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Impact on the head during collisions between university American football players - focusing on the number of head impacts and linear head acceleration -

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Abstract The aim of this study is to understand the head impact during actual collisions between American football players from Japanese universities. The subjects of this study were 23 players who belonged to T university in the Kantoh Collegiate American Football Association Division 2. We used a Vector Mouthguard (i1 Biometrics Inc.) equipped with 6 degrees of freedom (DOF) to measure the head linear acceleration (LA) and rotational acceleration (RA) as well as the head injury criterion (HIC), impact location, and number of impacts during collisions. The average number of collisions per player during a practice and during a game was 14.3 and 15.7, respectively. In terms of positions, the ratio (1:1.3) of total number of impacts for backs to linemen in Japan is lower than that (1:3) in the USA. Both during the games and practices, the range of $10 \text{ g} < X \leq 15 \text{ g}$ in the average peak LA values was the most frequent, and the distributions were largely skewed toward low values ($p < 0.05$). The medians during the games and practices were 16.77 g and 15.87 g, respectively. The number of collisions during practices in Japan was significantly higher than that in the USA. Particularly, linemen undergo more head collisions than those of backs. Another common factor is that the impact of head collision during a game is significantly higher than that during a practice. However, data on Japanese university players is limited, and further data collection should be done before determining an accurate estimate of the practical concussion risk threshold.

Keywords : American football, head impact, number of head impacts, linear head acceleration, concussion

Introduction

American football is an intense contact sport. A high injury rate is one of the problems of this sport¹⁻⁴). Improvements in helmets and rule changes resulted in more effective prevention of serious head trauma up to the 1980s;^{5,6}) however, in the 1990s, retirement of some famous NFL players because of repeated concussions or mild traumatic brain injury (MTBI) led to greater attention being directed toward this injury⁵⁻⁷). According to the Centers for Disease Control and Prevention (CDC), USA, approximately 300,000 cases of sport-related concussions in the US emerge every year, with about one-third occurring in American football^{8,9}). Dick et al. (2007) used injury data accumulated over a period of more than 14 years on university American football players affiliated to the National Collegiate Athletic Association (NCAA), and reported that the concussion rates during practices and games in the fall season were 5.5% (0.21/1000 A-Es) and

6.8% (2.34/1000 A-Es), respectively, and that the concussion rate during the games was 11 times higher than that during practices¹).

In Japan, according to the reports³) on trauma published over a period of more than 20 years, during official games in the fall season of the Kantoh Collegiate American Football Association, concussions were the third-most common trauma (8.9%), followed by ankle sprains (15.7%) and knee sprains (15.2%). According to our study conducted over a period of more than 10 years on injuries suffered by university American football players, the concussion rates during practices and games in the fall season were found to be 8.4% (0.6/1000 A-Es) and 11.1% (3.9/1000 A-Es)⁴), respectively, indicating that the concussion rate in Japan is higher than that in the USA. While these studies on injuries are significant, they did not consider other factors related to concussions, such as the frequency of head collisions and their impact point, magnitude, and cumulative number. In other words, when calculating the injury rates, these studies did not account for players who received head collision impacts of dif-

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ferent frequencies and magnitudes but did not get injured^{10,11)}. Therefore, in order to understand concussions, it is important to obtain a detailed understanding of head collisions.

