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A Wearable Safety Device for the Body Protection of Motorcyclists

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ABSTRACT

This paper presents the development process for airbag safety devices fitted in motorcyclists' garments. Motorcycle riders often sustain multiple injuries in crashes since rider post-impact kinematics depend on several variables. This study proposes a newly inflatable safety system connected to the motorcycle by a cable. An airbag device with a mechanical triggering system is deployed when the cable detaches from its mounting clip. Airbag filling tests are performed to determine the mixing ratio of compressed gases with the severance of temperature. To estimate the airbag effectiveness to reduce riders' injuries, numerical analysis is performed using the finite element method. A comparative analysis (i.e., with and without the chosen device) was conducted to evaluate its protective efficacy. Prototype garments based on the proposed design have been created and have undergone sled tests. The proposed safety device could also be beneficial in accidents during other sports activities.

Keywords : Motorcycle(모터사이클), Safety Device(안전장치), Airbag(에어백), Inflator(인플레이터), Sled Test (슬레드 시험)

1. Introduction

The production of two-wheel vehicles is consistently increasing worldwide due to the constant demands for personal means of transport. However, the riders of motorcycles, scooters, and powered bicycles have a relatively high risk of fatal injuries and mortality compared to automobile drivers because of driving instability and the absence of proactive safety systems[1]. In motorcycle accidents, the entire body is generally subjected to complex injuries; therefore, since head injuries increase the mortality rate the most, a helmet was the first safety device developed[2,3].

A motorcycle rider can present different degrees of injury after an accident depending on whether the driving control ability was lost and/or the fall motion was controlled. Thus, airbags have been investigated to protect also motorcyclists. The first

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airbag system for motorcycles was mounted in 2006 in the fuel tank area of the newly introduced Honda Gold Wing model (Japan); it was an inflator module whose expansion was activated from four collision sensors located on both sides of the front fork. However, the installation cost of such a frame-embedded airbag system, unfortunately, increases along with the production cost of the vehicle[1]. Hence, airbags wearable by motorcyclists have been investigated for a long time, but those using an inflator were recently applied mostly to the motorcycles themselves due to various technical problems[3]. In the Republic of Korea, Do et al.[4] performed clothing manufacturing and dynamic experiments on jackets equipped with airbags, and Kim et al.[5] tried to develop airbags for cyclists by using motion sensors and wireless communication.

This paper proposes a wearable safety device with a mechanical operating system for motorcyclists. The inflator to fill the airbag with compressed gas was designed and its efficiency was evaluated through numerical analysis; besides, a prototype was realized by applying the proposed device to motorcycle clothing and its effectiveness in reducing injuries was accessed via a sled test.

2. Overview of Safety Devices for Human Body Protection

Previous studies have demonstrated the efficiency of clothing-mounted airbags for motorcyclists in preventing damages to soft tissues, such as lacerations, bruises, and abrasions, because of their structural characteristics. Besides, these systems protect against skin damage and muscle loss due to friction, as well as infection complications caused by wound contamination[1].

Fig. 1 illustrates the structure and operation principle of a typical wearable safety device for motorcyclists. The airbag is located beneath the outer skin of the clothing and helps to prevent traumas to the major body parts, including the cervical, thoracic, abdominal, lumbar, and thoracic areas, from external shocks; it achieves this by inflating the compressed gas charged in the cartridge with a triggering system connected to a flexible wire, which signals when the rider deviates from the motorbike. The abovementioned clothing outer skin hosting the airbag can be in the form of a jacket or a vest depending on the user taste, but it must not structurally interfere with the airbag inflation. Furthermore, the front and rear parts of the airbag should be connected through a single gas passage to ensure simultaneous expansion, making the protective area uniform and preventing twisting.

