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Original Article

Fall Protection Characteristics of Safety Belts and Human Impact Tolerance

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Abstract: Many fatal accidents due to falls from heights have occurred at construction sites not only in Japan but also in other countries. This study aims to determine the fall prevention performance of two types of safety belts: a body belt[1)], which has been used for more than 40 yr in the Japanese construction industry as a general type of safety equipment for fall accident prevention, and a full harness[2, 3)], which has been used in many other countries. To determine human tolerance for impact trauma, this study discusses features of safety belts with reference[4–9)] to relevant studies in the medical science, automobile crash safety, and aircrew safety. For this purpose, simple drop tests were carried out in a virtual workplace to measure impact load, head acceleration, and posture in the experiments, the Hybrid-III pedestrian model[10)] was used as a human dummy. Hybrid-III is typically employed in official automobile crash tests (New Car Assessment Program: NCAP) and is currently recognized as a model that faithfully reproduces dynamic responses. Experimental results shows that safety performance strongly depends on both the variety of safety belts used and the shock absorbers attached onto lanyards. These findings indicate that fall prevention equipment, such as safety belts, lanyards, and shock absorbers, must be improved to reduce impact injuries to the human head and body during falls.

Key words: Falling accident, Safety belt, Shock-absorber, Head injury, Neck injury, Human impact tolerance

Introduction

Labor accident statistics

Numerous labor accidents have happened not only in Japan, but also in many other countries. Figure 1 shows the numbers and rates of labor accidents in the Japanese construction industry in 2011[11)]. More than 16,000 labor accidents occur each year in Japan. In 2011 alone, the industry registered 1,024 fatal labor accidents, of which 342 are due to fall. The percentage accounts for 33.4% of the total fatal labor accidents. Labor accidents in the Japanese construction industry occur very frequently because construction workers account for about 8% of the total workforce in the country. A breakdown of construction-related labor accidents shows that the number of fall accidents reached 5,802, making these the most common types of mishaps (34% of the total, Fig. 1). Figure 2 shows the numbers and rates of labor accidents related to the recovery or reconstruction work conducted after the 2011 Great East Japan Earthquake. Many fall accidents tend to occur at high rates particularly in unconventional situations, such as relief work for natural disasters. Those that transpired at work sites for the Great East Japan Earthquake relief efforts account for 47% of the total that year. Disaster relief work is nearly a constant in different parts of Japan because natural disasters, such as earthquakes, ty-

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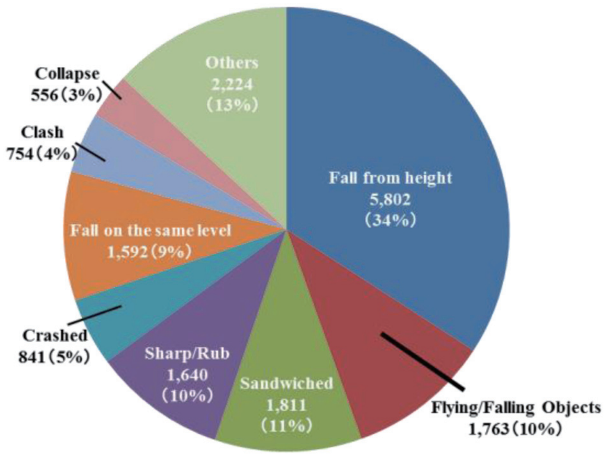

Fig.1. Numbers and rates of labor accidents in the construction industry in Japan (2011).

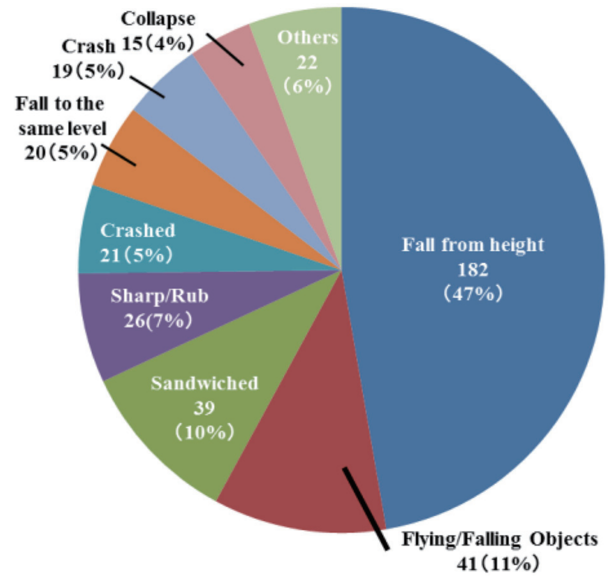

Fig.2. Numbers and rates of labor accidents related to the recovery or reconstruction work sites for the Great East Japan Earthquake (2011).

phoons, and heavy rainfall, occur each year in the country. This backdrop highlights the importance of implementing countermeasure against falls at relief sites.

