ORIGINAL

A study on the diagnostic support system of the repetitive brain concussion based on the reconstruction analysis of the accident －The accident cases of Judo and American football－

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Abstract : In this paper the effectiveness of the support system which predicts the risk of the repetitive brain concussion is studied biomechanically. In the risk prediction system, the accident that caused the concussion is reconstructed by analyzing the game video via multibody dynamics and the resulting brain injury is calculated in detail by the finite element method. In order to calculate the aggravation of the brain injury by the repeated brain concussion, the following two methods are examined. In the first method, the material properties of the part of the brain damaged by the1st impact are changed in the simulation of the 2nd impact. In the second method, each brain damage caused by the repeated impacts is accumulated. The system was applied to the real-life accidents that occurred during Judo and American football games. As a result of the simulations, the aggravation of the brain damage due to repetitive concussion was determined numerically in terms of the maximum strain of the brain and the brain damage rate of the whole brain. The biomechanical process of the collision accidents and the resulting brain damage were reconstructed based on the video and the results are effective to prevent the future repeated concussion accidents. J. Med. Invest. 70 : 213-220, February, 2023

Keywords : *repetitive concussion, traumatic brain injury, multibody dynamics, finite element method, Judo and American football*

INTRODUCTION

Impact to the head due to a collision accident may cause traumatic brain injuries (TBI), and the repeated TBI may result in cumulative damage to the brain cells even if each damage is mild in terms of concussion. Furthermore, it may lead to rapid catastrophic deterioration (second impact syndrome) or chronic traumatic encephalopathy (CTE) presenting with cognitive dysfunction as shown in Fig.1. Concussions may occur in most contact sports and even noncontact sports in which unexpected head collision occurs. The second impact syndrome is believed to be the catastrophic consequence of the repeated head injuries in sports (1). The phenomenon of the second impact syndrome appears in the medical literature despite the lack of systematic evidence for its existence. Moreover one poorly understood aspect of TBI is mild traumatic brain injury (mTBI), such as concussion, since the post-injury sequelae are difficult to address at the cellular level *in vivo* (2).

One of the approaches to predict the repeated concussion is to analyze the first concussion mechanically and to add the results in the medical information, because the player who sustained the first head injury, most often concussion, sustains the second head injury before the symptoms of the first injury recover (3, 4).

In order to estimate the risk of the mTBI represented by a concussion in sports, the real world accidents suspected of causing concussion must be analyzed biomechanically, where the collision is simulated kinematically and the brain distortion is determined mechanically. If the impulsive force added to the head in collision is known, the damage to the head can be analyzed in detail by using the finite element method (FEM) in detail. A clear understanding of the injury mechanism may help explain concussion risks and lead to further improvement in safety equipment. However, the absence of an effective method to obtain the mechanical information in the concussion accident remains as an important challenge.

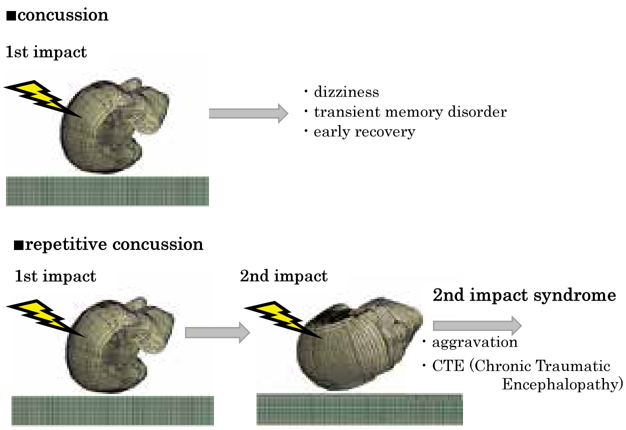

Fig 1. Brain concussion is a disorder that results in temporary loss of normal brain function, and even though the symptoms seem to be improved after the injury, it causes aggravation and remote dementia when repeated in a short term.

One of the most reliable methods to determine the collision kinematics is the analysis of the game videos. Records of video camera are becoming more popular with increased resolution by rapid technological development at lower expense. In recent

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years, video recordings of daily practices and games are often used to check the formation designs, and the assignment of players, as well as to analyze the tactics of the opponents. The information obtained from the videos is important for improving the performance of the players. Video recordings also play an important role in confirming the course of events and their effects on the players during a collision accident. In particular, a TBI represented by concussion is rather difficult to diagnose visually than a trauma to the extremities, hence the videos are often indispensable to confirm the movement of the players just before and after the collision.

