following simulations. The most suitable pedestrian model is selected according to the height and weight of the patient and placed within the accident environment, which can be described using planes, cylinders, ellipsoids and facet surfaces.

In order to reconstruct these accidents, certain initial conditions need to be applied to the model. Due to the fact that all data regarding the accidents were collected from the field, there is necessarily a degree of uncertainty regarding the precise conditions under which each accident took place. Without instrumentation attached to the person involved, it is impossible to know exactly the velocities of the people during the fall. The cases presented here have at best an eyewitness account of the accident, which is of course useful and necessary, but not scientifically rigorous. Initial conditions in MADYMO are defined by specifying the X, Y and Z components of both linear and angular velocity, and initial joint rotations and positions. For each case reconstructed here, an estimate was made of these components of the initial velocities and positions, based on available information regarding the accident. These were used to run an initial test simulation. If the graphical representation of the simulation appeared unrealistic, slight alterations were made to the initial velocities until the kinematics of the impact appeared physically realistic and correct. This method still leaves some uncertainty as to the validity of these initial conditions. In order to systematically consider the effect of these values on the results, the initial conditions were then varied by $\pm 10\%$ and $\pm 50\%$. Figure 1 shows a sequence of events taken from one of the accident simulations. The relevant results obtained from these simulations are in the form of linear and angular accelerations (a , $\ddot{\vartheta}$), velocities (v , $\dot{\vartheta}$) and forces experienced by the head.

[Insert Figure 1 here]

The velocity output from the MADYMO simulations is used as input for a three-dimensional finite element model of the head. The baseline UCDBTM, which was refined to differentiate between the grey, white and ventricular matter, is used for this analysis. The scalp elements (which completely encase the head apart from the foramen region where the brain elements are unconstrained) are redefined to be rigid and the full time histories of the six velocity components of the centre of the MADYMO head are applied to a reference node located at the COG of the head. The FE head model is also scaled so as to represent the same weight head that is used in the multibody simulations, since this affects the intracranial pressure, Von-Mises stress and shear stress responses [9]. Two FE model formulations were tested, namely the coupled node brain/CSF approach and a sliding brain/skull boundary approach [13]. In this second approach the solid elements previously defined as CSF material were redefined to correspond to the material of the dura, falx and tentorium (the shell elements which had previously been assigned to these regions were removed from the model). The simulation, therefore, modelled the brain in direct contact (sliding with friction) with the intracranial membranes and the inner surface of the skull.

3. Case studies

3.1. Case 1: Boy fainting at a fountain.

Suffering from heat exhaustion, an 11 year old boy fainted after straightening up from drinking at a water fountain on a city street. According to witnesses he fell straight backwards and his head rebounded off the ground. The ground was reported to be level and concrete. The patient experienced a brief loss of consciousness. Upon revival his Glasgow Coma Scale (GCS) score was 14/15, indicating mild confusion. Detailed clinical examination of the patient revealed that the fall resulted in impact just over the occiput. CT imaging on presentation to hospital revealed a right lateral frontal intracerebral haemorrhagic contusion and a traumatic subarachnoid haemorrhage (Figure 2).

[Insert Figure 2 here]

3.2. Case 2: Lady falling from step

The second case involved a 76 year old lady who lost her balance while standing on the back step of her house, facing the door. She fell straight backwards, hitting her head off a vertical concrete/cement wall. This lady did not lose consciousness and presented to hospital with a GCS score of 14/15. Detailed clinical examination of the patient revealed that the fall resulted in impact to the occipital bone. CT scans revealed a large parenchymal haemorrhage of the right temporal lobe, and a small focal bleed on the cortical surface of the left frontal lobe (Figure 3).

[Insert Figure 3 here]

4. Results

The results of two of the accident cases are presented here. The results of the multibody dynamics simulations are presented in Table 1 along with a summary of

the relevant literature. Figures 4 and 5 show the results from the sensitivity analysis of the MADYMO simulations. A summary of the finite element simulations is presented in Table 2, which reports the levels predicted in the area where the actual injury occurred, as well as the maximum values predicted for the finite element brain.

[Insert Table 1 here]

[Insert Figure 4 here]

[Insert Figure 5 here]

[Insert Table 2 here]

5. Discussion

5.1. MADYMO results

Table 1 shows the results from the multibody dynamics simulations. Both sets of results correspond to the ranges found by other researchers. For example, Auer *et al* [5] proposed tolerance curves for contusion stating that linear accelerations above approximately 200G at very short duration impacts would be sufficient to cause contusion. These values have been exceeded in both cases here and contusion has been observed in both cases. The other values also fall within the ranges observed by other researchers. Although the values for the boy appear quite high it is likely that his injuries were not as severe as expected due to the fact that at age 11 his skull would not be as stiff as that of an adult [29]. Overall, the MADYMO results are in the ranges expected, indicating that MADYMO is a useful tool for reconstructing accidents involving head injury.