National laws and regulations for fall accident prevention

The typical countermeasures stipulated in the Japanese laws and regulations for fall prevention are shown in Table 1. Article 21, 42, and 119 of the Labor Safety and Health Law are the most important. Article 21 regulates the measures for fall prevention. Article 42 regulates the standards for several kinds of safety equipment, and its implementation as overseen by the Ministry of Labor and Welfare. Article 119 regulates punishments. The Labor Safety and Health Regulation contains more concrete provisions, of which the most essential for fall prevention is paragraph 1 of articles 518 and 519. The former mandates the provision of safety floors and the latter mandates the provision of enclosures, such as guardrails. When available safety floors are insufficient, temporary scaffolds are erected as a typical countermeasure. Such scaffolds have also been sometimes used as foundation for enclosures to prevent falls from floor edges. Paragraph 2 of Articles 518 and 519 detail alternative preventive measures, such as the use of safety belts at mainly repair or disaster relief work sites, in case workers sometimes cannot conform to the standard countermeasures as shown in the paragraph 1.

Current issues in fall prevention

Few labor accidents have thus far occurred at new construction site. Despite the existence of the aforementioned laws and regulations, concrete and effective measures against falls during repair and disaster relief work have not been established because typical enclosure are difficult to fabricate. The formulation of effective and safety standards for selecting safety belts in conjunctions with related equipment (e.g., connecting device for lanyard hooks) is an urgent requirement given the high number of repair or relief work sites in Japan. An important task, therefore, is to ascertain the safety performance of currently available safety belts from the perspective of human tolerance for impact trauma. Such data would facilitate the design of ideal protective equipment for workers. This study aims to determine the fall prevention performance of two types of safety belts. The first is a body belt, which has been used for more than 40 yr in the Japanese construction industry as a general type of safety equipment for fall accident prevention. The other is a full harness, which has been used in many other countries. This study also discusses the features of safety belts in relation to human tolerance for impact trauma, with reference to relevant studies in medical science, automobile crash safety, and aircrew safety.

Subjects and Methods

Figure 3 shows the experimental conditions used in each test. The experimental parameters are the hook height of lanyards, two types of safety belts, and several kinds of lanyards (Table 2). The labels (Table 2) used in the experiment are described as follows. The first letter

Table 1. Laws and regulations in Japan

Labor Safety and Health Law	
Article 21	Prevention measure against falls from heights
Article 42	Standard for several kinds of safety equipment (formulated and supervised by the Minister of Labor and Welfare)
Article 119	Punishment
Labor Safety and Health Regulations	
Paragraph 1 of article 518	Provision of safety floors
Paragraph 2 of article 518	Alternative countermeasures, such as the use of safety belts
Paragraph 1 of article 519	Installation of enclosure, such as guardrails
Paragraph 2 of article 519	Alternative countermeasures, such as the use of safety belts