While various maintenance systems for the health care of the players continue to achieve results, a more biomechanical approach is also strongly required because TBI research represented by concussion has been advancing remarkably for years, leading to a greater insight into the cause and effects of mTBI (5).

Previously, the pathogenic mechanism of brain injury due to the impact has been studied (6, 7) and an impact analysis by using a FE human head model has been reported to evaluate the type and severity of the brain injury using the mechanical parameters inside the skull.

In order to evaluate the concussion caused by the head-to-head collision quantitatively, the translational and the angular accelerations during the impact have been measured using the acceleration sensors installed in the helmet (8). In laboratory experiments, to measure the acceleration during the impact, the collision event has been reconstructed by using human dummy models. The relative velocity and location of the collision of the players' heads have been determined by analyzing the game videos and used as the initial conditions of the experiments (9, 10). Reports from these studies discuss the tolerance of concussion evaluated by the indexes such as Head Injury Criterion (HIC), the Severity Index (SI), the Generalized Acceleration Model for Brain Injury Threshold (GAMBIT) or Head Impact Power (HIP) which have been calculated from the measured accelerations. Furthermore, an impact analysis using the FE human head model have been performed to determine the distribution of the mechanical parameters inside the skull caused by the impact (11, 12). In these reports the tolerance of the brain concussion has been evaluated by strain, strain rate and von Mises stress of the brain.

Concerning the brain concussion, a simulation study based on the various dynamics of the contact sports, mainly American football has been reported. In recent years the risk of the second impact syndrome has been reported in medical articles but lacking sufficient clinical data. Further, to the best of authors' knowledge, a method that simulates the repetitive brain concussion and points out the risk of the second impact syndrome biomechanically has not been presented in the literature before.

Therefore, in this paper, the diagnostic support system for the repetitive brain concussion based on the reconstruction analysis of the accident is proposed and applied to the accidents that occurred in Judo and American football. In the system, four accident cases, two cases in Judo and two other cases in American football, are analyzed. Although the two accidents occurred independent of each other, one is defined as the 1st accident and the other is defined as the repetitive 2nd accident since the quantitative data and the corresponding video recording for a repetitive brain concussion accident, which are needed for the simulation, has not been presented in literature before.

In the system, two methods are tested to predict the aggravation of the brain damage by the repeated impact. The first method is to change the material properties of the brain part damaged by the 1st impact and the second method is to add the damages of the 1st impact and the 2nd impact mathematically. As a result of the simulations, the aggravation of the brain damage by repeating a concussion was shown quantitatively by the maximum strain and the damage rate of the brain.

The assessment system based on the accident videos will contribute to improving the understanding of the risk of the mTBI quantitatively and make a good correlation with the concussion diagnostic program based on interviews and observations as SCAT2 (Sports Concussion Assessment Tool 2). The details of the proposed assessment system and the results of two on field cases are reported below.

MATERIALS AND METHODS

Injury assessment system by multibody dynamics and FEM

The schematic illustration of the assessment system for a concussion accident is shown in Fig.2 in the case of American football game. The brain injury is simulated through two calculation

