1. Introduction

Bicycling is popular because it provides the convenience of short transportation and physical exercise, is environmentally friendly, and is more cost effective compared with modes of mechanical transportation. The environmental and health benefits of bicycling are attractive to people of all ages. Approximately 7.2 million bicycles...
were owned in Japan in 2013 (JBPI, 2013). However, cyclists are often exposed to a high risk of injury in traffic. In 2017, traffic accidents resulted in 3,694 fatalities, 36,895 serious injuries, and 543,955 minor injuries in Japan, of which 480 of the fatalities (13%) were cyclists, and 8,242 (22%) involved serious injuries to cyclists (ITARDA, 2018). Head injuries (n = 305, 64%) were the predominant cause of death among cyclists in these accidents.

Several papers have reported that traumatic head injuries to cyclists are a major cause of fatalities and disabilities (Airaksinen et al., 2010, Chen et al., 2013, Deck and Willinger, 2008, Kurt et al., 2016, Scholten et al., 2015). Moreover, a traumatic head injury can cause permanent disability, such as behavioral changes or impairment in concentration or cognitive function (Watanabe et al., 2009). Since 2006, the Japanese government has provided medical-social services to patients diagnosed with higher brain dysfunction (HBD). The Ministry of Health, Labor, and Welfare of Japan estimated, based on a survey, that approximately 300,000 people in Japan had sustained HBD caused by traffic accidents or cerebral vascular disease (Watanabe et al., 2009). HBD is generally considered to correlate strongly with consciousness disturbance (Watanabe et al., 2009). Patients who sustain traumatic head injuries sometimes exhibit consciousness disturbance in the acute phase. Consciousness has two dimensions: wakefulness and awareness. Consciousness disturbance in the acute phase is primarily diagnosed based on the level of wakefulness. When a patient spontaneously regains a state of wakefulness from a sleep cycle, he or she is regarded as being in a wakeful state (Yanamoto, 2014). However, only a few studies have shown a correlation between the types of traumatic head injuries and consciousness disturbance in the acute phase with a focus on head injuries to cyclists.

The head is the most vulnerable part of the human body and thus the most critical to protect. Several studies have proposed methods to effectively protect cyclists against traumatic head injuries using bicycle helmets (Bambach et al., 2013, Elvik, 2011, Fahlstedt et al., 2016, McNally and Whitehead, 2013, Minowa et al., 2000). Some analytical methods have been applied to study the effectiveness of helmets. According to the German Road In-Depth Accident Study (GiDAS), the use of helmets may lead to a 33% reduction in head injuries among cyclists with a severity of AIS3+, a 15% reduction in isolated soft tissue injuries, and a 46% reduction in full skull and skull base fractures (ETSC, 2015). Bambach et al. (2013) conducted a study linking police-reported road crashes with hospital admissions and mortality data. The results showed that bicycle helmet use was associated with a reduction of as high as 74% in the risk of such head injuries to cyclists in collisions with vehicles, such as skull fractures, intracranial injuries, and open head wounds.

Moreover, computational modeling, such as by using mathematical dynamic models (MADYMO) (TASS, 2012) and finite element (FE) models, has come to be widely used to assess the effectiveness of bicycle helmets. McNally and Whitehead (2013) performed a simulation using the MADYMO software to show the effectiveness of bicycle helmets in reducing the average probability of fatality in certain scenarios studied from 40% to 0.3%, where the results were based on data from the Head Injury Criterion (HIC) generated on MADYMO. However, the results showed no anatomical features of human brain injuries, as the head model of the MADYMO software had a solid part. The use of FE models of the human head has become prevalent for studying the complex mechanical responses of the skull and brain upon impact (Gabler et al. 2016, Fahlstedt et al., 2016). In most previous studies that used computational modeling, the results depended on the impact conditions. A few studies have been based on specific scenarios involving traffic accidents to determine the effectiveness of bicycle helmets in protecting against traumatic head injuries to cyclist, including consciousness disturbance. To more accurately assess the effectiveness of bicycle helmets, the impact on the head in case of accidents needs to be properly simulated.