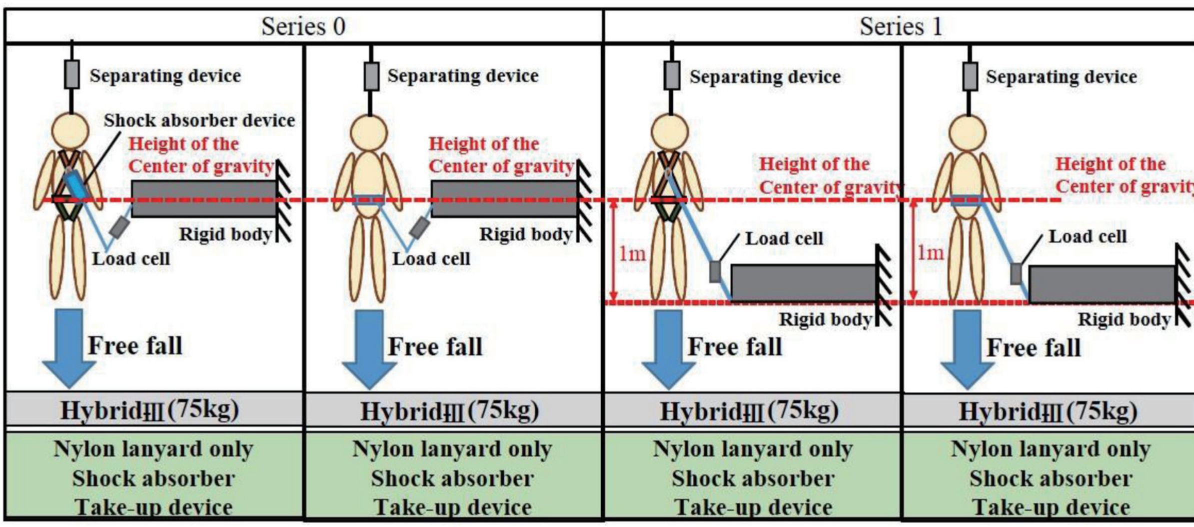

Fig. 3. Experimental conditions used in each test.

Table 2. Experimental parameters

Test	Experimental condition			
	Fall height*	Types of safety belts	Type of lanyards	
			Take-up device	Shock absorber
B-NN-1	1 m	Body belt	Nothing	Nothing
B-NA-1	1 m	Body belt	Nothing	Attached
B-AA-1	1 m	Body belt	Attached	Attached
F-AA-1	1 m	Full harness	Attached	Attached
F-NN-0	0 m	Full harness	Nothing	Nothing
F-NA-0	0 m	Full harness	Nothing	Attached
F-AA-0	0 m	Full harness	Attached	Attached

* Length from the foot sole to the connection point of the hook.

in a given series denotes the type of safety belt (i.e., "B" denotes a body belt and "F" represents a full harness). The pair of letters denotes the lanyard function. The first letter in the pair denotes the existence of a take-up device and the second signifies the existence of a shock absorber. "A" refers to the addition of a function and "N" represents the absence of function. The number in the series indicates the length that spans from the foot sole to the hook of a lanyard. Two condition are assumed in this experiment. The first is a fixed foot sole-to-hook length of 1 m, which indicates the use of a guardrail on temporary scaffolds as a connection point. The other condition is a fixed hook distance of 0 m near the foot sole, which indicates the use of a main rope on a roof. As previously stated, two types of safety belts are examined (body belt and full harness). Figure 4 shows the human dummies that are equipped with the body belt and full harness. The weight of each falling body is 75 kg. Three kinds of lanyard are examined. The first is a basic lanyard made with 1.7 m nylon. The second type is a shock absorber attached onto the first type of lanyard. The third type of lanyard is a take-up device attached onto the second type of lanyard. The hook of the safety belts is fixed to the load cell (LTR-S-50KNSAi:, Kyowa Dengyo Co., Ltd.), to which a ridged steel beam is connected for impact load measurements. Three dimensional head acceleration at the center of gravity is measured using the LTR-A-500SA5 instrument (Kyowa Dengyo). The sampling frequency is set to 10,000 and the data are filtered in accordance with the standards for class1000 equipment, as defined in the ISO6487 2002 edition[12]. A high-speed camera is also used to capture the basic postural movements of the human dummy as it falls.

Body belt Full harness

Fig. 4. Human dummies with a body belt and a full harness.

Results

Overview

Table 3 outlines the experimental results. The experiments involving the 1 m foot sole-to-hook length are first verified. The results derived for B-NN-1 (body belt and basic lanyard) indicate a maximum impact force of more than 4kN, measured at the moment when the human dummy stopped falling. The acceptable maximum impact force in Japan is less than 8kN, regardless of whether a body belt or a full harness is used. By contrast, the acceptable value for body belt in US is less than 4kN. For the experiments in which a shock absorber was attached onto the lanyard (i.e., B-NA-1, B-AA-1, F-AA-1), the maximum impact force registered were all less than 4kN. The experiments involving the fixed hook length of 0 m near the foot sole were then analyzed. The results for F-NN-0 (full harness and basic lanyard) indicate a maximum impact force of about 10kN, measured also at the moment when the human dummy stopped falling. This value exceeds the acceptable values stipulated in the Japanese, US, and ISO standards. For the experiments in which a shock absorber is attached onto the lanyard, the maximum values were all less than 4kN. These results indicate that the safety performance of the F-NA-0 or F-AA-0 combination conforms to all the standards. The finding also shows that the safety performance at the period when the human dummy stopped falling strongly depended on the type of safety belt and the use of the shock absorber. Aside from the experimental results, the head injury criteria (HIC) used in automobile crash safety tests all over the world are listed in Table 3. The HIC values calculated with this experimental data were all well below the limit for human head injury. Specifically, the HIC derived in this study was less than 1,000, giving us such an impression that the possibility of human head injury was minimal.

