Prediction of Traumatic Brain Injuries by FEM Through Accident Reconstructions

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Abstract. In the head injury accidents, the injuries such as a bone fracture, bleeding or the cerebral contusion can easily be observed by the primary care and quick treatment is possible, but the nerve axonal damage is hard to be discovered and treatment tends to be late. In this paper, the method that predicts the detailed traumatic brain injury including the axonal injury by computer simulation based on emergency medical treatment data are presented and the items which are indispensable for the computer simulation in the medical data are shown. The medical data of 213 head injury accidents were provided by the hospital and they were classified into two groups, the group which can be reconstructed and the group which cannot be reconstructed. It was judged that 10 cases of the traffic accident of all 134 cases can be reconstructed and 23 cases of the fall/fall down accidents of all 61 cases can be reconstructed. As examples, the typical traffic accident and the fall down accident cases were introduced, and the reconstruction process of the accidents and the result of the brain injury prediction are explained in detail.

Introduction

Traumatic brain injury (TBI) is a significant cause of morbidity and mortality in recent years. Since the nerve axonal damage, which is a one of the causes of TBI, is hard to be diagnosed by image diagnosis such as CT and MRI, a prediction method to diagnose the nerve axonal damage is strongly required. On the other hand, studies on the prediction method of the risk of various head injuries including the nerve axonal damage have been reported based on the mechanical background. Deck et al. [1] reconstructed a variety of head injury accidents and calculated the mechanical response in the head during the impact. By using this method, they correlated dynamical parameters with the onset of skull fractures and nerve injury by statistical methods. Therefore, we propose the method which can support the diagnosis of the nerve axonal damage by presenting the risk of head injury using the head injury onset threshold obtained in the previous study.

In order to predict the onset of a head injury, it is necessary to reconstruct the accident as accurately as possible and the information of the accident is quite important to analyze how the accident occurred. However, a hospital does not have all information, and other information is managed dispersedly in the police and the fire department. As the barriers between these administrations are high, the all necessary information for the reconstruction cannot be easily obtained. Therefore, indicating the necessary information for accident reconstruction is important in order to promote the information disclosure in the future. In this report, we introduced the accident reconstruction method and summarized the necessary information for accident reconstruction firstly. Secondly, we analyzed the information of 213 head injury accidents obtained from Acute Care Medicine and Trauma Surgery of Dokkyo Medical University Koshigaya hospital and showed the accident cases which can be
reconstructed. By analyzing the information of accident cases which cannot be reconstructed, the information that is short for accident reconstruction was indicated. Finally, the reconstruction of two accident cases, the traffic accident and fall down accident, are illustrated in detail and it is shown that the accident reconstruction is effective to evaluate the risk of the nerve axonal damage.

**Method**

**Classification of the Accidents**

The 1083 cases of medical data during 2011-2013 were provided by Acute Care Medicine and Trauma Surgery of Dokkyo Medical University Koshigaya hospital. The 213 of the all 1083 cases were related to head trauma and they were classified according to the cause of the accident. Among these 213 cases of head trauma accidents, 134 cases were classified into the traffic accident, 61 cases were classified into fall/fall down accident, 10 cases were classified into the others and 8 cases were unidentified.

The 134 cases of traffic accidents are classified into four groups. The accidents where injured person is pedestrian are classified as "pedestrians", and the accidents where injured person is occupant such as vehicle occupant, motorcycle driver or bicycle rider are classified as " occupants". The accidents where injured person is rolled up in a wheel and is trailed are classified as "others", and the ones that lack of injured person’s information are classified into “unclear”.

The fall/fall down accidents are defined as to fall down in the flat ground or to fall from the high place on the ground. The reconstruction of the accident case where the injury person falls from stairs is more complicated than the other cases. Therefor the 61 cases of fall/fall down accidents were classified into “fall from the stairs” and “others”.

The 10 accidents classified as "others" are the accidents that occurred by the cause except traffic and fall/fall down, and 3 accident cases were caused by the violence of other person, and others were caused by tornado or invasion to a railroad crossing.