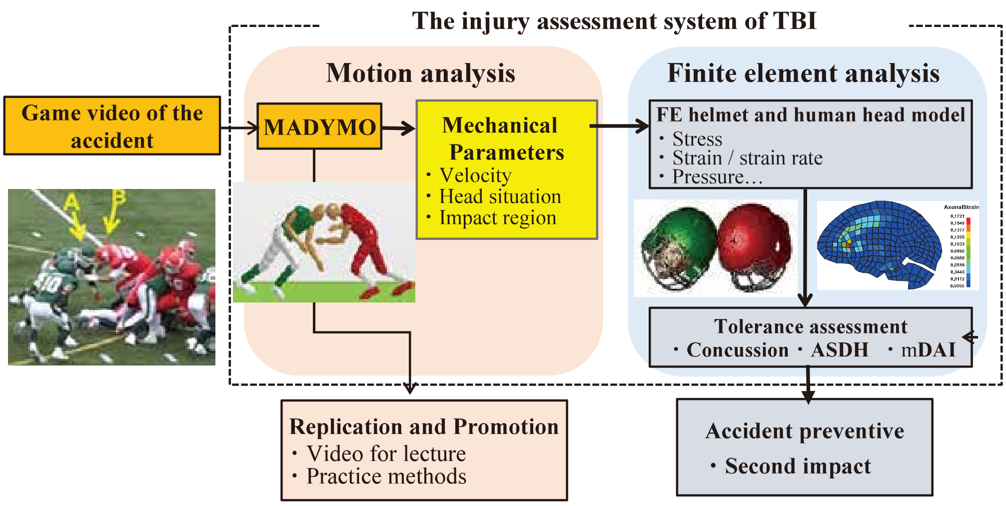


Fig 2. The risk assessment system of traumatic brain injury (TBI) by motion analysis and finite element analysis based on the accident game video in the accident case of American football. (ASDH : acute subdural hematoma, mDAI : mild diffuse axonal injury)

steps.

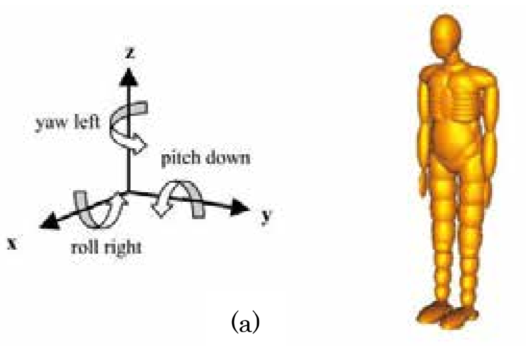
The first step is to reconstruct the motion of the whole body during the accident by using the mathematical dynamic model (MADYMO) software shown in Fig.3(a). The MADYMO is the world standard software for dummy injury prediction and design optimization for occupant restraint equipment. In this step, to obtain the initial relative head velocities and the position of the two players just before the collision, the motion analysis based on the game video was performed by using human models, which were implemented in MADYMO, and validated against post-mortem human tests (MADYMO Human Body Models Manual 7.5).

The second step is to evaluate the mechanical parameters involved with the observed brain injury by using FEM. In the finite element simulation, the relative velocities and positions of the heads were input to the helmeted FE human head models as the initial condition. In this study LS-DYNA ver.8.0 is used for FE analysis.

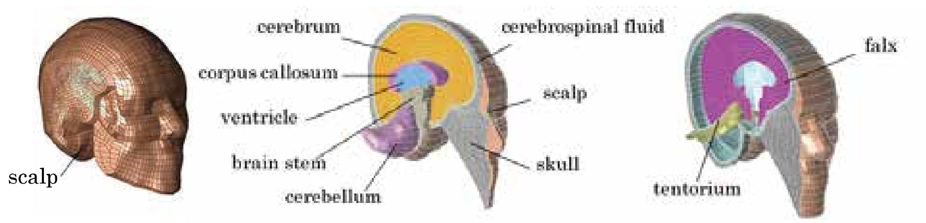
A FE human head model was constructed using sagittal-sectional T1 weighted MRI data of a human head. The model includes the main anatomical features such as scalp, skull, cerebrospinal fluid (CSF), cerebrum, corpus callosum, ventricle, brain stem, falx and tentorium as shown in Fig.3(b). The three-layered structure of the skull, which consists of an outer table, diploe, and inner table, was also reproduced. In this model, the falx and tentorium were constituted by shell elements, and the others were constituted by hexagon elements. The finite element model consists of 89,226 nodes and 74,462 elements with a total mass of 4.2 Kg. The material properties of each part of the model are shown in Table 1. Elastic properties were assigned to the scalp, skull, falx and tentorium, whereas viscoelastic properties were assigned to the CSF, cerebrum, brain stem, corpus callosum and ventricle.

In the case of the Judo accident, since the Judo tatami is designed specifically to protect the player by absorbing the strong shock, and the surface is designed so that the player does not slip on it, the FE Judo tatami model is designed separately. In the finite element simulation for a Judo accident, to obtain the deformation of the head, the contact characteristic of Judo tatami and the head is necessary. The defined contact characteristics were inspected by the drop test of the head-form impactor as shown in the upper part of Fig.4.

The FE helmet model is indispensable in accident simulations in American football. In this study, after the FE helmet model was designed, a drop test of the helmet was carried out to validate the helmet model. In the experiment, the helmet in which a



(a)



(b)

Fig 3. (a) Multibody human model by MADYMO and (b) finite element human head model.