Postural movements during falls

Figure 5 shows the posture results for B-NN-1, for which the measurements were carried out at the period when the dummy stopped falling. The neck and body of the human dummy were considerably bent as it fell. The posture shown in Fig. 5, indicates that spinal cord injury (spanning from neck to the waist) may occur when a worker used a body belt with a nylon lanyard under the same fall conditions as those in the B-NN-1 experiment. Figure 6 illustrates the posture for F-NN-1, for which the same measurement conditions as those for B-NN-1 were applied. No bending of body parts was visually observed, but major neck rotation to the front occurred during the fall. By contrast, the experiment involving the combined harness and shock absorber exhibited no neck and body bending.

Discussion

Analysis of the possibility of head injury due to impact acceleration

The comparison of the experimental results and HIC values indicate a very low possibility of head injury due to inertia. Nevertheless, the impact response observed during previous experiments on automobile crash safety lasted

Table 3. Overview of experimental results

Test	Experimetal results				
	Impact force*1		Head acceleration*4		HIC (36)*5
	Maximum value*2 (kN)	Duration of impact*3 (msec)	Maximun value (G)	Duration time of impact*3 (msec)	
B-NN-1	4.41	400	32.03	360	21
B-NA-1	3.63	402	33.43	450	21
B-AA-1	3.64	330	39.33	350	18
F-AA-1	3.60	298	10.15	250	1
F-NN-0	9.90	300	33.5	410	19
F-NA-0	4.16	401	13.2	350	2
F-AA-0	4.03	274	10.62	250	1

*1 Impact force acting on the hook when the fall stops. *2 JAPAN: less than 8kN (regardless of the kind of safety belt) US: less than 4 kN (body belt), less than 8kN (full harness) ISO: less than 6kN (full harness). *3 At the start of the experiment, the force decreased to a level close to the weight of dummy. *4 Three dimensional acceleration at the center of gravity of the head. *5 Possibility of seriou injury is estimated when HIC exceeds 1000. This index considers the head impact tolerance used in determining automobile crash safety.

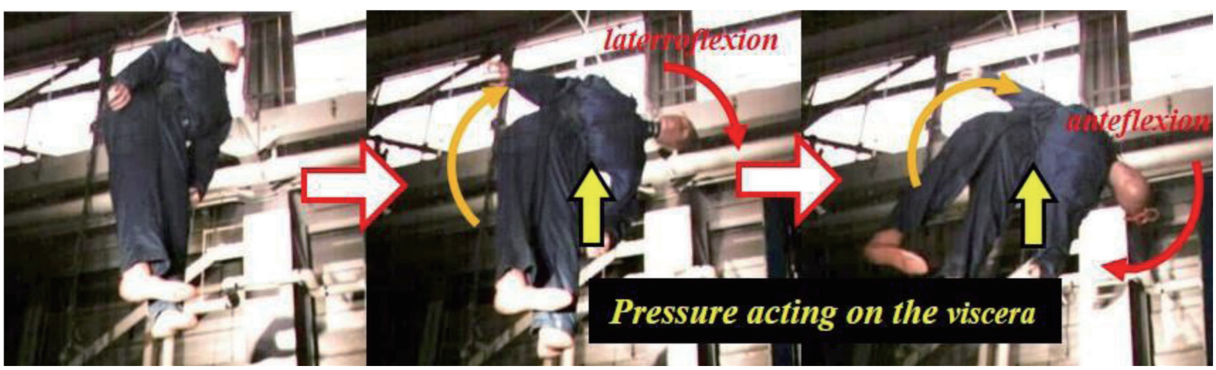

Fig. 5. Posture results for B-NN-1 (body belt and basic lanyard), measured at the moment when the fall stopped.