Biomechanical studies on concussions in American football significantly advanced in the beginning of the 1970s¹¹⁻¹³⁾. Reid and Moon equipped the inner suspension pad inside a helmet with a frequency-modulation acceleration sensor and an electroencephalograph to measure the head impact during practices and games. Consequently, they confirmed a total of 650 impacts, with the maximum acceleration ranging from 40 to 530 g and collision times in the range of 20-420 ms¹¹⁻¹⁵⁾. However, these studies only used one subject. In addition, the obtained results were problematic because the measuring equipment, due to its size, restricted the movement of the player¹¹⁻¹³⁾. Pioneered by Pellman and Newman et al. around the year 2000, video analyses of the impacts that led to concussions in the National Football League (NFL) games were performed, and impact reproduction experiments were conducted using a hybrid dummy III^{3,16,17)}. On the basis of the results, it was reported that the average maximum head linear acceleration (LA) during concussion-causing impacts was 98 ± 28 g and an LA of 98 g would lead to a concussion with a probability of 74%^{3,16,17)}. Moreover, they proposed the following nominal reference values for the probability of concussion: a maximum LA of 79 g, maximum rotational acceleration (RA) of 5757 rad/s², severity index (SI) of 300, and head-injury criterion (HIC) of 250. In the year 2000, Naunheim et al. equipped the inner pad of a helmet with a three-axis acceleration sensor to measure the impact of head collisions and reported that the average peak LA was 29.2 g¹⁸⁾. The subjects of this study were high school players, and there was no record of concussion or MTBI.

In the 2000s, many researchers started to use a head-impact telemetry system (HITS, Simbex, Lebanon NH) equipped with an acceleration sensor installed inside a Riddell (Elyria, OH) helmet to collect real-time head-acceleration data during head collisions between American football players^{9-13,19-28)}. The data collected by HITS is transmitted to a PC application in real time via a sideline response system (Riddell, Chicago, IL). Duma et al. (2005), who first reported the use of HITS, found that the average peak LA was 32 ± 25 g, and the following research results led to the reference value of 10% for concussion risk: a peak LA of 165 g, HIC of 400, and head peak rotational acceleration of 9000 rad/s²¹²⁾. Since then, many researchers have validated the accuracy and the data sorting method of HITS^{12,17,25-27)}, thus, it is a highly reliable measuring device. However, HITS uses LA to estimate RA, which is considered to be a major factor in the injury mechanism of concussions²⁸⁾. While the reliability of the RA and rotational velocity (RV) measurements via HITS and a six-axis sensor (6DOF) is high, with a measurement error of only 1%-4%, information

on RV, which is crucial for understanding the concussion risk threshold, could be obtained²⁸⁾. Therefore, more direct measurements of RA and RV were necessary. Later, an improved version of HITS, 6DOF, which is equipped with a three-axis acceleration sensor and a three-axis gyro sensor, was developed. Rowson et al. (2009) recorded head collisions during practice sessions and games for 10 university American football players using 6DOF²³⁾. The results show that the peak LA during most of the collisions was below 20 g²³⁾. As described above, studies conducted in the USA collect real-time acceleration data of human bodies during collisions. In Japan, however, there has been no study on head impacts during collisions between players on actual fields. To prevent concussions in Japanese American football players, it is vital to better understand about head impacts during collisions considering the physical characteristics and strength of the Japanese players. Therefore, the aim of this study is to better understand head impacts during actual collisions between American football players from Japanese universities.

Materials and Methods

Subjects. The subjects of this study were 23 players who belonged to T university in the Kantoh Collegiate American Football Association Division 2 and were starting team members (14 backs and 9 linemen (including tight end [TE], Table 1). We did not consider the existing diagnosis of concussions when selecting the subjects. We thoroughly explained the purpose of the study to the subjects and obtained their consent. Furthermore, this study was performed with the approval of the Tsukuba University Sport Theory Committee (approval number: 28-55).

Measurement method. We used a Vector Mouthguard (i1 Biometrics Inc.) (Photograph 1) equipped with 6DOF (a three-axis acceleration sensor and a three-axis gyro sensor) to measure the head LA and head RA during collisions as well as for recording the HIC values, collision location, and number of collisions. The sampling frequency of the three-axis acceleration sensor (ADXL377, Analog Devices) was 1024 Hz, and it can measure LA up to 200 g. The sampling rate of the three-axis gyroscope (L3GD20H, ST Microelectronics) was 760 Hz, and it can measure RA up to 2000 deg/s² (34.9 rad/s²). We conducted the measurements during three games and 22 practice sessions in

Table 1. Physical characteristics of the subjects.