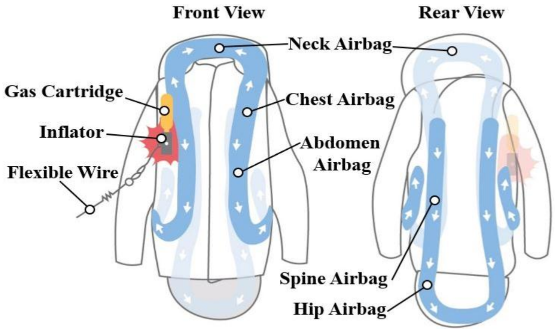


Fig. 1 Safety device for motorcyclists

3. Safety Device Design

3.1 Inflator Design

Most wearable airbags are mechanical and manual systems mounted on the rider clothing and operated by the tensile force of cables connected to the vehicle; a system operating via an electrical signal from an acceleration sensor was recently developed [1]. In France, the Helite company[6] investigated various application plans for mechanical triggering devices connected to motorcycles by cables. In & Motion[7] studied the application of a percussion system by using electrical devices such as

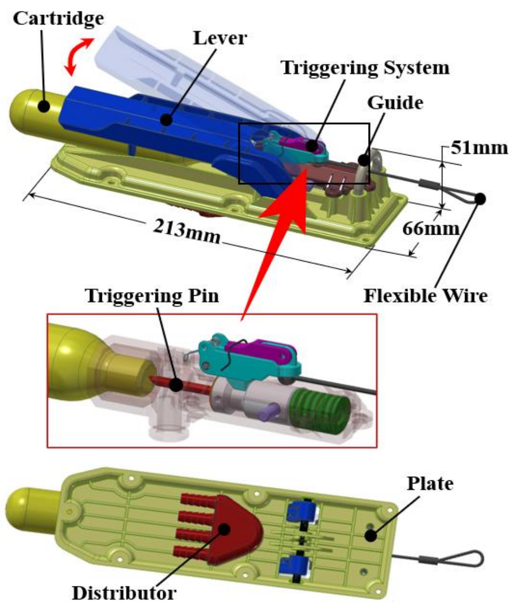


Fig. 2 The 1st proposed inflator

accelerometers and gyroscopes.

Among the operating systems of clothing-mounted airbags for motorcyclists, those based on electrical signals ensure a relatively shorter reaction time compared to the mechanical and manual ones and can be controlled separately via wireless communication. However, in most cases, their parts cannot be recycled after the inflator has been operated and the frequent errors in the detection signals, according to the driving posture, lead to malfunctioning. Therefore, given the practical requirements of motorcyclists and the economy, this paper proposes the design of a mechanical/manual inflator that can be reused by simply replacing the cartridges and can also be operated in various free-fall positions.

Fig. 2 displays the shape and structure of the proposed inflator in the first design stage; the cartridge filled with compressed gas is separated from the triggering pin or connected to it by rotating the lever up or down, respectively. When the rider falls, the flexible wire connected to the motorcycle body separates the ball inside the percussion device connected to the wire from the hinge due to tensile force. In this system, the separated ball releases the hinge fixing, the pin of the percussion device punches the cartridge due to the elastic force of the built-in spring according to the lever operation principle, injecting the compressed gas into the distributor. The distributor is located at the plate bottom, and a guide is installed to prevent interference by the elastic wire and constantly control the tensile force direction. Various experiments indicated that the most suitable inflator is the one where the compressed gas is first injected where it stably filled is discharged after being injected into the airbag was circulated to the front and rear sides, respectively. This can be explained as follows: when a separate exhaust port is installed inside the airbag, rupture occurs due to relatively weak internal pressure strength, the compressed gas completely fills the airbag and is discharged simultaneously, and the maximum pressure inside the airbag cannot be maintained for long. Therefore, in the proposed design, the compressed gas injected through the gap generated after cartridge drilling by processing a separate groove inside the percussion device pin is partially discharged with some delay.

Fig. 3 shows how the inflator shape was changed in the second design stage; the triggering system for the lever operation of the hinge has been deleted and the ball connected to the flexible wire now directly controls the drilling pin operation. This design variation resulted from testing the percussion device through a mock-up. The initial hinge system caused frequent malfunctioning because the load acting along the tensile direction of the flexible wire was not constant. Moreover, in the second design stage, the sizes of the lever and fixing parts were reduced to the minimum to decrease the overall weight, since the system must be mounted on clothing.