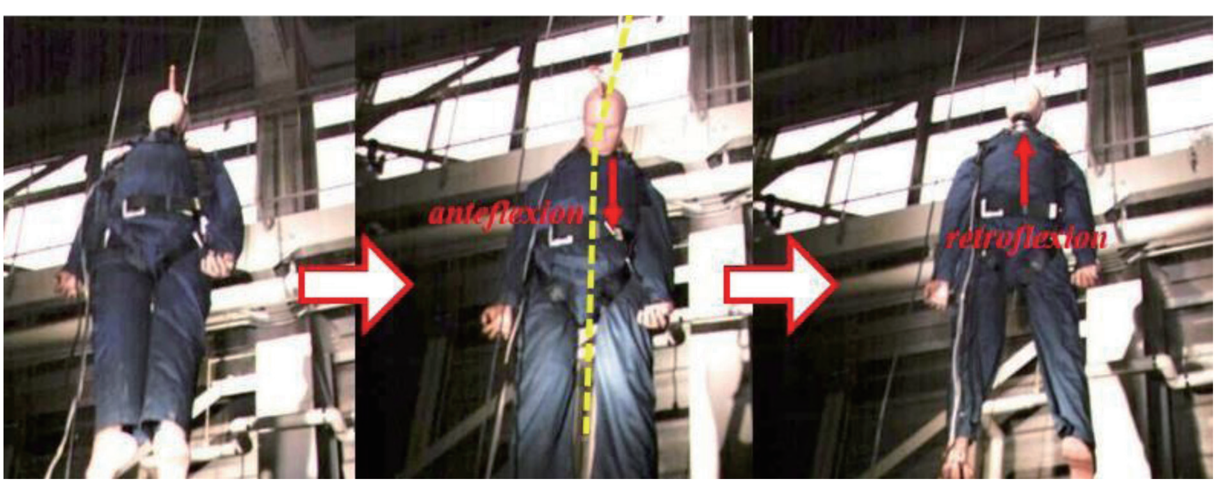

Fig. 6. Posture results for F-NN-1 (harness and basic lanyard), measured at the moment when the fall stopped.

for only 10 msec. The estimate of the possibility of head injury at the moment when the fall stops may be inappropriate when calculated on the basis of HIC because the duration derived in the present study was approximately or

Table 4. Relationship between head acceleration and tolerance value

Test	Head Accerelation (G)[*1]					
	+Ax (Right	-Ax (Left)	+Ay (Front)	-Ay (Back)	+Az (Downward	-Az (Upward
B-NN-1	12.5	25.0	11.2	7.2	1.7	23.9
B-NA-1	10.8	17.8	6.5	25.4	11.7	28.9
B-AA-1	10.3	19.5	8.9	13.8	4.0	22.6
F-AA-1	2.9	3.2	7.3	0.8	7.3	2.4
F-NN-0	2.9	3.4	33.3	6.7	20.4	8.0
F-NA-0	2.0	4.0	10.9	2.2	10.9	2.9
F-AA-0	1.4	2.4	7.6	1.1	9.1	3.9
Tolerance[*2]	45*	45*	45.0	45.0	15.0	15.0
Tolerance(50%)[*3]	22.5	22.5	22.5	22.5	7.5	7.5

[*1] Words in the parenthese denotes direction. [*2] Tolerance value proposed in a previous survey[8, 9)] [*3] Experimental data obtained from a past survey[8, 9)] are those on yound professional soldiers. However, most Japanese victims are older people. Consequency, the tolerance would decrease to an estimated 50%.

longer than 100 msec. To address this problem, the safety index for seatbelt-wearing aircrew is proposed. This index taken from previous research, in which the durations are particularly similar to that obtained in the current work. The possibility of head injury is analyzed with the use of this safety index. Table 4 shows the experimental results and the safety index values for impact tolerance. The safety index shown in the table is used in correspondence with a duration of about 100 msec; in the calculations, a different safety index value is matched to each impact duration. The experimental results on head acceleration under the B series (body belt) were all greater than 20 G in the upward direction. These values exceed the prescribed 15 G. safety index. Thus, head injury is highly likely to occur when workers wear a body belt, regardless whether a shock absorber or take-up device is attached onto the belt. In addition, this safety index experiment involved young professional soldiers who were asked to sit and wear a seatbelt. Directly estimating the safety index under such conditions is an unsafe approach because most of the accident victims in Japan are older, and the severity of posture abnormality at the period when the falls stopped is higher than those indicated in past investigations. The probability of head injury cannot be negated from the results of both the body belt and full harness experiments, as supported by the comparison of experimental values and the underestimated values of the safety index (50% decreased values as a bold hypothesis).

