

Article

Evaluation of Cushioning Effect and Human Injury According to Occupant Posture and Use of Air Mat in Case of Elevator Fall

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Abstract: Because of the function of facilities that transport individuals and luggage to elevated locations, poor maintenance and human errors by users and workers can result in many elevator accidents annually. In particular, given the characteristics of an elevator used by an unspecified number of people, in the event of a fall accident due to wire rope cutting, an occupant's body may be fatally injured, thereby causing substantial human damage. To minimize human injury, it is important to reduce the relative impact speed between the car and the pit by utilizing the buffer effect according to the role of the safety device and the posture of occupants. The AIS (Abbreviated Injury Scale) is an anatomical-based coding system established by the Association for the Advancement of Automotive Medicine that classifies and describes the severity of injuries. In this study, through human injury analysis, safety device operation such as speed governor and buffer when cutting elevator wire rope, occupant's behavior, and air mat usage were used to derive force and torque values for the injured part, and then determine the amount of impact and degree of injury to the human body using the multibody model provided by the MADYMO program and AIS by analyzing the buffering effect of the impact.

Keywords: MADYMO; cushioning effect; elevator; human injury; injury severity; safety device



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1. Introduction

Typically, an elevator, which includes machines such as elevators, escalators, or wheelchair lifts, is installed in a building or fixed facility to transport individuals or cargo along a certain route to a defined platform. Based on the driving method, elevators are divided into rope, hydraulic, linear motor, screw, and rack/pinion types. Because of the function of facilities that transport individuals and luggage to elevated locations, poor maintenance and human errors by users and workers can result in an average of approximately 100 elevator accidents annually, according to the announcement of the National Elevator Information Center [1]. In particular, given the characteristics of an elevator used by an unspecified number of people, in the event of a fall accident due to wire rope cutting, an occupant's body may be fatally injured, thereby causing substantial human damage. To minimize human injury, it is important to reduce the relative impact speed between the car and the pit by utilizing the buffer effect according to the role of the safety device and the posture of occupants. Although most elevators are equipped with safety devices, such as governors and shock absorbers, limited data are available on the buffering effect of safety devices on human impact. In addition to the safety device, the cushioning effect differs substantially depending on the posture of the occupant and air mat usage. However, there is no study on the buffering effect on human body impact according to the posture of the occupant and the use of air mats in relation to the elevator. The Mathematical Dynamic Model (MADYMO) is a passenger behavior analysis program developed by The Netherlands Organization for Applied Scientific Research. Computer program simulations are widely used, owing to the practical limitations of employing real vehicles and individuals to analyze and evaluate vehicle safety and traffic accidents. In particular,

MADYMO models have been used widely for pedestrian crash reconstructions [2–4] and the prediction of injury through vehicle accident reconstructions [5,6]. In the current study, we utilized the multibody model provided by the MADYMO program, which is most commonly used for evaluating the degree of impact and injury to the human body, elevator falls on cutting the wire rope, and operating safety devices, such as governors and shock absorbers. Performing a human injury analysis, the injury site force and torque values were derived based on the occupant's posture and the presence/absence of an air mat. Finally, using the human injury judgment tool, we compared and analyzed the buffering effect of the human shock in each case.

2. Basic Theory for Injury Analysis and Evaluation

2.1. Elevator Specifications

Typically, an elevator comprises a machine room, hoistway, pit section, hoisting machine, electric motor, control panel, and governor, which are installed in the machine room for elevator operation. Considering the structure and driving principle of the elevator, as shown in Figure 1, a fixed pulley exists at the top of the route on which the elevator runs, with a wire rope connected to the fixed pulley. A car that can accommodate an individual or cargo is connected to one end of the wire rope, and an electric motor moves the car while unwinding and winding the wire. A counterweight equal to or 1.5 times the car weight is connected to the other end of the wire rope. The counterweight is placed on the opposite side of the car to reduce the load on the motor. The counterweight is generally 40–50% of the maximum weight, and the tension of the wire rope is designed to be approximately twice the maximum weight. When the elevator speed exceeds the rated speed during operation, the governor, a device that safely stops the car at a preset speed, primarily operates; however, the car does not stop and goes through the lowest floor into a pit. In the event of a fall, a buffer, a device used to mitigate the impact, comes into action. The elevator specifications used in the analysis were 2 m (horizontal) $\times$ 2 m (length) $\times$ 2.5 m (height) of elevator space, the rated capacity was 15 passengers (1000 kgf), and the rated speed was 60 m/min. Activating the governor safety device resulted in a car speed of 1.4 m/s, which is 1.4 times the rated speed of 60 m/min (1 m/s). The shock absorber was a spring shock absorber type, with one installed in the pit; it had a diameter of 151 mm, a length of 570 mm, a stroke of 135 mm, nine steel 9, and a spring constant of 80.38 kgf/mm. In order to increase the cushioning effect to mitigate the impact force transmitted to the human body, 2.0 $\times$ 1.0 $\times$ 0.3 m air mats were installed under the passengers in the elevator car. The air mat had a maximum pressure of 180 kPa, a minimum pressure of 140 kPa, and a thickness of 30 cm. Figure 2 shows the air mat model created for the human impact analysis.