The first objective of this study was to examine the correlation between types of traumatic head injuries to cyclists and consciousness disturbance in the acute phase by using emergency patient data (EPD). The second objective was to quantify the effectiveness of bicycle helmets in reducing traumatic head injuries by means of a case study that uses the EPD of cyclists who had sustained head injuries and consciousness disturbance from impact accidents. FE simulations were also performed to assess the risk of skull fractures owing to skull strain and brain contusions owing to brain von Mises stress.

2. Method

This study examined the correlation between types of traumatic head injuries to cyclists and consciousness disturbance in the acute phase. Analyses were conducted by using EPD from the medical emergency center mentioned in Section 1. The case study focused on a cyclist in the EPD who had not been wearing a bicycle helmet at the time of accident and had sustained a head injury and consciousness disturbance in the acute phase. The reconstruction assessed virtually the potential protective effect of a bicycle helmet with respect to head injuries. The study analyzed data concerning cyclists involved in traffic accidents who had been admitted to the Emergency Center of Dokkyo Medical
University Koshigaya Hospital in Saitama Prefecture, Japan. The data used were approved by the ethics’ committee of the hospital.

2.1 Traumatic head injuries to cyclists

The analysis used EPD from Dokkyo Emergency Medical Center from 2011 to 2013. This center is one of six in Saitama prefecture that serves the needs of an eastern population of approximately 1.7 million. The EPD contained personal data for all patients with fractures, open wounds, and/or intracranial injuries, including data on the clinical procedures, diagnoses, and severity of injuries as well as consciousness disturbance and the Glasgow Coma Scale (GCS) (INS, 2018). The EPD also included information on the traffic accident involved and its external causes, such as accident site and type (e.g., single-cyclist accident or vehicle-versus-bicycle accidents). Some cases included information on whether the cyclist was wearing a bicycle helmet while others did not. Considering a study that revealed a low percentage (8%) of cyclists wearing bicycle helmets in traffic accidents in Japan (Matsui and Oikawa, 2015), in the EPD, most cases of cyclists taken to hospital by ambulance after the accident were assumed to have not used a bicycle helmet, as in Japan, the use of bicycle helmets is recommended but not required by law.

We thus focused on cyclists with traumatic head injuries in the EPD and classified them into two groups: one consisting of patients with consciousness disturbance in the acute phase, and the other consisting of those who had not suffered from it. Injured cyclists who had tested positive for alcohol as well as fatally injured cyclists were excluded because the study strove to correlate head injuries and consciousness disturbance. The number of cyclists and their average ages in the two groups were investigated by sex. Moreover, the GCS was used to assess the level of wakefulness specifically the depth of coma, and the duration and level of impaired consciousness (INS, 2018). Patients in coma condition have closed eyes, no ability to follow commands, and cannot speak. The GCS is divided into three categories: eye opening (E), motor response (M), and verbal response (V). The score is determined based on the sum of scores in each of the three categories, of which the maximum was 15 and the minimum 3. A GCS score of 8 defines head injuries classified as severe or less serious, that of 9 to 12 indicates moderate injuries, and that of 13 to 15 represents mild head injuries (INS, 2018). In this study, the two groups of patients with and without consciousness disturbance were assessed by three ranges of GCS: 8 or less, 9 to 12, and 13 to 15.

To ascertain the correlation between a traumatic head injury and consciousness disturbance in the acute phase, head injuries were classified into two groups: head fractures and brain injuries. The number and types of head injuries were investigated based on the two groups of cyclists with and without consciousness disturbance. We compared the number of brain injuries by types, focusing on cyclists with consciousness disturbance. For example, when a cyclist with consciousness disturbance sustained two types of brain injuries, such as brain contusion and subdural hematoma, we counted this as an instance of each. From the comparison of number, we selected the following top six types of brain injuries in terms of number of occurrences: brain contusion, subdural hematoma, subarachnoid hemorrhage, extradural hematoma, cerebral edema, and concussion.