Analysis of the possibility of neck injury due to impact force

Figure 7 shows the three-dimensional head accelerations measured at the center of gravity of the human dummy. The wide line denotes the vertical acceleration of the dummy; a positive value indicates download acceleration and a negative value indicates upward acceleration. The dashed-dotted line pertains to acceleration in the front-back direction; positive and negative values indicate the front and back direction, respectively. The dotted line refers to crosswise acceleration, for which positive and negative values denote the right and left directions, respectively. The vertical accelerations of the dummy equipped with body belt were all negative when it stopped from falling, through the acceleration on the dummy with a full harness were positive. Tension force acted on the head and neck of the dummy in the experiment involving the body belts. The dislocation of the cervical vertebrae is attributed to the strong upward inertia acting on the head and neck. Legal medical studies[13, 14)] indicate that such dislocation may result in respiratory arrest because of damage to the nerve fiber that controls the diaphragm. Such a situation may end in death before the administration of emergency medical support. Table 5 shows horizontal force, vertical force, and moment calculated using the experimental data. Neck injury criteria are obtained from the applicant examination administered through static tests on the tolerance limits of the human neck and through dynamic impact tests on the probability of heavy injury (cadavers were used for these tests). The horizontal and vertical force are calculated by

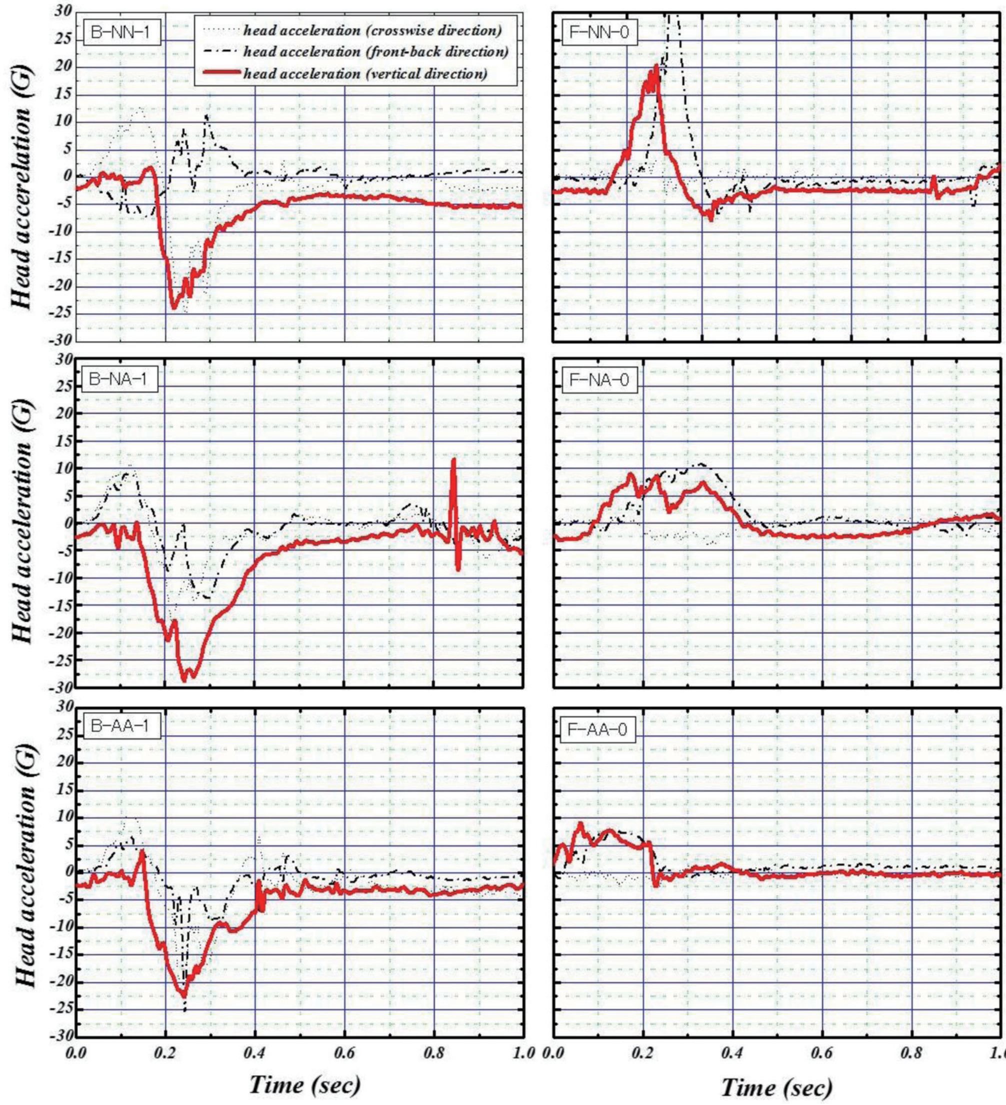

Fig. 7. Three-dimensional head accelerations measured at the center of gravity of the human dummy