	Height(cm)	BW(kg)	Age(years)
ALL (n=23)	173.7±5.0	85.0±12.9	21.3±0.9
Linemen (n=9)	177.7±2.1	97.9±7.8	21.4±0.7
Backs (n=14)	171.1±4.2	76.7±7.5	21.3±1.0

Pic. 1 Vector Mouthguard (i1 Biometrics Inc.) equipped with 6DOF to measure the head LA and head RA during collisions as well as for recording the HIC values, collision location, and number of collisions.

3DOF Gyro sensors

Sampling 760Hz

Detect up to 2000 deg/S²

(34.9rad/S²) angular acceleration

3-DOF Accelerometers

Sampling 1024Hz

Detect up to 200G linear acceleration

Pic. 2 Remote System for the Vector Mouthguard.

When the Vector Mouthguard detected head impacts, it sent a real-time record of various measured values during the collision to the application on the PC through a receiver (antenna).

the fall regular season.

The subjects wore the Vector Mouthguard and participated in practice sessions and games as usual. When the Vector Mouthguard detected impacts such as tackles, it sent a real-time record of various measured values during the given collision to an application on a PC through a receiver (antenna) (Photograph 2). The recorded data were computationally up-sampled to 5000 Hz, and the calculations were automatically performed for LA, RA, HIC, and collision location. In the calculations, low-pass CFC 180 filters were used as the acceleration sensor and CFC 65 was used as the gyro sensor. The measured values recorded in the PC were extracted as Microsoft Excel data and collected.

Evaluation items. The data were categorized into impacts with a peak LA higher than 10 g and those with less than 10 g. For the data on the impacts of more than 10 g, we calculated the number of impacts during a game or a

practice session, frequency distribution of the peak LA, average peak LA, average RA, and average HIC. For the average peak LA, average peak RA, and average HIC, we also calculated 95% confidence intervals. Moreover, we calculated the average values for the number of impacts, peak LA, peak RA, HIC, and 95% confidence intervals for each position (backs and linemen).

HIC, a head injury reference value, is generally used for evaluating the degree of impact to the head in accidents such as traffic accidents, falls, and sports-related accidents, as well as for determining the safety standards of sports products²⁹⁾. HIC is calculated using the temporal change in the acceleration and is given by⁵⁾

$$HIC = \left[\left\{ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t) dt \right\}^{2.5} (t_2 - t_1) \right]_{max},$$

where $a(t)$ is the temporal change in the acceleration (integration time [s]: $t_2 - t_1$), and t_1 and t_2 are the initial and

final times of integration, respectively. The symbol “max” signifies that HIC takes the maximum value and t_1 and t_2 are assigned to maximize HIC. Also, t_1 and t_2 are usually selected so that the time range does not exceed 15 ms or 36 ms^{5,29,30}. In this study, the maximum integration time for HIC calculation was set at 15 ms.

Statistical processing. We used IBM SPSS Statistics Ver. 22 (IBM Japan, Tokyo, Japan) for statistical processing. We used the Kolmogorov–Smirnov test for the normality test and the Mann–Whitney U test for comparing the games and practice sessions in terms of the average peak LA, average peak RA, and average HIC for the entire set of subjects and for each individual position. The significance level was set to 5%.

Results

Number of impacts. Table 2 shows the detailed data for the number of head impacts during the games and practice sessions observed during the measurement period. The total number of head impacts that occurred in the measurement period was 1,085 during the games and 7,231 during the practice sessions. In terms of the positions, the number of impacts during the games was 441 for the backs and 644 for the linemen, and 232 for the backs and 3,999 for linemen during the practice sessions. Additionally, the number of head impacts with a peak LA less than 10 g was 96 during the games (backs: 40, linemen: 56) and 710 during the practice sessions (backs: 284, linemen: 426).

In terms of individual players, the maximum and minimum numbers of head impacts during the games were 128 and 11, respectively, (median: 40.5). During the practice sessions, the maximum and minimum numbers of head impacts were 775 and 11, respectively, (median: 282).