Table 1. Material properties of the finite element human head model (11)

	Scalp	Facial bone	Outer/inner table	Diploe	CSF/ Ventricle	Cerebrum	Brain stem	Corpus callosum	Falx/ Tentorium
Density ρ (kg·m^{-3})	1200	2500	1800	1500	1040	1040	1040	1040	1130
Young's Modulus E (MPa)	16.7	5000	7350	4500	-	-	-	-	11.5
Bulk Modulus K (MPa)	-	-	-	-	2190	2190	2190	2190	-
Short Time Shear Modulus G_0 (MPa)	-	-	-	-	5.28	10	22.5	12.5	-
Long Time Modulus G_∞ (MPa)	-	-	-	-	0.5	2	4.5	2.5	-
Poisson's Ratio ν (-)	0.42	0.23	0.26	0.05	-	-	-	-	0.45

head-form impactor was set (13) was dropped from 1.5 m height (impact velocity 4.4 m/s), impacted to a flat anvil at parietal region as shown in the lower part of Fig.4.

Reconstruction of the accident cases based on the video

In this study, four accident cases as shown in Fig.5(a), two cases in Judo and 2 cases in American football are used. Since a video with two consecutive concussions occurred on the same player repeatedly could not be obtained, these two cases are regarded as consecutive accidents even though each case happened independently.

■The 1st impact of the Judo case as shown in Fig.5(b) upper : The player that will receive the injury is standing on the left side in the first 2 frames in the video and he is modeled in red in the corresponding MADYMO picture. After hitting the occipital region of his head by an "Oosotogari (Judo Waza)" during the game of the world judo championship in 2013, the player experienced a disturbance of consciousness for a short time (about one minute) and headache. The signs of retrograde amnesia were also present, and a brain concussion was diagnosed by a doctor.

■The 2nd impact of the Judo case as shown in Fig.5(b) lower : The player with the imminent injury is the person wearing the blue uniform on the left side in the video and modeled in red in the MADYMO picture. He hit the left side of his head by a "Kosotogari (Judo Waza)" during the semifinals of the championship. He did not have subjective symptoms, but a brain concussion was diagnosed by a team doctor.

■The 1st impact of the American football case as shown in Fig.5(c) upper : The injured player is a defensive back player and is wearing a red uniform with number 27 on it in the video and modeled in red in the MADYMO picture. He hit the right side of his head and the athletic trainer of the team promptly removed the player from the game because of a suspected concussion and he was then diagnosed with a concussion by the team doctor.

■The 2nd impact of the American football case as shown in Fig.5(c) lower : The injured player is an offensive lineman and the collision accident occurred just after the game started. The injured player is wearing the red uniform with No.52 standing at the left side of the two red players in the first frame of the video. He was then diagnosed with a concussion and left the game. He finally returned to play after 13 days.

In this study the video for the Judo game was recorded by a single video camera from one direction, but the video for the American football game was recorded by two cameras from two directions. The reconstruction of the colliding motion of the Judo players was possible from the video from one direction, however, in the case of the American football, the second video was used in addition to the first one when the target player moved behind the other players (14).

The method to express the damage from the repeated concussions : Many mechanical parameters such as von Mises stress, strain, strain rate, translational acceleration, rotational acceleration and brain damage rate as shown in Table 2 have been proposed as a dynamic evaluation standard of the onset of the brain concussion until now (15-19). In this study the strain (= 0.1) of the brain is used as the threshold of the onset of the concussion, and the brain damage rate (=50%) is used to observe the intracranial expanse of the concussed elements repeated under the 2nd impact. The brain damage rate is given as follows :

$$\text{the brain damage rate} = \frac{\text{the number of the elements beyond the strain threshold}}{\text{the total element number of the whole brain}} \times 100\ [\%]$$

Here the two methods are investigated to predict the aggravation of the cerebral damage due to the repetitive brain concussion by improving the function of analyzing an individual brain concussion.