**The Accident Reconstruction and the Risk Estimation of Head Injuries**

The reconstruction method of head trauma accident is shown in Figure 1. The accident reconstruction is carried out as following process by using the human whole body numerical model (MADYMO ver. 7.5), and the finite element head model.

![Figure 1. Accident reconstruction performed with a mechanical approach.](image)
(a) The human whole body numerical model is scaled according to the height and weight of the injured person. The other objects (such as vehicle, stairs and stepladder) are modeled according to the accident information. By setting the initial speed and posture of the human whole body numerical model and the objects, the accident scene is reconstructed in MADYMO software [2].

(b) The posture, translational and rotational velocity just before the collision of the injured person’s head are obtained by the human whole body numerical model. The obtained mechanical response of the injured person’s head is input to the finite element human head model as initial conditions. The dynamic response of inside the brain is calculated in detail by the finite element human head model.

(c) By comparing the obtained dynamic response with the threshold of skull fracture and cerebral contusion, the onset of the skull fracture and the cerebral contusion is evaluated by the simulation result. In order to estimate whether the accident reconstruction is consistent with the actual accident or not, the simulation results are compared with the diagnosis data (such as CT and MRI). The steps from (a)–(c) are repeated until the accident reconstruction is consistent with the actual accident. By comparing the obtained dynamic response with the threshold of concussion and diffuse axonal injury (DAI), the onset of concussion and DAI is predicted.

(d) Accidents where information necessary for reconstruction is insufficient, the accident situation are ambiguous and the accident reconstruction gives more than one scenario.

MADYMO software is widely used to reconstruct traffic accident [3] and fall accidents [4]. And the finite element head model THM (Tokyo metropolitan university finite element head model) was verified by reconstruction of a cadaver experiment [5], and the parts which it consists of are shown in Figure 2.

![Figure 2. The detailed configurations of the head model.](image)

The threshold of skull fracture used in this report is the linear regression analysis result of age and ultimate strain obtained by tensile experiment of cadaver bone performed by McCalden et al. [6]. The threshold of cerebral contusion is that a pressure below -100kpa is generated in the cerebrum [7]. The risk estimation of concussion is calculated by the maximum values of von Mises stress generated inside the skull, and the risk function is shown below [8]. When the maximum values of von Mises stress generated inside the skull exceeds 18kpa, the risk of developing moderate DAI will be over 50%, and above 38kpa the risk of developing severe DAI will be over 50%. And moderate DAI is defined that unconsciousness lasts less than 24 h and longer than 30 min, severe DAI is defined that unconsciousness lasting more than 24 h [9].

\[
P = \frac{1}{1 + e^{-(2.228 - 0.2652 \cdot vMS)}}
\]

(1)

**Probability Analysis of Accident Reconstruction Based on Medical Information**

The traumatic head injury occurs by the collision between the injured person and another object and the onset of brain injury can be explained from a dynamic viewpoint. Consequently, the following information is necessary for traumatic accident reconstruction; This information will be used as input data to reconstruct a trauma accident in MADYMO software.

(a) “Shape” of all of the objects including the injured person

(b) “Contact stiffness and friction coefficient” between injured person and another object

(c) “Velocity” of all the object before the collision
Based on the information which mentioned above, we summarized the concrete information which is necessary for each kind of accident as shown in Table 1.

Table 1. Information available for accident reconstruction.

<table>
<thead>
<tr>
<th>Input data</th>
<th>Object</th>
<th>Traffic Accident</th>
<th>Fall/fall down Accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>shape</td>
<td>Injured person</td>
<td>Injured person’s posture and position, type of vehicle</td>
<td>Injured person’s posture and position</td>
</tr>
<tr>
<td></td>
<td>others</td>
<td>Type of accident partner vehicle / shape of impact object</td>
<td>Shape of impact object</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shape of road surface*</td>
<td>Shape of foothold</td>
</tr>
<tr>
<td>contact stiffness and friction coefficient</td>
<td>Injured person</td>
<td>Type of vehicle**</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>others</td>
<td>Type of accident partner vehicle / material of impact object</td>
<td>Material of impact object</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Material of road surface</td>
<td>Material of foothold</td>
</tr>
<tr>
<td>Velocity</td>
<td>Injured person</td>
<td>Injured person’s traveling velocity</td>
<td>Injured person’s fall / fall down velocity</td>
</tr>
<tr>
<td></td>
<td>impact object</td>
<td>Accident partner’s vehicle / impact object’s traveling velocity</td>
<td>-</td>
</tr>
</tbody>
</table>