Maximum LA, peak RA, and HIC. Figs. 1 and 2 show

the frequency distributions of the peak LA during the games and practice sessions, respectively. Both during the games and practice sessions, the range of $10 \text{ g} < X \leq 15 \text{ g}$ was the most frequent, and the distributions were largely skewed toward low values ($p < 0.05$). The median (50 percentile value) during the games was 16.77 g, and the 95 percentile value was 43.18 g. The median (50 percentile value) during practices was 15.87 g and the 95 percentile value was 37.68 g.

Table 3 shows the data for the average peak LA, average peak RA, and average HIC during the games and practice sessions. The values measured during the games were significantly higher than those measured during the practice sessions ($p < 0.05$). In terms of positions, the values measured during the games were also significantly higher than those measured during the practices ($p < 0.05$).

Discussion

Recently, the development of HITS, which collects impact information from the acceleration sensor attached inside the helmet and the sideline response system, which transmits the data, has made it possible to collect collision data from players on actual fields^{9-13,19-28}. However, HITS only measures LA, and RA had to be estimated²⁸. Later, the 6DOF sensor made it possible to accurately collect LA and RA data during collisions²⁸. While in the USA, there have been a number of reports on head collisions in American football that have used acceleration data, this study is the first such report in Japan.

In this study, we used a Vector Mouthguard equipped with a 6DOF sensor instead of installing the 6DOF sensor inside the helmet. The validity of the mouthguard equipped with a 6DOF sensor has been verified using a personification test device, and a high correlation with HITS has also been reported³¹. This ensures the validity and reliability of the results obtained via the Vector Mouthguard used in this study.

The total number of collisions observed in this study

Table 2. Number of head impacts during practice sessions and games.

Group	Category	Participants	Number of impact						
			10 G $\leq$	< 10 G	times/game/personal	Median	Minimum–Max	25% quartile	75% quartile
ALL	Game (3 games)	n=20	1085	96	18.08	40.5	11–128	24.75	87.5
	Practice (22 times)	n=23	7231	710	14.29	282	11–775	143	447
Backs	Game (3 games)	n=12	441	40	12.25	38	11–83	24	42
	Practice (22 times)	n=14	3232	284	10.49	196.5	11–498	128.25	316.5
Linemen	Game (3 games)	n= 8	644	56	26.83	103.5	13–128	39	115
	Practice (22 times)	n= 9	3999	426	20.20	424	63–775	258	651

The average numbers of head impacts per player during a game and a practice were 18.01 and 14.29. The average number of head impacts in linemen is higher than that in backs.

Fig. 1 Frequency distribution of the head impact measurements of peak linear acceleration during games.

The average peak LA value during the games was 20.82 ± 12.1 g. The median (50 percentile) and 95 percentile values of the peak LA were 16.77 g and 43.18 g during the games. For the peak LA frequency distribution, the range of $10 \text{ g} \leq X < 15 \text{ g}$ was the most frequent, and the distributions were largely skewed toward low values.

Fig. 2 Frequency distribution of the head impact measurements of peak linear acceleration during practices.

The average peak LA value during the practice sessions was 19.04 ± 10.1 g. The median (50 percentile) and 95 percentile values of the peak LA were 15.87 g and 37.68 g during the practice sessions. For the peak LA frequency distribution, the range of $10 \text{ g} \leq X < 15 \text{ g}$ was the most frequent, and the distributions were largely skewed toward low values.

was 8,316 (7,231 during the practice sessions and 1,085 during the games). The average numbers of collisions per player during a practice session and during a game were 14.3 and 18.1, respectively. However, considering the fact that not all 23 subjects took the field, the number of impacts per player was actually higher. In terms of individual players, the maximum and minimum numbers of collisions were 42.7 during a game and 3.7 during a practice session, respectively. There was a large differ-

ence between the players. Duma reported that a university player experienced 7.6 and 15.0 impacts during a practice session and a game, respectively¹². Crisco reported that a university player experienced 6.3 and 14.3 impacts during a practice session and a game, respectively¹⁰. Also, Schnebel reported that the number of impacts per player during a training session was approximately 13²². These findings and our results were similar in terms of the number of collisions during the games. While a single game is

Table 3. Average values of peak linear acceleration, peak rotational acceleration, and head-injury criterion (HIC) during games and practices.