■Method1 : In this method the mechanism of the aggravation by repetitive brain concussion is assumed to be the change of the material properties of the brain part damaged by the 1st impact. And the material properties of the brain part damaged by the 1st impact are changed at the time of the analysis of the 2nd impact. The material property to be changed is the shear modulus of the damaged part as shown in Fig.6. The shear modulus of the cerebrum is reduced by 60% and that of the brain stem is reduced by 28% based on the experimental data of the injured brain tissue in a mouse model (20, 21). The following five different patterns depending on the damage part are analyzed, and the effectiveness of the method is examined. The result of the 2nd impact

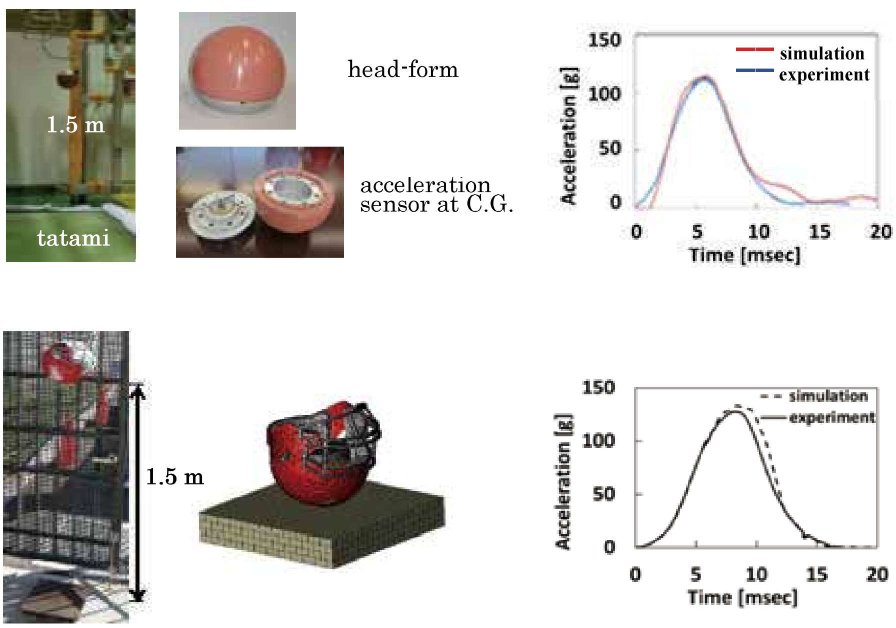


Fig 4. The drop test of a head-form impactor on the Judo tatami mat and comparison with the simulation result of the acceleration change (upper) and the drop test of the American football helmet on the anvil and comparison with the simulation result (lower).