*This information was not included in the medical records.
**This information already existe

For traffic accident reconstruction, firstly, the “shape” information of the injured person includes “posture and position” and “type of vehicle” such as SUV,1-BOX and so on. The “shape” information of the other objects are “type of the accident partner’s vehicle”, “shape of the impact object” and “shape of road surface”. The item “shape of the impact object” means the obstacles on the road such as barrier and telegraph pole. Secondly, the “contact stiffness and friction coefficient” information include the injured person’s “type of vehicle”, and “type of the accident partner’s vehicle”. There are plenty studies on the contact stiffness and friction coefficient of various vehicle [10], which make it easy to obtain the contact stiffness and friction coefficient if the type of vehicle is known. “The material of the impact object” and “the material of the road surface” are essential for setting the contact condition and the friction between the injured person and the impact object/road surface. Lastly, the “velocity” information include velocity of the injured person and the accident partner or the impact object, which is usually recorded in the medical information by the rescue team of hospital.

For fall/fall down accident reconstruction, firstly, the “shape” information includes “injured person’s posture and position”, “shape of impact object” and “shape of stepladder”. Secondly, “the material of impact object” and “the material of stepladder” are essential for setting contact condition and friction between the injured person and the impact object and stepladder. Lastly, the “velocity” information means “injured person’s fall/fall down velocity”. By repeating the steps (a)-(c) of the method of head trauma accident reconstruction, which is mentioned above, the injured person’s fall/fall down velocity is adjusted until the simulation result agrees with the diagnosis result (such as onset of skull fracture and contusion).

The 10 accidents classified as "others” can’t be reconstructed by using the method mentioned above, because it is hardly to reconstruct these kinds of accidents by the method mentioned in this report.

By using Table 1 as a criterion, we analyzed the medical data of 213 head injury accidents provided by the hospital. The accident which is lack of necessary information is considered unable to be reconstructed. In the case of accident where some information is insufficient, the reconstruction has more than one scenario, and we judged them to be reconstructed.
Result

Probability of Accident Reconstruction

By analyzing the medical data of 213 head injury accidents, 33 cases were considered able to be reconstructed as shown in Table 2. Among the 134 traffic accidents, 7 cases which are classified as "other" and 11 cases which are classified as "unclear" were considered unable to be reconstructed. In the 10 traffic accidents to be reconstructed, 3 cases are “Pedestrian”, and 7 cases are “Occupant”.

23 fall/fall down accidents can be reproduced, and 13 cases of them are “Fall from the stairs”, 20 cases of these are “Other”. Among the 213 head injury accidents, 10 cases classified as "other" and 8 cases classified as "unclear" were considered unable to be reproduced.

In order to ascertain the missing information for accident reconstruction, we analyzed the information of accident cases which can’t be reconstructed. We arranged these accidents according to the number of missing details. For each item, the number of accidents lacking information is shown in Table 3.

Table 2. Total number of head injury accidents and number of accidents that were reconstructed.

<table>
<thead>
<tr>
<th>Accident type</th>
<th>Detailed classification of accident</th>
<th>Total number of cases</th>
<th>Number of accidents reconstructed</th>
</tr>
</thead>
<tbody>
<tr>
<td>traffic accident</td>
<td>Pedestrian</td>
<td>28</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Occupant</td>
<td>95</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Unclear</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>fall/fall down accident</td>
<td>Fall from the stairs</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>48</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Unclear</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>213</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 3. Number of traffic accidents and the number of information which are short for reconstruction.