2.2 Protective effect of a bicycle helmet in case study

A case study from the EPD was reconstructed to assess the protective effect of a bicycle helmet against head injuries. The methodology used for a case study in this vein is shown in Figs. 1(1), (2) and (3). Based on an accident scenario involving a cyclist (Fig. (1)), the case study used a whole-body mathematical model in the MADYMO software to obtain the head impact conditions (Fig. (2)), which were then applied to perform an FE simulation by using an FE model of the human head and that of a bicycle helmet (Fig. (3)).

2.2.1 Accident scenario

The scenario of a cyclist with head injuries and consciousness disturbance was selected from the EPD. The case study was selected using detailed information concerning the situation and the site. It was a single-impact accident involving a male cyclist who was 22 years of age (1.68 m tall), and had not been wearing a helmet. The cyclist collided with a concrete wall after losing control of the bicycle shortly after traveling down a narrow slope of approximately over 10 m, as shown in Fig. 1(1). Bicycling down this slope section had been prohibited. The cyclist sustained a traumatic head injury, including a skull fracture above the left eyebrow, basilar skull fractures, acute extradural hematoma, brain contusion in the left frontal cortex, optic nerve injury of the left eye, pneumocephalus, and an open facial wound. The cyclist also
suffered from consciousness disturbance in the acute phase, whereby the GCS score was 11, lost sight in the left eye, and was subsequently discharged from hospital three weeks later. There were 12 cases (12.6%) of single-impact accidents among 95 cases involving cyclists in the EPD from 2011 to 2013. In only one out of the 12, a cyclist had sustained head injuries and also suffered from consciousness disturbance in the acute phase. The scenario in this study might be less-frequent cases, considering a situation that the number of cyclist impacts with outside constructions including walls was 240 (1.6%) among traffic accidents involving cyclists in Japan in 2017 (ITARDA, 2018).

(1) Accident scenario of a cyclist colliding with a concrete wall.

(a) Initial posture of model of cyclist on a bicycle model.  
(b) Posture of cyclist model on impact against wall model.

(2) Reconstruction using a whole-body model.

(a) No helmet (accident scenario).  
(b) With a helmet (the protective effect of a bicycle helmet).

(3) Simulation configuration for impact of FE model of the human head.

Fig. 1 Methodology of case study.

2.2.2 Simulation using a whole-body model

The impact scenario involving the cyclist, as shown in Fig. 1(1), was reconstructed based on information in the EPD using the MADYMO commercialized software (TASS, 2012) to estimate the impact on the head against the wall, as shown in Fig. 1(2). The results obtained were used for FE simulations of the impact on the head to assess the protective effect of a bicycle helmet against head injuries. The reconstruction of the impact involved the use of a rigid whole-body model of an adult male (a cyclist model), a bicycle model, and a wall model in MADYMO. The height of the cyclist in the model was set to 1.68 m, the same as that of the cyclist in the actual case. The bicycle model was a city bike for adults
commonly used in Japan, and consisted of a handle, fork, saddle, saddle post, frames, and tires. The wall model was assumed to be a rigid surface. The cyclist model was validated against post-mortem human tests (TASS, 2012). We used a bicycle model in a dataset of MADYMO (TASS, 2012).

Figure 1(2)(a) shows the initial posture of the cyclist on the bicycle as modeled. The cyclist model was set in front of the wall model vertically so that the facial area around the left eye of the cyclist hit the wall, as the cyclist had been injured in the left eye in the accident. The impact velocity of the bicycle model was set to 8.9 m/s (32 km/h), assuming that the bicycle had traveled downward on the slope for 10 m from a maximum height of 4 m at an initial velocity of 0 km/h without braking. Figure 1(2)(b) shows the posture of the cyclist model on impact against the wall model, from which we obtained values of the angle of the cyclist’s head against the wall, angular velocity, and translator velocity just before the cyclist’s head collided with the concrete wall.