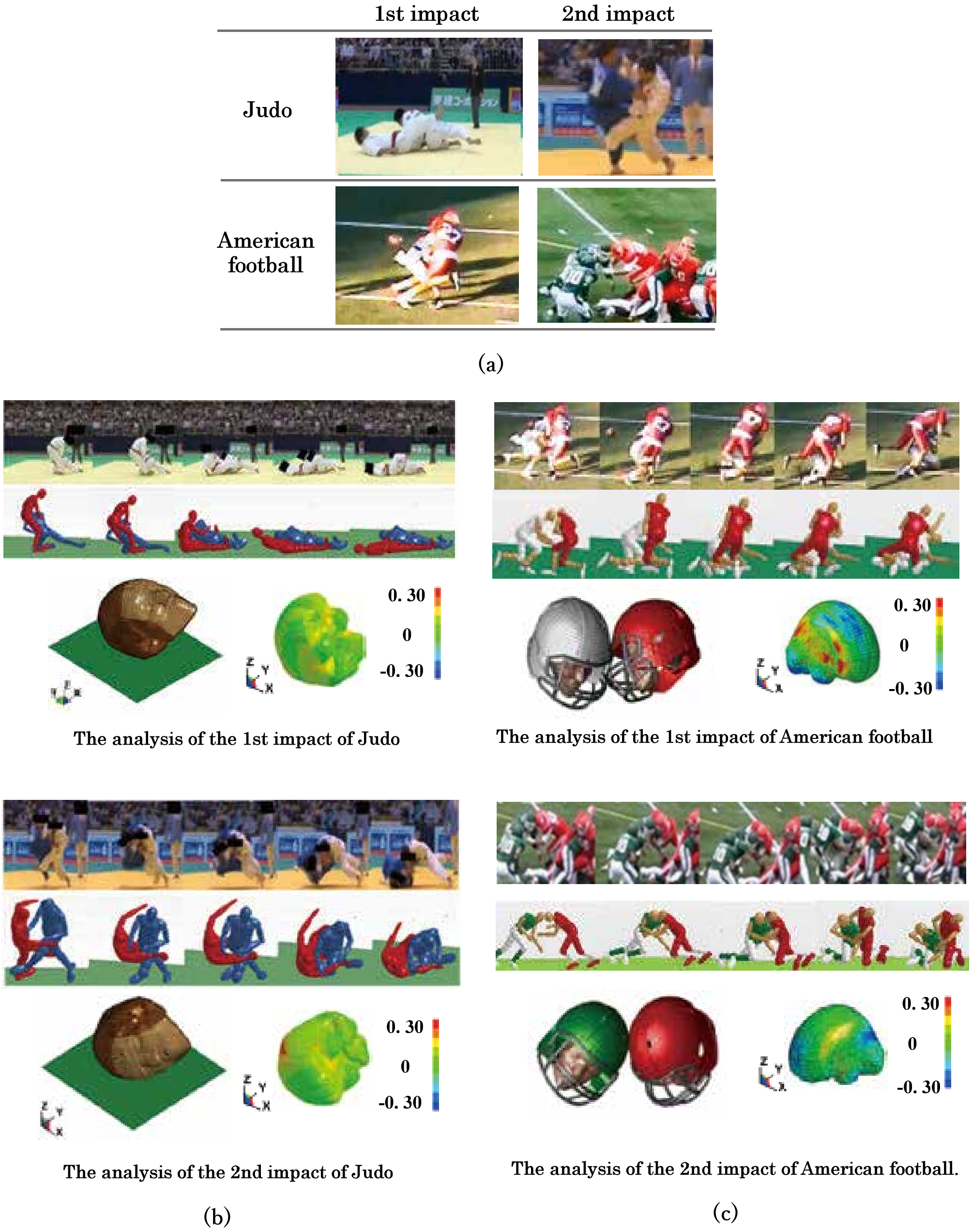


Fig 5. The four accident cases, two cases in Judo and other two cases in American football, (a) each accident happened independently, however are analyzed as happened in succession, (b) the collision motion of the two players in Judo is reconstructed based on the game video, the upper still photographs are from the game video and the lower still photographs are from MADYMO simulation, (c) 〃 in American football

Table 2. The threshold of an onset of a concussion by various evaluation indexes

	von Mises stress [kPa]	strain	strain rate [1/s]	translational acceleration [m/s²]	rotational acceleration [rad/s²]	brain damage rate [%]
threshold	7.8[15]	0.1[16]	37[17]	686[18]	2,615[19]	50[19]

analysis is regarded as the final result.

Method1-1 : no part of the brain is damaged by the 1st impact

Method1-2 : the cerebrum is damaged by the 1st impact

Method1-3 : the brain stem is damaged by the 1st impact

Method1-4 : the cerebrum and the brain stem are damaged by the 1st impact

Method1-5 : only the elements beyond the injury threshold (the damage reflection method)

■Method2 : In this method the results obtained by the analysis of both impacts are added as shown in Fig.7. In the case of Method2-1, two accident cases are analyzed independently and both results are added. In the case of Method2-2, the material properties of the elements that are beyond the injury threshold after the 1st impact are changed at the time of the 2nd impact analysis and both results are added in the same way as Method2-1.

Method2-1 : the results of the 1st impact and the 2nd impact are added

Method2-2 : the material properties of elements beyond the injury threshold by the 1st impact are changed before the 2nd impact (the damage reflection method)

■The damage reflection method : In this method only the material properties of the finite elements that beyond the injury threshold after the 1st impact are changed at the time of the 2nd impact analysis. This method is applied to Method1-5 and Method2-2. The elements beyond the injury threshold of strain after the 1st impact are shown in Fig.8 in both Judo and American football cases.

RESULTS AND DISCUSSION

Results

First, the four accident cases (two cases in Judo and two cases in American football) were simulated independently and the maximum translational and rotational accelerations are shown in Table 3. In this case the four accidents were occurred independently and only the maximum translational acceleration of the 1st case of Judo did not exceed the threshold of the brain concussion.

Next, Method1-1〜Method1-5 and Method2-1 and Method2-2 for both Judo and American football were simulated under the definition of each method and the corresponding maximum strain values in the brain are shown in Table 4 as well as the corresponding brain damage rates which are shown in Table 5.

In the case of Method1-1, as it was assumed that the cerebral damage over the threshold after the 1st impact did not occur as shown in the left side in Fig.6 of the Method1-1, the final result of Method1-1 shows the result only by the 2nd impact. The result only by the 1st impact is observed in the 1st impact of Method2-1 and Method2-2.