Table 5. Relationship between impact force acting on the neck and the tolerance value

Test	Vertical Force (N)[*1,*2]		Horizontal Force (N)[*1,*2]				Moment (N・M)[*1,*3]			
	+Fz (Pressure)	-Fz (Tension)	+Fx (Right)	-Fx (Left)	+Fy (Front)	-Fy (Back)	+My (Anteflexion)	+Mx (Lateroflexion)	-Mx (Lateroflexion)	-My (Retroflexion)
B-NN-1	83	1170	613	1225	550	352	99	110	221	63
B-NA-1	572	1414	530	873	319	1245	57	95	157	224
B-AA-1	194	1108	502	955	436	676	78	90	172	122
F-AA-1	355	115	144	157	358	38	64	26	28	7
F-NN-0	1001	390	143	167	1633	329	294	26	30	59
F-NA-0	536	140	99	194	536	109	96	18	35	20
F-AA-0	444	189	67	117	372	55	67	12	21	10
Tolerance[*4]	1100	1100	1100*	1100*	1100	1100	50.2	47.5	47.5	20.3
Tolerance(50%)[*5]	550.0	550.0	550*	550*	550.0	550.0	25.1	23.8	23.8	10.2

[*1] Words in the parenthese meand the direction. [*2] Horizontal and vertical forces calculated by multiplying each direction of head acceleration by a head mass of 5 kg. [*3] Moment values calculated by multiplying the calculated force by the length from the edge of the neck to the center of gravity of the head. [*4] The tolerance value proposed in the past survey[6, 7]. [*5] The experimental data obtained in the past survy[6, 7] are subject to yound professional soldier. However the majority of Japanese victims are aged people. The tolerance value estimated to reduce into 50% as a bold hypothesis.

multiplying each direction of head acceleration (measured at the center of gravity) by a head mass 5 kg. The moment values are calculated by multiplying the calculated force by the length spanning the edge of the neck to the head's center of gravity. The comparison of neck tolerance values and experimental values for the body belts indicates a high possibility of the serious neck injury because the neck tolerance values for two individuals were both 1,100 N and the experimental tension values all exceeded 1,100 N. The tension values derived during the experiments on the full-harness dummy were all less than 1,100 N; the pressure derived from the experiment on F-NN-0 (no shock absorber) was close to 1,100 N. The vertical forces acting on the dummy equipped with a shock absorber were half the tolerance limit. Thus serious neck injury due to vertical force can be avoided through the use of shock absorbers. In addition, the horizontal force strongly depended on the type of safety belts and the use of shock absorbers. In the same situation, the maximum horizontal values can exceed the human tolerance limit when a body belt or a basic lanyard without a shock absorber is used. Moreover, the probability of neck injury can be attributed to anteflexion, regardless of whether a full harness or shock-absorber is used (Table 5). A necessary measure in preventing injury upon impact, therefore, is to consider the control of neck bending movements (anteflexion, retroflexion, and laterroflexion) in the design of personal protective equipment.

Conclusion

The safety performance of several safety belt-lanyard combinations is experimentally investigated. The means of the experimental data are analyzed, with reference to human impact tolerance values proposed in previous medical science studies, automobile crash safety, and aircrew safety. The comparison results show that safety during the instant when a fall stops (for the safety belt and lanyard combination) depends on the kind of safety belt and the use of shock absorber. The use of the full harness resulted in relatively higher tolerance than the use of the body belt. Nevertheless, attaching a shock absorber onto such equipment is at least necessary for prevention of serious injury. This study also maintains that the control of neck bending movements, such as heavy anteflexion, retroflexion, and laterroflexion should be incorporated into the design of personal protective equipment to prevent serious injury and death due to damage to the cervical vertebrae and consequent loss of control over the diaphragm.

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