<table>
<thead>
<tr>
<th>Number of information which are short for reconstruction</th>
<th>Number of traffic accidents</th>
<th>Shape</th>
<th>Contact stiffness and friction coefficient</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of accidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>27</td>
<td>5 0 -</td>
<td>0 0 20</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>42</td>
<td>25 0 -</td>
<td>0 0 25</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>34</td>
<td>34 0 -</td>
<td>0 0 34</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1</td>
<td>0 1 -</td>
<td>1 0 1</td>
</tr>
</tbody>
</table>
The medical information of this traffic accident is that a 45-year-old man fell over the street when he was running on a bicycle. He broke the right shoulder and the right rib. A right cranial base fracture and a left frontal cerebral contusion were diagnosed by CT. At the time of arrival on hospital, the injured person was clear of consciousness and the Glasgow coma scale (GCS) was 14 points (E4V4M6).

The accident reconstruction is shown in Figure 3(a). The simulation results of the fracture site accorded with the site of the fracture on CT which are marked with the red circle as shown in Figure 3(b). Regarding contusion, it was estimated that a pressure of -318.2 kpa was generated in the left forehead of the cerebral model, and the risk of contusion in the left forehead was high. This is also consistent with the diagnosis that cerebral contusion occurred in the left forehead as shown in Figure 3(c). The maximum von Mises stress value generated in the brain was 9.08 kpa, and the risk of concussion was 54.1%, the risk of onset of moderate DAI and severe DAI was estimated to be less than 50%. The risk evaluation result of contusion and DAI can be considered to accordant with the symptom that the injured person is clear of consciousness at the time of arrival on hospital. Based on
the calculation results of brain parenchyma, corpus callosum and brain stem model, high-risk areas of moderate and severe DAI are indicated in red as shown in Figure 3(d) and (e).

(A): Traffic accident reconstruction results

(B): The site of the fracture on computed tomography (CT; red circle) and the simulation results of the fracture site (red circle). ※The gray areas are the parts of the head model other than the facial bone and skull model

(C): The site of the contusion on magnetic resonance imaging. The possibility of the occurrence of a cerebral contusion in the left forehead, which is shown in blue, is high. ※The gray areas are the parts of the head model other than the cerebral model other than the facial bone and skull model

(D): The high-risk areas of moderate DAI

(E): The high-risk areas of severe DAI

Figure 3. A traffic accident reconstruction and risk evaluation of head injuries.

A Fall/Fall Down Accident Reproduction and Risk Evaluation of Head Injury

The medical information of this fall/fall down accident is that an 80-year-old man fell backwards from a stepladder of about 50 cm in the bathroom. A fracture in the occipital region was diagnosed by CT and contusion in the left forehead was diagnosed by MRI. At the time of arrival on hospital, he was unconscious and it was 3 points of GCS (E1V1M1). He was discharged after 7 days and transferred to other neurosurgical departments.

The accident reproduction is shown in Figure 4(a). The simulation results of the fracture site and the site of the fracture on CT are marked with the red circle and are shown in Figure 4(b). It was estimated that a pressure of -150.7kpa was generated in the left forehead, which exceeded the threshold of contusion. The simulation results can be considered to accordant with the diagnostics result as shown in Figure 4(c). The maximum value of von Mises stress in the brain was 20.8kpa, and the risk of concussion was 96.4%, the onset risk of moderate DAI is above 50% and the risk of severe DAI is less than 50%. From the calculation result, the consciousness disappearance time is estimated to be longer than 30 min and 24 hours. At the time of arrival on hospital, the injured person was
unconscious so that the calculation result has potential to accordant with the actual situation. The high-risk areas of moderate and severe DAI are shown in Figure 4(d) and (e).

(a): Fall/fall down accident reconstruction results.

(b): The site of the fracture on CT (red circle) and the simulation results of the fracture site (red circle). ※The gray areas are the parts of the head model other than the facial bone and skull model

(c): The site of the contusion on CT. The possibility of the occurrence of a cerebral contusion in the forehead, which is shown in blue, is high. ※The gray areas are the parts of the head model other than the cerebral model.

(d): The high-risk areas of moderate DAI

(e): The high-risk areas of severe DAI

Figure 3. A fall/fall down accident reconstruction and risk evaluation of head injuries.

Discussion

213 cases of the medical information of brain injury accidents were analyzed and it was judged to be able to reconstruct 33 cases. We analyzed the information that was short for the reconstruction of the accident and summarized it in a management list of the accident information for head injury accident reconstruction.