In the case of falls onto rigid surfaces the impact duration is usually quite short with an associated high peak value. Even though very high values for acceleration are observed in these cases, the duration for which these peaks occur is very short. This factor is not taken into account by injury measures such as GAMBIT.

5.2. Sensitivity analysis

Due to the uncertainty regarding the initial conditions of real-life accidents a sensitivity analysis was carried out by varying both the initial joint positions and the initial joint velocities, both on their own and combined, by $\pm 10\%$ and $\pm 50\%$. For the cases presented here, there was good agreement in the results of the sensitivity analysis due to the fact that these accidents occurred in one plane only, i.e. they fell directly backwards. It can be seen that the difference between these curves is modest, with the greatest difference occurring for the accelerations in the case of the lady on the step ($\pm 21\%$). In this case the lady's head impacts the wall behind her, and not the ground, so slight differences in head position are likely to lead to larger differences in acceleration values. In a study looking at ten accident cases [30] it was noted that falls in which the movement occurred in one plane only gave much better agreement in the results for the sensitivity analysis than more complicated falls. However, in the case of falls with out of plane motion it was more likely that changes in the initial conditions would alter the simulation to such an extent that it no longer represented the accident, so there is still a good level of confidence in the initial conditions used.

The study also showed that in cases where the fall was from a height greater than standing height there was a wider range of resulting velocities and accelerations for the same accident description. In these cases there is more time for the person to react as they are falling, thereby increasing the amount of possible movement for the simulation. As a result, there is less certainty in the initial conditions for these cases.

5.3. *Finite element analysis*

The results of the finite element analysis have shown that the UCDBTM demonstrates stress and strain levels in agreement with those of the literature, though availability of tolerance limits for fall cases are fewer than for those obtained from tests conducted for investigating RTAs. Strain rate and the product of strain and strain rate appeared to be good predictors of injury in the case of the boy at the fountain. For the study of contusion, the case studies suggest that a sliding boundary model has better prediction capabilities, with the sliding model showing higher strain and Von-Mises stress levels in closer proximities to the region that was injured. For the case studies analysed, the tied brain/CSF model always experienced maximum strain and stress in the midbrain region. The tied model also experienced higher levels of stress and strain in the occipital lobe than the sliding model, but no injury was observed in that location.

6. Conclusions

This analysis has shown that combining multibody dynamics modelling with finite element analysis is a useful method for reconstructing real-life accidents. Our results agree well with those found by other researchers in terms of accelerations and forces for the multibody dynamics simulations, and stresses and strains for the finite element analysis. The results from the finite element analysis so far have shown that the model with the sliding interface is better at predicting injury than the tied interface model. The sensitivity analysis demonstrated that for a particular accident description of a fall from standing height, there is a limited range of input conditions that will result in a good simulation of the accident, and for these input conditions there is reasonably good agreement in the output in terms of forces, velocities and accelerations of the head.

Preliminary work shows that some improvements need to be made to this model in order to deal with these impact conditions, in particular improving element shape in some parts of the model. Once the model has been updated all the accident cases will be analysed using this updated model. These finite element analyses will simulate the effect of the overall head movement on the cranial contents, so the local deformation parameters within the brain tissue can be examined and compared to the observed clinical results. Various parameters and stress/strain combinations will be analysed in order to develop tolerance levels associated with particular traumatic injuries and brain lesions.

In this study real-life accidents are being investigated. The main disadvantage of using real-life accidents is that most of the inputs rely on eyewitness reports which are often not accurate. However, in this study it can be seen that there is a limited range of input conditions that will result in a kinematically realistic simulation of the accident, and the outputs of these simulations generally agree quite well. The main advantage of using real-life accidents is that the injuries are known. If the initial conditions are accurately reported and the injuries are known, it should be possible to

see which kinematic inputs lead to particular types of brain lesions. Ongoing work in this study involves analysing a number of cases using both multibody dynamics and finite element analysis, and comparing the measures of brain tissue deformation with the clinical outcome of the patient in order to establish quantifiable mechanical thresholds for the occurrence of different types of trauma.

7. References

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Figures

- Figure 1. Images taken from the simulation of a boy falling at a water fountain
- Figure 2. CT scans taken from the case of the boy at the fountain showing frontal contusion and traumatic subarachnoid bleeding.
- Figure 3. CT scans taken from the case of the lady on the step showing a frontal contusion and a parenchymal haemorrhage.
- Figure 4. Linear acceleration results of the sensitivity analysis for variation in initial conditions for the case of the boy at the fountain.

Figure 5. Linear acceleration results of the sensitivity analysis for changes in initial conditions for the case of the lady on the step.

Tables

Table 1. Table of outputs from MADYMO simulation for both cases

Table 2: FE simulation results. Methods 1 and 2 refer to models using the tied CSF definition and the sliding brain dura boundary approach [13] respectively.