In the case of Judo, the reduction of the shear modulus of the cerebrum has a significant influence on the increase of the distortion, but, on the other hand, the reduction of the shear modulus of the brainstem has a substantial influence on the increase of the distortion in the case of American football. A similar tendency is also observed in the brain damage rate in Table 5. This remarkable difference in the influence on the brain damage by the 2nd impact may be attributed to the fact that the head receives a strong impact from the tatami mat in Judo directly, but the impact to the head passes through a rigid helmet in American football.

The brain damage rate increases by the repeated impacts in both Method1 and Method2 as shown in Table 5, but the ratio increases substantially in Method2 in particular, and the increase

Table 3. The maximum translational and rotational accelerations of the head in Judo and America football accident cases

Injury order	The maximum translational acceleration (m/s^2)		The maximum rotational acceleration (rad/s^2)	
	Judo	A.F.	Judo	A.F.
accident case 1	637	1,478	3,036	5,539
accident case 2	833	1,707	3,666	4,888

* The threshold of translational accerelation is 686 m/s^2 (18)
* The threshold of rotational accerelation is 2,615 rad/s^2 (19)

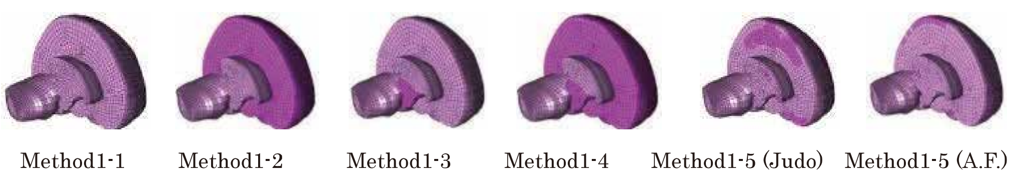


Fig 6. The injured part of the cerebrum and the brainstem by the 1st impact. The shear modulus of the elements that are colored dark red is reduced in the simulation of the 2nd impact.

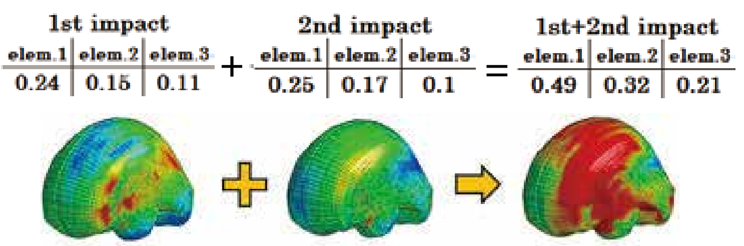


Fig 7. The final result is obtained by adding the result of the 2nd impact on the 1st impact in the Method2.

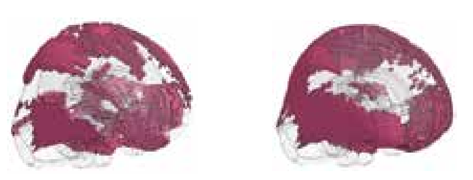


Fig 8. The finite elements those strain beyond the threshold by the 1st impact, in the case of Judo (left), American football (right).

Table 4. The maximum strain in the brain by the repetitive concussion

Method	Injury part by the 1st impact	The Final Results	
		Judo	A.F.
1-1	no injury	0.26*	0.22*
1-2	cerebrum	0.31	0.27
1-3	brainstem	0.26	0.42
1-4	cerebrum & brainstem	0.31	0.27
1-5	injury part reflection*	0.34	0.27
2-1	1st impact	0.24	0.30
	2nd impact	0.26	0.22
	1st + 2nd	0.44	0.41
2-2	1st impact	0.24	0.30
	2nd impact**	0.34	0.27
	1st + 2nd**	0.49	0.44

*It shows by the 2nd impact only because no injury in the 1st impact
** injury part reflection method is applied

Table 5. The ratio of the injury part in the brain by the repetitive concussion [%]

Method	Injury part by the 1st impact	The Final Results	
		Judo	A.F.
1-1	no injury	15.6*	4.8*
1-2	cerebrum	35.3	16.4
1-3	brainstem	16.1	49.1
1-4	cerebrum & brainstem	35.8	17.6
1-5	injury part reflection	23.5	7.5
2-1	1st impact	14.6	12.3
	2nd impact	15.6	4.8
	1st + 2nd	86.0	63.4
2-2	1st impact	14.6	12.3
	2nd impact*	23.5	7.5
	1st + 2nd**	86.4	63.4

*It shows by the 2nd impact only because no injury in the 1st impact
** injury part reflection method is applied

in the damage rate is more significant than the increase in the maximum strain. This can be attributed to the possibility that the elements which were not damaged by the 1st impact received damage after the 2nd impact. This phenomenon is rather emphasized in the second method which add the both results of the 1st and 2nd impacts mathematically.