2.2.3 Simulation using an FE model of the human head and an FE bicycle helmet model

FE analysis was first performed to simulate the impact of the head against the wall in the accident scenario, as shown in Fig. 1(3)(a). It was then performed for the same impact conditions with the cyclist wearing a bicycle helmet to assess the protective effect of the bicycle helmet against skull fracture and brain contusion, as shown in Fig. 1(3)(b). The angle of the head against the wall, angular velocity, and translator velocity obtained by the MADYMO models (Fig. 1(2)) were entered into the FE model of the human head as initial conditions.

The FE simulation used FE models of the human head (Aomura et al., 2016), the bicycle helmet (Oikawa et al., 2017), and the wall using the LS-DYNA (version 8.0) commercial FE software (LSTC, 2015). The FE model of the human head, developed by Aomura et al. in 2016, consisted of the main anatomical features, including the scalp, skull, cerebrospinal fluid, cerebrum, corpus callosum, ventricle, cerebellum, brain stem, falx, and tentorium. The sagittal-sectional T1-weighted MRI data of an adult man’s head was used to construct the FE model. To verify the FE model, the numerical results of an impact test using it were compared with those of a cadaver experiment by Nahum et al. (1997). The comparison showed that the FE model of the human head was sufficiently valid to predict intracranial pressure and acceleration. The brain and skull relevant displacements of the FE model of the human head were validated by comparing the results of the simulation with those of cadaver experiments by Hardy et al. (2001, 2007). The comparison showed that the FE model of the human head was sufficiently valid to predict the relevant displacement in the brain and skull.

The FE bicycle helmet model (Oikawa et al., 2017) was developed based on the FIGO G-1 commercial bicycle helmet for an adult male (OGK Kabuto, 2012). The model consisted of a polycarbonate outer shell and a polystyrene form liner (Milne et al., 2013), components of the FIGO G-1 helmet. The FE wall was assumed to be a rigid surface. The coefficient of friction between the head or helmet and the wall was set to 0.5, as was the friction coefficient between the head and helmet (Fahlstedt et al., 2016). The FE bicycle helmet model was validated by comparison with a drop experiment of the helmet against the pavement (Oikawa et al., 2016). The comparison yielded good agreement between the resultant accelerations in the simulation and the experiment.

Head-impact simulations were conducted to evaluate the risk of head injury with a focus on skull fractures and brain contusions. The risk of head injury was estimated using skull strain for skull fracture (Irwin and Mertz, 1997), and by brain von Mises stress for brain contusion (Miller et al., 1998). The criteria for a head injury for a 50% probability were 3.5% for skull strain (Irwin and Mertz, 1997, McCalden, 1993) and 8.6 kPa for brain von Mises stress (Miller et al., 1998). The criterion for skull strain (3.5%) was set in light of the cyclist’s age (22 years of age) (McCalden, 1993).

3. Results

3.1 Analyses of traumatic head injuries to cyclists in the EPD

The number of cyclists involved in traffic accidents in the EPD from 2011 to 2013 was 93, consisting of 66 (71.0%) injuries and 27 (29.0%) fatalities. Among the 66 cyclists involved, there were 32 cyclists who had sustained traumatic head injuries, of the data considered. Figure 2 shows the distribution of cyclists according to the three GCS ranges for each patient with and without consciousness disturbance. The GCS score defines head injuries as severe for 8 or less, moderate for 9 to 12, and mild for 13 to 15 (INS, 2018). For cyclists with consciousness disturbance, the highest percentage was GCS 9 to 12 for eight (n = 8) cyclists (53.3%), followed by GCS 8 or less for five (n = 5) cyclists (33.3%), and GCS 13 to 15 for two (n = 2) cyclists (13.3%). For cyclists without consciousness disturbance, all were recorded at
GCS 13–15 (100%).