Group	Category	Participants (No. of impact)	Average of Peak Linear Acceleration	Average of Peak Rotational Acceleration	Average of Head Injury Criterion
ALL	Game (3 games)	n=20 (1085)	20.82 ± 12.10 G * (95% CI: 20.10–21.54 G)	1233.26 ± 864.06 rad/s ² * (95% CI: 1181.79–1284.73 rad/s ²)	18.95 ± 32.05 * (95% CI: 17.04–20.86)
	Practice (22 times)	n=23 (7231)	19.04 ± 10.10 G (95% CI: 18.80–19.27 G)	1070.11 ± 698.91 rad/s ² (95% CI: 1054.00–1086.22 rad/s ²)	13.96 ± 21.44 (95% CI: 13.47–14.45)
Backs	Game (3 games)	n=12 (441)	23.26 ± 14.62 G * (95% CI: 21.89–24.63 G)	1368.60 ± 1006.08 rad/s ² * (95% CI: 1274.44–1462.76 rad/s ²)	24.85 ± 44.24 * (95% CI: 20.71–28.99)
	Practice (22 times)	n=14 (3232)	20.49 ± 11.61 G (95% CI: 20.09–20.89 G)	1101.49 ± 755.68 rad/s ² (95% CI: 1075.43–1127.55 rad/s ²)	15.60 ± 21.92 (95% CI: 14.84–16.35)
Linemen	Game (3 games)	n= 8 (644)	19.15 ± 9.69 G * (95% CI: 18.40–19.90 G)	1140.58 ± 738.14 rad/s ² * (95% CI: 1083.46–1197.69 rad/s ²)	14.90 ± 18.77 * (95% CI: 13.45–16.36)
	Practice (22 times)	n= 9 (3999)	17.86 ± 8.51 G (95% CI: 17.60–18.12 G)	1044.74 ± 648.40 rad/s ² (95% CI: 1024.64–1064.85 rad/s ²)	12.64 ± 20.96 (95% CI: 11.99–13.29)

* vs. Practice (p<0.05)

All the values (LA, RA, and HIC) in games are significantly higher than those in games.

played over four 15-min quarters in the USA, it is played over four 12-min quarters in Japan, a shorter time period. Also, one of the characteristics of American football games is that there is little difference in the number of plays between the teams¹⁰, so there isn't much variation in the number of collisions during matches among the teams. Therefore, the fact that the number of collisions is similar between the USA and Japan, despite the shorter matches in Japan, indicates that the actual number of collisions is higher among Japanese university players compared to players in the USA. In the USA, many studies are in agreement with the fact that the injury rate during games is higher than that during practice sessions^{1,2,4}, and have reported that the number of collisions during a game is 2-3 times higher than that during a practice session^{10,12}. However, in this study, the number of collisions during practice sessions was only 1.3 times higher than that in games. Again, these results show that the number of collisions during practice sessions is higher than that in the USA. Actually, we reported that the average number of practices per year in a 10-year injury survey at Japanese universities was about 190 days⁴, which was much more than 90 to 100 days reported in the USA¹. Therefore, it is considered that the number of practice days affects the number of head impacts at the time of practice, and thus head impacts are more frequent in Japanese university players. These findings indicate that players in Japan experience head impacts on a daily basis. However we did not take the number of practice hours into consideration, which should be considered in a future study.