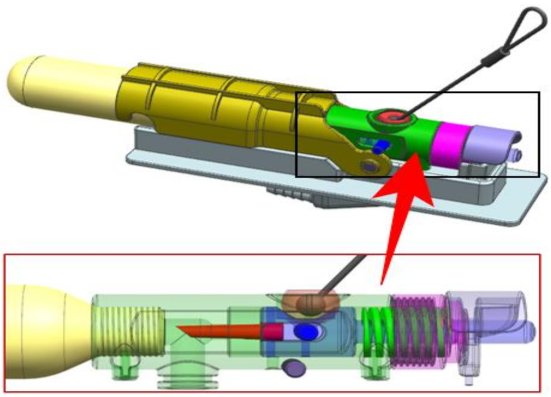


Fig. 3 The 2nd proposed inflator

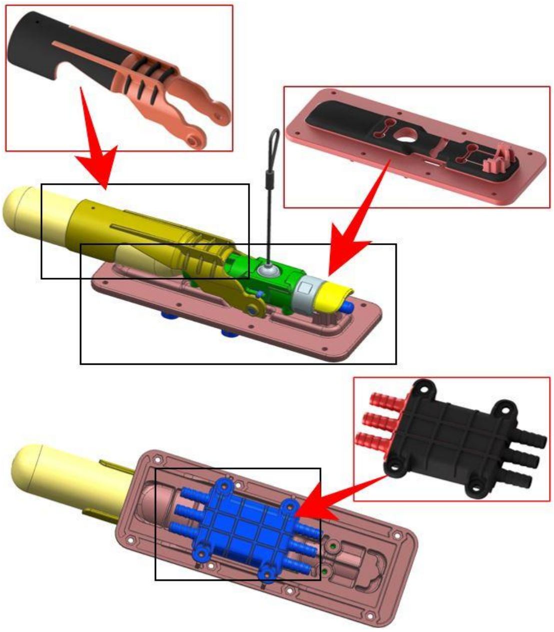


Fig. 4 The final proposed inflator

Fig. 4 illustrates the final inflator shape; at this design stage, the size of the lever, which frequently breaks, was increased in the longitudinal direction and reinforced by adding ribs. Furthermore, since the distributor at the bottom of the fixing part often bursts due to excessive pressure increase resulting from the compressed gas flowing in a single direction, the final compressed gas flow path was along both directions to have uniform pressure distribution and reinforced with ribs.

3.2 Airbag Inflation Test

To obtain an airbag that when mounted on motorcycle clothing, thermoplastic polyurethane was selected as the constituent material, with high-frequency fusion as the manufacturing technique. First, the following pattern was designed: the compressed gas in the inflator cartridge can flow uniformly into the airbag by using the percussion device. According to data reported by airbag manufacturers[6,7], the maximum pressure inside the inflated airbag, which expands within 0.5 s due to the compressed gas injection and is discharged within 30 s, is 25-30 kPa. Therefore, the performance target of this paper was as follows; the maximum inflation pressure of the airbag can reach 35 kPa within 0.5 s, considering the safety factor.

Since motorcyclists are consistently exposed to the outside while driving, unlike car drivers, the installed equipment is sensitive to seasonal temperature changes. Thus, compressed gas is required since it is insensitive to ambient temperature, even in the case of harsh external environments. Furthermore, the cartridge must have the appropriate capacity and pressure to inflate the designed airbag sufficiently and uniformly. Hence, based on these requirements, instead of using a commercialized cartridge, the validity of the mixing ratio of compressed gas was reviewed. Most commercialized cartridges are generally filled with CO_2, mixed with an inert gas if necessary; therefore, in the proposed design, N_2, which is relatively stable and has a low freezing point, was mixed with CO_2 at a constant ratio.