It was judged that 10 traffic accidents could be reconstructed in all built in all 134 accident cases. In three items of "injured person’s posture and position", "type of vehicle", "injured person’s traveling velocity" and "accident partner’s vehicle / impact object’s traveling velocity", the number of accidents without the information is 73, 89 and 80 cases each as shown in Table 3. The reconstruction of 103 more accidents is enabled if the information about these three items is given.

It was judged that 23 fall/fall down accidents could be reconstructed in all built in all 61 accident cases. In three items of "injured person’s posture and position", "injured person’s fall / fall down...
velocity " and " shape of impact object ", the number of accidents without the information is 33, 28 and 15 cases each as shown in Table 4. The reconstruction of 31 more accidents is enabled if the information about these three items is given.

The result of analysis shows that the medical information about the traffic accident has little information about the following three items, " injured person’s posture and position, type of vehicle ", " injured person’s traveling velocity " and " accident partner’s vehicle / impact object’s traveling velocity ".

A position of the injured person is the relative position of an injured person and the accident partner at the time of the collision and is generally guessed from the damage part of the vehicle [10].

Generally, if the injured person is a pedestrian or a bicycle rider and the collision object is a car, the collision speed can be estimated easily by the distance that an injured person was splashed [3]. In the case of a traffic accident, the distance that an injured person was splashed or the car speed is not usually included in medical information. Detailed findings such as the tire trace of the vehicle, the damage situation of the vehicle is necessary to estimate collision speed, but it is difficult to obtain this information from the hospital. It complicates the reconstruction of the traffic accident by the medical information.

The result of analysis shows that the medical information about the fall/fall down is insufficient about the following three items, " injured person’s posture and position ", " injured person’s fall / fall down velocity " and " shape of impact object ". It must make up for these insufficient information by a guess. "Posture and the position of the injured person" can often guess from the cause of a fall/fall down when there is not eyewitness information. When the injured person drops, influence by the gravity is dominant. And the reconstruction is possible because the collision speed roughly can be estimated from the injury situation. Many accidents that an injured person fell off the high place into are not reproduced. In such cases, the posture that an injured person fell to is not assume because there are many injury points. In such cases, the posture that an injured person fell to cannot be figured because of many injury points, and the collision speed cannot be obtained. The fall accident from the high place needs a more detailed investigation.

When there is not a layout of the scene of the accident, "the shape of collision object" is not estimated.

In the study on reconstruction of such a fall/fall down accident, they suppose the posture of the injured person and the collision object by recording the information of the eyewitness and an on-site layout [4].

As an example, two accidents that reconstruction was possible were illustrated, and the method to reconstruct the accident mechanically and to predict the brain injury in detail was explained. The risk of the onset of the brain injury was predicted and the result was summarized in Table 5. These accidents were reconstructed based on medical information by trial and error.

The time of loss of consciousness obtained by the risk of the brain injury agreed with the real situation. The prediction of the traumatic brain injury by accident reproduction is believed to give the valuable information for diagnosis.

Table 4. The results of computer simulation for the brain injury of 2 accident cases.

<table>
<thead>
<tr>
<th></th>
<th>Case1</th>
<th>Case2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concussion</td>
<td>54.1%</td>
<td>96.4%</td>
</tr>
<tr>
<td>moderate DAI</td>
<td>&lt; 50%</td>
<td>&gt; 50%</td>
</tr>
<tr>
<td>severe DAI</td>
<td>&lt; 50%</td>
<td>&lt; 50%</td>
</tr>
</tbody>
</table>

The risks of onset are calculated by using the statistical data of reference studies.

Conclusion

In this study, the method that predicts the detailed traumatic brain injury including the axonal injury by computer simulation based on emergency medical treatment data are presented. The medical treatment data are provided by Accute Care Medical and Trauma Surgery of Dokkyo Medical.
University. 213 cases of the medical information of brain injury accidents were analyzed and it was judged to be able to reconstruct 33 cases. The items which are indispensable for the computer simulation in the medical data were pointed out concretely and summarized in table.

**References**