The cyclists (n = 32) who had sustained traumatic head injuries consisted of 17 (53.1%) males and 15 (46.9%) females. The average age of the 32 cyclists was 33.9 years. The number of cyclists with consciousness disturbance in the acute phase was 15 (46.9%; average age of 38.1 years; SD of 26.6 years), as shown in Table 1. Cyclists with consciousness disturbance (n = 15) consisted of five (n = 5) males (33.3%) and 10 females (66.7%). On the contrary, the number of cyclists who did not exhibit consciousness disturbance was 17 (53.1%; average age of 27.4 years; SD of 24.6 years). Cyclists without consciousness disturbance (n = 17) consisted of 12 males (70.6%) and five (n = 5) females (29.4%). Table 1 also compares the distribution of male and female cyclists with and without consciousness disturbance. The rate of male cyclists without consciousness disturbance was significantly higher than that of males with consciousness disturbance (p = 0.035). The rate of female cyclists with consciousness disturbance was significantly higher than that of females without consciousness disturbance.

Table 1 Number, average age of cyclists who did or did not exhibit consciousness disturbance, and comparison of cyclists with and without consciousness disturbance by sex.

<table>
<thead>
<tr>
<th>Cyclists who exhibited head injury</th>
<th>Consciousness disturbance</th>
<th>Total</th>
<th>Difference</th>
<th>p-Value*1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exhibit</td>
<td>Not exhibit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>(%) Avg. age SD</td>
<td>n</td>
<td>(%) Avg. age SD</td>
</tr>
<tr>
<td>Males</td>
<td>5</td>
<td>33.3 15.2 5.4</td>
<td>12</td>
<td>70.6 24.8 19.9</td>
</tr>
<tr>
<td>Females</td>
<td>10</td>
<td>66.7 49.8 25.7</td>
<td>5</td>
<td>29.4 43.0 29.6</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>100.0 38.1 26.6</td>
<td>17</td>
<td>100.0 27.4 24.6</td>
</tr>
</tbody>
</table>

*1 A significant difference was determined using a statistical two-tailed test of the sample rates.

*2 Note: *p*-Value < 0.05

Head injuries were mainly classified into two groups: head fractures and brain injuries. We investigated all head fractures and brain injuries for the 32 cyclists according to type. For example, when one cyclist sustained a skull fracture (n = 1), facial fracture (n = 1), brain contusion (n = 1), and subdural hematoma (n = 1), the total number was two (n = 2) for head fractures and two (n = 2) for brain injuries because each head injury was counted. Table 2 shows the correlation between head fractures and brain injuries, and consciousness disturbance. In case of head fractures, skull fracture (n = 6, 46.2%) was the most frequently occurring type for cyclists with consciousness disturbance, whereas skull fracture (n = 4, 33.3%) and basilar skull fracture (n = 4, 33.3%) were the most frequently occurring types for cyclists without consciousness disturbance, as shown in Table 2(a). The total number of head fractures was 13 for 15 cyclists with consciousness disturbance and 12 for 17 cyclists without consciousness disturbance.

In focusing on the average number of head fractures for a cyclist, one with consciousness disturbance sustained an average number of 0.4 head fractures, which was higher than that of 0.2 for cyclists without consciousness disturbance. Of brain injuries, the top six in terms of number sustained by cyclists with consciousness disturbance were selected for
comparison, as shown in Table 2(b). Brain contusion was the most frequently occurring brain injury for both cyclists with consciousness disturbance \((n = 10, 34.5\%)\) and without consciousness disturbance \((n = 3, 33.3\%)\). Subdural hematoma was the second-most frequently occurring brain injury for those with consciousness disturbance \((n = 6, 20.7\%)\), followed by subarachnoid hemorrhage \((n = 4, 13.8\%)\). Subarachnoid hemorrhage and concussion were the second most frequent brain injuries for cyclists without consciousness disturbance \((n = 2, 22.2\% \text{ for each})\). The total number of six types of brain injuries was 29 for the cyclists with consciousness disturbance and nine \((n = 9)\) for those without consciousness disturbance. The average number of brain injuries for one cyclist was 1.9 for the case with consciousness disturbance, which was remarkably higher than 0.5 for the case without consciousness disturbance.

Table 2 Correlation between head injuries and consciousness disturbance.