Fig. 5 displays a photograph of the final shape of the manufactured airbag, whose total volume is 30 L. To test its inflation speed, two digital pressure sensors were installed on its front part (A), which protects the chest and abdomen, and rear part

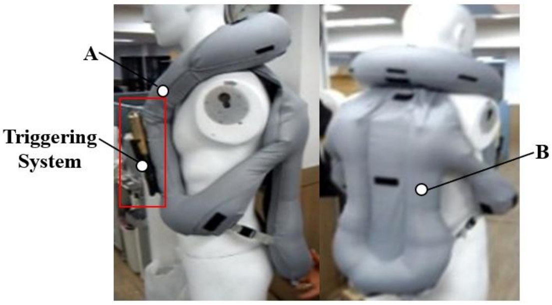


Fig. 5 Photograph of airbag system

Table 1 The duration time to maximum filling pressure in the airbag

Mixture gas	Location	-20℃	20℃	40℃
CO_2(45MPa)	A	0.42s	0.31s	0.27s
	B	0.70s	0.43s	0.45s
CO_2(33MPa)+ N_2(12MPa)	A	0.30s	0.25s	0.25s
	B	0.49s	0.37s	0.42s
CO_2(30MPa)+ N_2(15MPa)	A	Fail	Fail	Fail
	B	Fail	Fail	Fail

(B), which covers the cervical, thoracic, and lumbar vertebrae. After puncturing the cartridge with the percussion device, the installed pressure sensor transmits the signal to the pressure gauge. The time required to reach the maximum pressure of 35 kPa was measured with an oscilloscope; the results are summarized in Table 1 for A and B, according to the mixing ratio and temperature of the compressed gas. When the N_2 gas accounted for 1/3 of the total cartridge pressure (15 MPa), the measurement was impossible due to the rupture of the distributor; this probably occurred because of the excessive pressure due to the active fluidity of N_2, which has a relatively small molecular weight compared to CO_2. The experiment revealed that, as the external temperature increased, the time to reach the maximum pressure decreased in most cases, while the time of B, located relatively farther from the inflator than A, increased. When N_2 accounted for 26.7% (12 MPa) of the total capacity, the maximum pressure under all the tested ambient temperature conditions was reached within 0.5 s, satisfying the abovementioned performance target. Besides, compared to the use of only CO_2, the time to reach the maximum pressure was relatively short under all conditions, demonstrating the effectiveness of mixing it with N_2.

4. Safety Analysis

4.1 Analysis Conditions

The injury of the vehicle occupant during a collision is frequently predicted by using the finite element method and a dummy, which is a human body model. This approach is suitable to evaluate the protecting performance of a safety device, during vehicle collisions, that is currently commercialized and in use or to be released[8]. However, in the case of two-wheel vehicles, the collision phenomenon occurring while driving is significantly influenced by various variables such as relative position, driving posture, and driving speed[9]; therefore, for such scenarios, the efficiency of the safety device can be evaluated by comparing the cases with and without its application[1]. In the present study, a simulation was performed by using MADYMO[10], a passenger behavior analysis program, to determine the efficiency of the designed airbag.