In terms of player position, it has been shown that linemen undergo more head collisions of smaller magnitude than the backs^{12,20,22,24,25}. The results of the present study are in agreement with these findings of earlier studies. Offensive and defensive linemen repeat collisions from shorter distances than backs on both teams in each play^{22,24}. The characteristics of the sport, with the backs on both teams accelerating from further distances and having more intense collisions, are likely to have an effect

on the results^{22,24}. However, unlike the finding that the ratio of total number of impacts for backs to linemen was 1:3^{10,22}, this study showed that the ratio is closer to 1:1.3. In this study, the numbers of participating backs and linemen were different (backs: 14, linemen: 9), so we took the average per person and still obtained a 1:2 (262:516) ratio. One of the reasons for this finding can be that the backs undergo many collisions. Many players in Japan start playing the sport after university, and it has been pointed out that they engage in many practices and scrimmages, game-based practices, involving head impacts in practice sessions^{3,4} due to their lack of experience. Thus, the number of impacts is more frequent in backs.

Actually, in this study, the number of scrimmages was 20 out of 22 practices. In the United States, it is common to restrict the number of scrimmages or not tackle during practices in the regular season. I think that differences in the makeup of a typical practice session between Japan and the USA lead to an increase in the number of head impacts in Japan and affects the ratio of the total number of impacts in backs and linemen. In particular, the number of collisions during the practice sessions varies depending on the practice method, strategy, and coaching of each university¹⁰, so that the results obtained in this study may be affected by factors specific to T university. In the future, studies with multiple teams and for each position are necessary. Recent studies have reported that even collision impacts that do not lead to concussions can affect cognitive function if they occur frequently^{32,33}. Therefore, it is important to focus on the number of practice days, practice methodology and content, and number of head impacts in Japan.

In this study, the average peak LA values during the practice sessions and games were 19.04 ± 10.1 g and 20.82 ± 12.1 g, respectively. For the peak LA frequency distribution, both during the games and practice sessions, the range of 10 g ≤ X < 15 g was the most frequent, and the distributions were largely skewed towards low values, supporting previous reports^{11-13,19-25}. However, the

collision rate for LA higher than 40 g was 5%, which is lower than the 10% value reported by Rowson et al.²³⁾ For collisions with a magnitude higher than 79 g, using the reference value for peak LA with the probability of concussion proposed by Pellman^{5,6)}, 26 cases were recorded during practice sessions (0.36%) and four during games (0.37%). However, there were no players diagnosed with a concussion. According to Duma et al. (2005), who first reported the impact of head collision between humans in real time, the average peak LA was 32 ± 25 g for the measurements performed on 38 players during 10 games and 35 practice sessions¹²⁾. On the basis of a two-year study of different university players, Mihalik et al. reported that the average peak LA was 22.25 ± 1.79 g²⁴⁾. These values of the average peak LA were higher than those obtained in the present study. According to Crisco et al. (2012), who conducted a follow-up survey over a period of more than three years on 254 players from three universities, the median (50 percentile) and 95 percentile values of peak LA were 20.0 g and 49.5 g, respectively, during practice sessions, and 20.2 g and 49.6 g, respectively, during games¹¹⁾. In the present study, the median (50 percentile) and 95 percentile values of the peak LA were 15.87 g and 37.68 g during practice sessions and 16.77 g and 43.18 g during games. These values were higher for American players. One of the reasons for this could be the effect of physical characteristics, which many Japanese players are considered to lack, such as physique, acceleration during tackles, and sprinting ability. In this study, we did not measure acceleration during tackles, sprinting ability, muscle strength, etc. However, with regard to muscular strength of American football players, it has been reported that regular players are significantly stronger than non-regular players³⁴⁾, and upper ranking schools among divisions have significantly stronger players than lower ranking schools³⁵⁻³⁷⁾. In addition, in a study of head impacts comparing Division I university players and high school students, it was shown that university players sustained high-level impacts greater than 60 g more frequently than high school players and that the mean LA for the top 1, 2, and 5% of all impacts were also higher for university players²²⁾. Therefore, it is considered that better physical characteristics and higher competition levels would increase the peak LA in head impacts. Also, contact techniques could be a factor for peak LA. In American football, collision from the head is not recommended. In other words, a lack of contact technique can lead to a large impact during head collisions. In fact, in the study performed by Broglio et al., for players from 34 high schools participating in 13 games and 55 practice sessions, the average peak LA was 23.26 ± 14.48 g during practice sessions and 24.76 ± 15.72 g during games; these values are higher than those reported by Mihalik²⁰⁾. Also, Naunheim et al. reported that the average peak LA among high school players was 29.2 g¹⁸⁾. However, Broglio et al. set the cut-off value at 15 g²⁰⁾, and the study performed by