<table>
<thead>
<tr>
<th></th>
<th>(a) Head fractures.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Consciousness disturbance</td>
</tr>
<tr>
<td></td>
<td>Exhibit ((n = 15))</td>
</tr>
<tr>
<td>Head fractures to cyclists</td>
<td>Ave. number for one cyclist</td>
</tr>
<tr>
<td></td>
<td>(n)</td>
</tr>
<tr>
<td>Skull fracture</td>
<td>6</td>
</tr>
<tr>
<td>Basilar skull fracture</td>
<td>3</td>
</tr>
<tr>
<td>Facial fracture</td>
<td>2</td>
</tr>
<tr>
<td>Orbital fracture</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13</strong></td>
</tr>
</tbody>
</table>

|                                | (b) Brain injury.                    |
|                                | Consciousness disturbance             |
|                                | Exhibit \((n = 15)\)  | Not exhibit \((n = 17)\) |
| Brain injury* to cyclists      | Ave. number for one cyclist         | Ave. number for one cyclist |
|                                | \(n\)    | \(n / 15\) | \(m\)    | \(m / 17\) |
| Brain contusion                | 10       | 34.5      | 3        | 33.3      |
| Subdural hematoma              | 6        | 20.7      | 1        | 11.1      |
| Subarachnoid hemorrhage        | 4        | 13.8      | 2        | 22.2      |
| Extradural hematoma            | 3        | 10.3      | 1        | 11.1      |
| Cerebral edema                 | 3        | 10.3      | 0        | 0.0       |
| Concussion                     | 3        | 10.3      | 2        | 22.2      |
| **Total**                      | **29**   | **100.0** | **9**    | **100.0** |

*Brain injury listed: top six types of brain injuries in number of occurrences to cyclists with consciousness disturbance

3.2 Case study in reconstruction

3.2.1 Simulation using a whole-body model

The impact of the cyclist with the concrete wall was reconstructed based on information in the EPD by MADYMO models to estimate the conditions of the impact on the head. We obtained the angle of the cyclist’s head with the wall, angular velocity, and translator velocity just before the head collided with the wall, as shown in Table 3. The obtained conditions were used for the FE simulation.
Table 3 Angle of the cyclist’s head with the wall, angular velocity, and translator velocity just before collision with the wall.

<table>
<thead>
<tr>
<th>Head angle against the wall (degree)</th>
<th>Head angular velocity (rad/s)</th>
<th>Head translator velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resultant</td>
<td>–</td>
<td>0.9</td>
</tr>
<tr>
<td>x-axis</td>
<td>-5.0</td>
<td>0.1</td>
</tr>
<tr>
<td>y-axis</td>
<td>-4.8</td>
<td>0.6</td>
</tr>
<tr>
<td>z-axis</td>
<td>58.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

3.2.2 Simulation using FE model of the human head and FE bicycle helmet model

The impact of the cyclist’s head was reconstructed by the FE model of the human head and the FE helmet model with a focus on skull fractures and brain contusions. The results obtained by the MADYMO models (Table 3) were entered into the FE model of the human head as initial conditions. Table 4 shows a comparison of peak values computed in the FE model of the human head with and without the helmet. They indicate a reduction in skull strain by 95.9% and that in brain von Mises stress by 23.3%. The peak value of skull strain was 7.4% in case of the model of the cyclist’s head without a helmet, and decreased to 0.3% with helmet use. The skull strain of 7.4% surpassed the skull fracture with a 50% probability threshold of 3.5% (Irwin and Mertz, 1997, McCalden, 1993) without a helmet. However, it was far below the threshold for helmet use. The peak value of brain von Mises stress was 11.6 kPa for the model of the cyclist’s head without a helmet, and decreased to 8.9 kPa with helmet use. Both values of 11.6 kPa and 8.9 kPa surpassed the 50% probability threshold of 8.6 kPa for brain contusion.

Table 4 Comparison of peak values computed with the FE model of the human head with and without the FE helmet model.