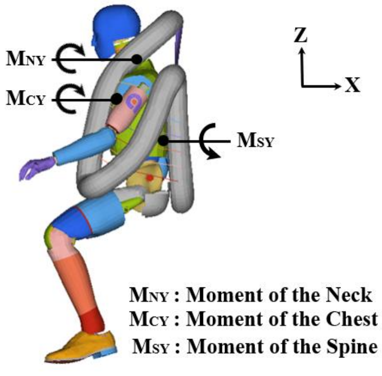
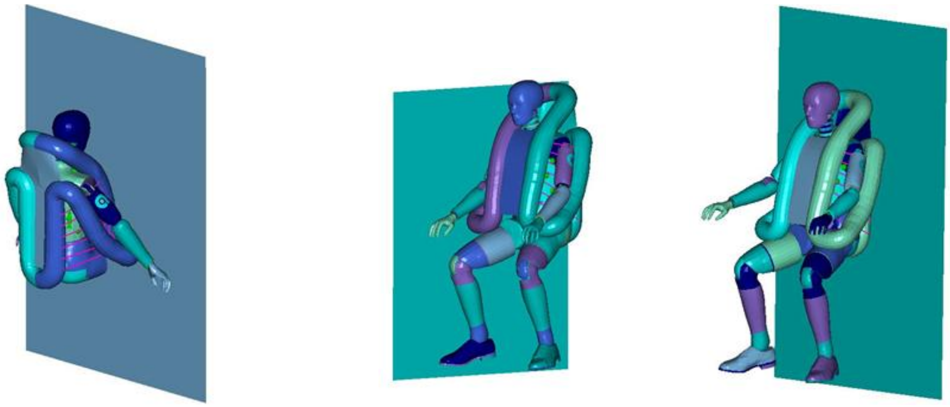


Fig. 6 FE model of Hybrid Ⅲ dummy



(a) frontal impact (b) lateral impact (c) rear impact

Fig. 7 FE model simulating impact analysis

Fig. 6 shows the modeling shape and moment when the proposed airbag is to a Hybrid III dummy built in MADYMO for finite element analysis. Given the large deformation of the airbag due to the collision, a triangular grid was applied, and additional diaphragms were modeled on the airbag front and rear sides to increase its adhesion to the dummy; furthermore, based on a preliminary simulation, the relative mounting position was adjusted in detail to maximize the contact area between airbag and dummy.

Fig. 7 illustrates the collision behavior used in the simulation to analyze the airbag performance, which was simplified into the following forms: the dummy collides with the fixed wall along the front, side, and rear directions. In a front collision, the lower body of the dummy was omitted due to its interference with the fixed wall model. Under these modeling conditions, the safety efficiency was evaluated for various collision speeds, with and without the designed airbag.

4.2 Analysis Results

Table 2 lists the simulated maximum momentum values for the upper part of the dummy according to the velocity change during collisions, with and without the designed airbag. The airbag reduced most of the injuries but, in some cases, they were increased for a specific body part by up to 16.1%. In the front collision, the reduction in neck injuries was the greatest at high speed, but its numerical distribution was unstable for some cases. The overall injury reduction by the airbag was the lowest in the case of side collision; in particular, for most speeds, the safety improvement by the airbag was small in the spine part, but some chest injuries were reduced at high speed. In the rear collision, the reduction in the neck injuries was as high as in the front collision, and the injuries to the spine part were more reduced at high speed than at low speed.

These results indicate that the safety improvement efficiency of the designed airbag is the highest for the cervical spine and the lowest for the spine part. This can be attributed to the relatively stiff spine structure of the Hybrid III dummy compared to an actual human body and the excessive force applied due to the strong impact on the fixed wall.

5. Prototyping and Evaluation

5.1 Prototype

In a motorcycle accident, as a result of the dynamic tracking of the causal relationship between internal bleeding in the chest and abdomen and neurological damages[3]. there is a close relationship

Table 2 Impact FE analysis results (W/O and with the airbag)

Impact category	Velocity(kph)	Neck moment(N·m)		Chest moment(N·m)		Spine moment(N·m)	
		W/O	with	W/O	with	W/O	with
Frontal	20	155	138	191	139	115	79
	30	323	308	353	316	156	148
	40	4,668	2,120	817	506	353	285
	50	4,781	4,436	661	724	370	401
	60	4,554	405	832	899	411	477
Lateral	20	263	268	414	437	329	315
	30	357	357	565	608	453	472
	40	503	502	867	624	422	455
	50	642	633	988	653	401	412
	60	832	829	1,015	733	385	390
Rear	20	211	85	189	154	275	306
	30	319	190	359	306	331	335
	40	379	244	469	402	365	398
	50	361	250	483	493	457	421
	60	249	208	514	588	560	452

between the safety of the rider clothing and prevention of such physical damages. Therefore, major motorcycle apparel companies, such as Spidi, Brembo, Alpinestars, and Dainese, are introducing airbag jackets. Since these safety devices protect important parts of the upper body, they are also used for snowmobile riding, horseback riding, and mountain biking[1].