The maximum strain shows the degree of the brain damage, and the brain damage rate expresses the expanse of the damage in a brain. These two parameters appropriately express the partial and general damage to the brain respectively due to the brain concussion.

The methods with the damage reflection (Method1-5 and Method2-2) suggest a greater maximum strain and higher brain damage rate compared to the methods without it (Method1-2, 1-3, 1-4 and Method2-2), and the reduction of the shear modulus has a definite influence on the injured elements. Hence, it is believed that the analytical method that let the damage degree by the 1st impact reflect before the 2nd impact analysis is effective.

Discussion

In the analysis of the repetitive concussion accident, characterization of the brain damage is crucial, because the trace of the brain damage by the first impact must be kept to express the aggravation by the 2nd impact. Although the reduction of the shear modulus of the brain seems to be effective for expressing the brain injury for the analysis of the 2nd impact, the relation between the reduction rate and the degree of the damage is still uncertain, and further inspection of the degree of the reduction is needed.

Moreover, the brain damage recovers with the time passing, but the quantitative medical information for the degree of the recovery has not been reported. Therefore, in this study, the recovery of the brain damage after the first accident is not considered, meaning that the two shocks are added to the head almost at the same time.

The first 2 weeks after the injury is crucial to the recovery of the brain damages. Based on the guidelines, the detailed schedule for the player appeared in the 2nd impact case in Fig.5(c) until he is allowed to come back to the daily exercise is shown in Table 6 for reference. He finally returned to the play after 13 days according to the instructions. The progress of the brain recovery has to be observed for such a long time.

Through the whole reconstruction works, the reconstruction of the collision movement from the video needed the longest time and needed almost one day for one accident, and some more hours are needed to transfer the mechanical information to the FEM analysis too. Recently, some reports have been reported concerning the automatic reconstruction of a human motion from a video, if the angle of the video camera is fixed and the item of the sports is limited, the automatic reconstruction of the collision motion from the video and FE analysis could be possible in a day.

Limitations

This system was not applied to the real repetitive brain concussion in which the two impacts are added continuously on the same person. The utilized data for the repetitive concussion accidents were only from the combination of the two cases with two independent accidents. Although the medical and kinematic information on the brain concussion itself is scarce, further medical information about the repetitive brain concussion is needed.

The degree of recovery of the brain damage between two impacts was not considered in this simulation, since the biomechanical expression of the recovery of the brain damage has not

Table 6. Daily schedule of the injured player until he is allowed to come back to the exercise : accident case 2 in American football

Date	Exercise
1st. Day : the injured day	・loss of consciousness (-) ・loss of memory (-) ・headache (+) ・CT scan (no findings)
8th. day	・no physical symptoms ・pass Cogsport test
9th. day	・30 min. jogging
10th. day	・running 40yds ×10 ・agility ・60% weight training
11th. day	・position skill menu ・80%~ weight training
12th. day	・normal training after medical clearance
13th. day	・game play

been reported.

CONCLUSION

Effectiveness of the risk prediction system of the repetitive brain concussion was investigated biomechanically by analyzing the game video of the accident cases in Judo and American football. Two methods were proposed to predict the aggravation of the brain damage due to the repetitive impacts on the brain by improving the conventional function of analyzing an individual brain concussion. In the 1st method the material properties of the brain part damaged by the 1st impact were changed before the analysis of the 2nd impact. In the 2nd method the results obtained by the analysis of both impacts were added to each other. Although the both methods were effective to obtain the aggravation of the brain damage mechanically, it is necessary to inspect the further compatibility from the medical point of view.

The video recording of the accident is indispensable to the reproduction of the head collision and the analysis of the brain injury because there is no biomechanical information to indicate a brain concussion other than the medical interview.

For the practical use of the risk prediction system, the auto reproduction of the collision movement from the accident video and the auto analysis of the cerebral damage are necessary.

CONFLICT OF INTEREST

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