<table>
<thead>
<tr>
<th>Head injury</th>
<th>Injury risk predictors</th>
<th>Criteria</th>
<th>No helmet (a)</th>
<th>With a helmet (b)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skull fracture</td>
<td>Peak skull strain (%)</td>
<td>3.5 1) 2)</td>
<td>7.4*</td>
<td>0.3</td>
<td>7.1</td>
</tr>
<tr>
<td>Brain contusion</td>
<td>Peak brain von Mises stress (kPa)</td>
<td>8.6 3)</td>
<td>11.6*</td>
<td>8.9*</td>
<td>2.7</td>
</tr>
</tbody>
</table>

1) Irwin and Mertz, 1997
2) McCalden, 1993
3) Miller et. al 1998
*Head injury criteria at 50% probability obtained

4. Discussion

In a comparison of the distribution of male and female cyclists based on the presence or absence of consciousness disturbance, the rate of male cyclists without consciousness disturbance was significantly higher than that of males with consciousness disturbance ($p = 0.035$), while the rate of female cyclists with consciousness disturbance was significantly higher than that of females without consciousness disturbance (Table 1). The significant difference in female cyclists supported the results obtained by Antona-Makoshi et al. (2018), who showed that belted female occupants in light vehicles were estimated to be 1.5 times more likely to sustain a concussion than belted male occupants in traffic accidents. Research on sports-related concussion by Zuckerman et al. (2015) also showed that female athletes might be up to 2.6 times more likely to sustain a concussion than their male counterparts. Further studies are needed to clarify the correlation between the differences in sex and consciousness disturbance by considering other factors, such as the degree of severity of traumatic head injury, age, traffic environments in accidents, and considering a greater number of cyclist patients over longer periods.

Of 32 cyclists in the EPD who had sustained traumatic head injuries, GCS 13 to 15 accounted for 59.4% ($n = 19$), followed by GCS 9 to 12 for 25.0% ($n = 8$) and GCS 8 or less for 15.6% ($n = 5$). GCS 13 to 15 having the largest percentage is congruent with the results reported by Suehiro et al. (2017), who stated that mild traumatic brain injury (GCS 14 to 15) was more often recognized in cyclists than pedestrians involved in traffic accidents. Even though traumatic...
brain injury constitutes a mild degree on the scale, it has the potential for causing higher brain dysfunction and post-concussion syndrome (Suehiro et al., 2017). In contrast, the percentage of head injuries among cyclist fatalities (85.2%, \( n = 23 \)) was higher than those among pedestrians (66.7%, \( n = 16 \)) and drivers/passengers of motor vehicles (36.4%, \( n = 4 \)) in the EPD from 2011 to 2013. Nevertheless, even when they are not fatal, traumatic head injuries can lead to critical conditions.

For cyclists with consciousness disturbance, a GCS of 12 or less accounted for 86.7% (GCS 9 to 12 of 53.3% and GCS 8 or less of 33.3%). For cyclists without consciousness disturbance, a GCS 12 or less accounted for 0%. Considering this result, a GCS of 12 can be considered a threshold for the assessment of cases with and without consciousness disturbance. Although this study did not investigate the correlation between consciousness disturbance and disabilities in the chronic phase, Watanabe et al. (2009) targeted patients with a GCS of 12 or less to estimate the prevalence of higher brain dysfunction (HBD). Therefore, when cyclists experienced consciousness disturbance with a GCS of 12 or less, they might have developed HBD in a chronic phase. Patients with HBD have attention-deficit disorders, memory disorders, executive dysfunction, and disorders of emotion and social communication to varying degrees (Shinoda and Asano, 2013).

In the emergency medical center at Dokkyo Medical University Koshigaya Hospital, patients must relocate to a different hospital when they need rehabilitation for long periods on account of certain disabilities, such as HBD. As this study focused on consciousness disturbance in the acute phase by traumatic head injuries, further research is required to clarify the correlations among traumatic brain injuries, consciousness disturbance in the acute phase, and permanent disabilities in the chronic phase, including HBD, by targeting a larger number of patients in hospitals and rehabilitation institutions over a longer period.