Fig. 8 shows a photograph of the prototype of motorcycle clothing equipped with the designed airbag. Besides jacket-type clothing, vest-type clothing was additionally manufactured considering the convenience regardless of the seasonality and utility for other sports events excluding motorcycling. To realize the prototype, the standard human body dimensions for Koreans, indicated by the National Center for Standard Reference Data of the Korea Research Institute of Standards and Science, were used. Moreover, preferences for design, wearing sensation, etc. were surveyed in advance among professional fitting models and members of motorcycle clubs; the results were reflected in the clothing styling and, then, a wearing test was conducted.

(a) jacket type

(b) vest type

Fig. 8 Photograph of prototype

5.2 Sled test

The impact sled test is widely used to evaluate human injuries in various environments. It is performed with a dummy closely reproducing the biological characteristics and musculoskeletal system of the human body[11]. In the case of automobiles, the standards for evaluating collision injuries are established by the US Federal Motor Vehicle Safety Standards and the European New Car Assessment Programme. However, in the case of two-wheeled vehicles such as motorcycles, there are no local nor international standards. Therefore, in this study, the safety performance of the prototype was verified through a sled test that evaluates the motorcyclist injuries for the safety of the seat against collision, the behavior of interior materials, and the airbag inflation by using a bogie.

Fig. 9 displays a photograph of the Hybrid III dummy and jig used in the sled test. The injury values were compared with and without installing the manufactured vest-type clothing, equipped with the airbag, on the dummy. The dummy was seated on a separately manufactured jig in the basic driving conditions of the motorcycle and was able to move within a limited distance toward the front and rear directions. German IST equipment was used for the sled test; the front/rear collision tests were conducted under an acceleration condition of 14 G at a speed of 42 km/h.

Table 3 summarizes the sled test results. The overall safety was improved when the airbag was deployed compared to the case without it; in particular, consistently with the previous numerical simulation, the reduction in the neck injuries was the greatest in the front collision. Compared to the front collision, the rear collision test showed less efficiency in injury reduction, and the difference between acceleration characteristics and chest deformation was measured as almost same.

Fig. 9 Photograph of sled test

6. Conclusion

This paper presented a wearable safety device for the protection of motorcyclists during accidents. It was based on an airbag filled by a mechanical manual inflator, the economical aspect was considered, and its efficiency was verified through both simulations and a sled test. The following conclusions were drawn.

1. The inflator must be designed to allow the cartridge to be easily replaced by a lever and the compressed gas to be discharged after some delay when it is triggered in response to various free-fall positions of the rider.
2. The airbag inflation test showed that compressed gas consisting of a mixture of CO_2 and N_2 is relatively insensitive to external temperature changes compared to CO_2 alone.

Table 3 Sled test results (W/O and with the airbag)

Impact category	Neck moment(N·m)			Chest resultant acceleration(G)			Chest deflection(㎜)		
	W/O	with	Δ_{value}	W/O	with	Δ_{value}	W/O	with	Δ_{value}
Frontal	117	52	-55.6%	65	51	-21.5%	85.1	72.1	-15.3%
Rear	138	113	-18.1%	112	88	-21.4%	15.2	13.5	-11.2%

3. Numerical simulations demonstrated that the designed airbag provides the greatest safety improvement for the cervical spine and its injury reduction differs slightly depending on the collision type.
4. A sled test conducted using a dummy and motorcycle clothing equipped with the proposed airbag confirmed the efficiency of the designed safety device in reducing injuries to the human body.
5. The proposed clothing-mounted safety device can be used by not only motorcyclists but also snowmobile riders, horseback riders, skiers, and mountain bikers, who are expected to have various types of fall accidents.

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