Naunheim et al. involved only two players¹⁸⁾; therefore, both of these results are inconsistent. However, both studies point out the lack of contact technique^{18,20)}. Therefore, analysis of the impact of a running head collision and contact motion is a problem that should be addressed in future studies. Currently, American players receive stronger head collisions than Japanese players, but it was revealed that in both countries, players receive head collisions of with an average of 20 g, both during practice sessions and games. Another common factor is that the impact of head collisions during a game is significantly higher than during a practice session, which would mean that the injury rate would be higher as well during games than during practices^{1,2,4)}; this indicates the effect of the collision impact magnitude. However, data on Japanese university players are limited, and further data collection should be done before comparing them with their American counterparts.

While measurements of LA, RA, number of collisions, and locations of head collisions have been made possible by 6DOF sensors, there is still a lack of data for concussion diagnoses, and an estimate of the concussion risk threshold has not been obtained. Mihalik et al. reported that out of 1,858 collisions with a peak LA higher than 80 g, only seven collisions resulted in concussions (0.4%)²⁴⁾. Duma et al. (2005) reported that out of 290 collisions with a peak LA higher than 75 g, only three collisions resulted in concussions (1.0%)¹²⁾. Pellman et al. proposed 75 g as the 41% concussion risk threshold; however many reports have doubted the reliability of this estimate^{12,19,22,24,28)}. Funk et al. have also proposed a 10% concussion risk threshold at a peak LA of 165 g and a peak RA of 9000 rad/s²; these values were obtained on the basis of limited concussion data and estimated RA¹⁹⁾. King et al. used a logistic regression method on the results of the NFL collision-reproduction experiment and set a 75% concussion risk threshold at a peak LA of 98 g and a peak RA of 7,130 rad/s^{2,38)}. However, Schnebel et al. reported that out of 620 collisions with a peak LA higher than 98 g, only six collisions resulted in concussions (1%)²²⁾. In other words, obtaining an accurate estimate of the practical concussion risk threshold is still problematic.

An issue that should be investigated in the future is the original concept behind the occurrence of concussions, i.e., they occur because of the strain response of the brain caused by RA on the head²⁸⁾. However, currently, all safety standards, including HIC, are based on the prediction of skull fracture based on LA^{9,28,39)}. We also calculated the RA and HIC. These standards must be investigated together with the impact location and occurrence of concussions, and this was difficult to analyze in the present study because no concussions were observed. All collisions involve LA and RA, and the research on the mechanism of concussion requires a large amount of data collection, including concussion data, and the processing of these data via multivariate analyses^{28,40)}. Another issue is the cutoff

value. In this study, we removed the data with a peak LA less than 10 g. In previous studies as well, the data with a peak LA of 10 g or less were removed because these data included noncontact motions such as quick stand-up, running, and jumping⁴¹⁾. However, the data with a peak LA less than 10 g amounted to 9.7% of the total number of impacts. Considering that not only the concussion-causing impact, but also the accumulation of subconcussion is important, setting the cutoff value is another challenge. Since 10 g is the cutoff value used in the USA, it is also necessary to determine an appropriate cut-off value for Japanese players who, on average, lack in physical characteristics and physical fitness in comparison to players in the USA. Finally, there is the need to investigate in detail players of different competitive levels. Then we can more accurately determine the characteristics of head impacts for American football players in Japan.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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