This study examined the average number of head fractures and brain injuries by types for a cyclist in case of accident (Table 2). For head fractures, the results revealed that the average number (\( n = 0.9 \)) for a cyclist with consciousness disturbance was higher than that (\( n = 0.7 \)) for a cyclist without consciousness disturbance. For brain injuries, the average number (\( n = 1.9 \)) for a cyclist with consciousness disturbance was also higher than that (\( n = 0.5 \)) for a cyclist without consciousness disturbance. This finding implies that both head fractures and brain injuries may increase the probability of consciousness disturbance. As this result was based on EPD from a hospital, further research is needed to clarify the correlation between head fractures and brain injuries, and consciousness disturbance using data from several hospitals.

There are some limitations to this study. The statistical analysis of cyclists on the EPD was applied to the comparison only by sex. To clearly understand consciousness disturbance among cyclists in the acute phase requires further statistical analysis focusing on cyclist age, types of traumatic brain injuries, and other factors relating to consciousness disturbance.

The second limitation is that the bicycle model in MADYMO software was not validated by impact tests or literature appropriate to the impact scenario. In this study, it was estimated that the simulation using a whole-body model can reconstruct the scenario with a certain degree of accuracy, as the cyclist model involved impact in the facial area around the left eye by collision against the wall, which was the major head injury suffered by the cyclist considered.

The limitation of the reconstruction case study was that consciousness disturbance could not be assessed by the FE head model because the mechanism of consciousness disturbance by traumatic head injuries has not been clarified. However, the peak values in the FE simulation showed reduced skull strain by 95.9% for a skull fracture and reduced brain von Mises stress by 23.3% for a brain contusion due to helmet use. Moreover, the analyses of traumatic head injuries to cyclists in the EPD revealed that head fractures and brain injuries can increase the probability of consciousness disturbance. The average number of skull fractures for a cyclist was 0.2 without consciousness disturbance, whereas it was 0.4 with consciousness disturbance. For a brain contusion, the result indicated 0.2 for a cyclist without consciousness disturbance and 0.7 for one with consciousness disturbance (Table 2). From these results, it appears that the use of a bicycle helmet can reduce the probability of consciousness disturbance.

Furthermore, a reconstruction case study was conducted for an accident involving a cyclist. The simulation by a whole-body model in MADYMO software (TASS, 2012) was performed an impact pattern based on a hypothesis from the information in the EPD. Other cases of impact and other possible impact patterns must be considered by means of an FE simulation to examine the effectiveness of bicycle helmets. In the actual accident selected, as mentioned earlier, the cyclist sustained basilar skull fractures, acute extradural hematoma, an injury to the optic nerve in the left eye, pneumocephalus, and a facial open wound as well as primary skull fracture and brain contusion. This study assessed the skull fracture and brain contusion in the FE simulation because they were the most frequently occurring types of head injuries among cyclists in the EPD (Table 2). Further research is needed to assess the effectiveness of wearing a bicycle helmet for other types of head injuries by using an FE simulation.
5. Conclusion

This study investigated the correlation between types of traumatic head injuries sustained by cyclists and consciousness disturbance in the acute phase by focusing on the difference by sex. The rate of female cyclists with consciousness disturbance was significantly higher than that for females without consciousness disturbance. Skull fractures and brain contusions were the most frequently occurring head injuries for both cyclists with and without consciousness disturbance. The average numbers of head injuries by types for a cyclist with consciousness disturbance were higher than those for one without consciousness disturbance for both head fractures (0.9 versus 0.7) and brain injuries (1.9 versus 0.5).

The reconstruction case study was undertaken on a cyclist using an FE model of the human head and an FE bicycle helmet model. The results showed that with a helmet, the skull strain was reduced by 95.9% and the brain von Mises stress by 23.3%. These results suggest that cyclists can reduce the risk of skull fractures and brain contusions in accidents by wearing a helmet. Further, the use of a bicycle helmet can reduce the probability of occurrence of acute phase consciousness disturbance without a skull fracture and brain contusion.

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References


Institute of Neurological Sciences (INS), The Glasgow structured approach to assessment of the Glasgow Coma Scale (2018), http://www.glasgowcomascale.org/who-we-are/.