2.2. Assessment of Injury Severity

Several studies, including the AEP-55 issued by the North Atlantic Treaty Organization, have explored the injury site and degree of injury by analyzing human injuries using MADYMO [7–9]. The AIS is an anatomical-based coding system established by the Association for the Advancement of Automotive Medicine that classifies and describes the severity of injuries [10,11]. AIS represents the threat to life associated with the injury rather than a comprehensive assessment of its severity [12]. AIS is one of the most common anatomic scales for traumatic injuries and is an up-to-date medical term that provides an internationally recognized tool for assessing injury severity [13]. The Abbreviated Injury Scale (AIS) is an anatomical-based coding system created by the Association for the Advancement of Automotive Medicine to classify and describe the severity of injuries. It represents the threat to life associated with the injury rather than the comprehensive assessment of the severity of the injury. The cervical/thoracic spine is the part most closely related to life in car accidents, and the AIS grade is mainly classified according to the degree of damage to the cervical/thoracic spine. In addition, the spinal cord is also included. The injury grade of AIS is mainly related to cervical/thoracic spine: damage to the spinal cord. Accordingly, it is a global severity scoring system that classifies individual injuries

by body part according to their relative severity based on a six-point scale (1 = minor, 6 = maximum). The standard table of human injuries presents the injury standards for six parts of the human body, including the head, neck, thorax, spine, femur, tibia, and non-auditory pressure-induced injuries.

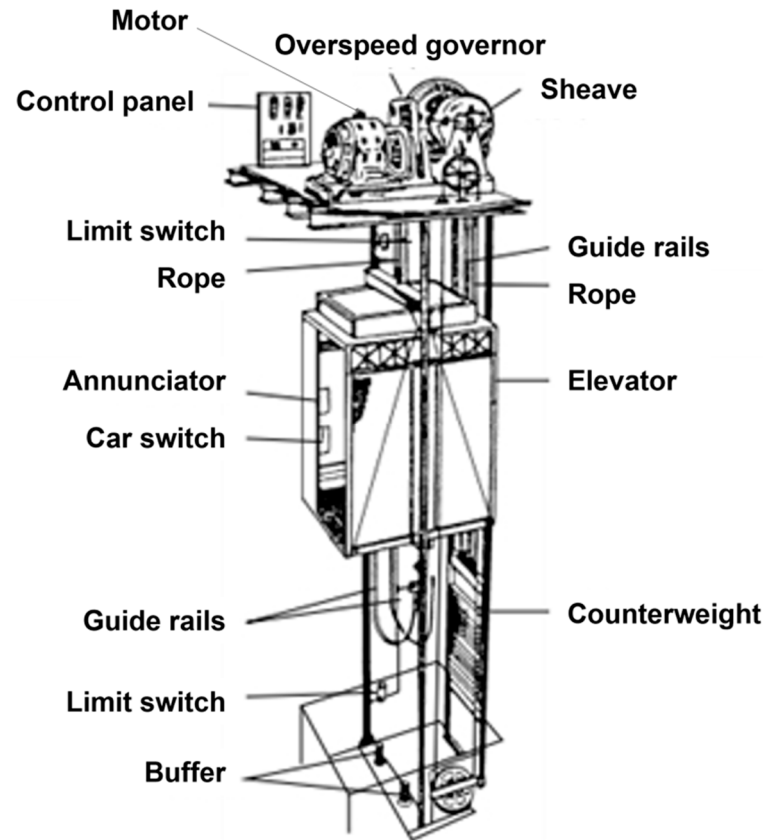


Figure 1. Structure and operation principle of elevator.

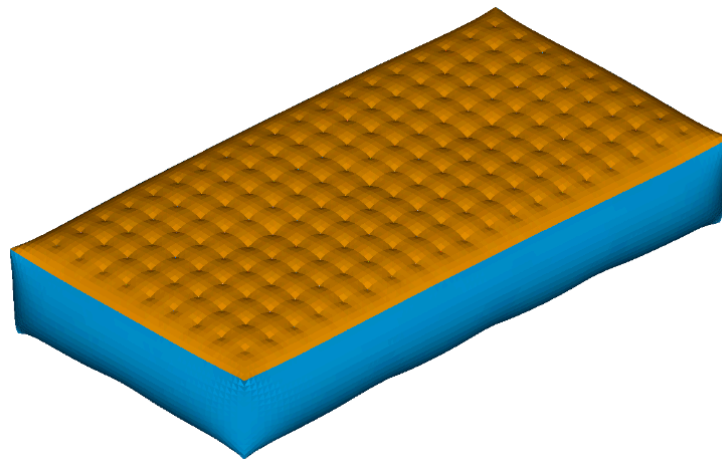


Figure 2. Air mat model for human impact analysis.

3. Analysis of Human Injury

3.1. Free Fall

Herein, four fall heights, i.e., the 20th, 15th, 10th, and 5th floors, were established by cutting the elevator wire rope (free fall). Table 1 lists the fall height and speed for each floor, calculated considering the distance between floors as 2.5 m. The human body model used was a standard human model with a height of 174 cm and weight of 75.7 kg, constructed

into the DB program. First, considering the scenario where the elevator wire rope was cut, and the elevator fell freely from the 5th floor at a speed of 14 m/s, a fall and injury analysis was performed, assuming that one individual was lying down. According to the analysis results, despite the fall from the fifth floor, i.e., the lowest floor, the maximum impact force on the human body, as shown in Figure 3, was 70,000 kg m/s². This impact value results in the rupture of all the parts and joints of the human body. Based on the above results, we established that comparing the amount of impact and degree of injury according to the occupant's posture and the use of air mats was not meaningful for floors above the 5th floor, as presented in Table 1.

Table 1. The fall height and fall speed for four levels.

No.	Floor	Height (m)	Fall Velocity (m/s)
1	20	47.5	30.5
2	15	35.0	24.2
3	10	22.5	21.0
4	5	10	14.0

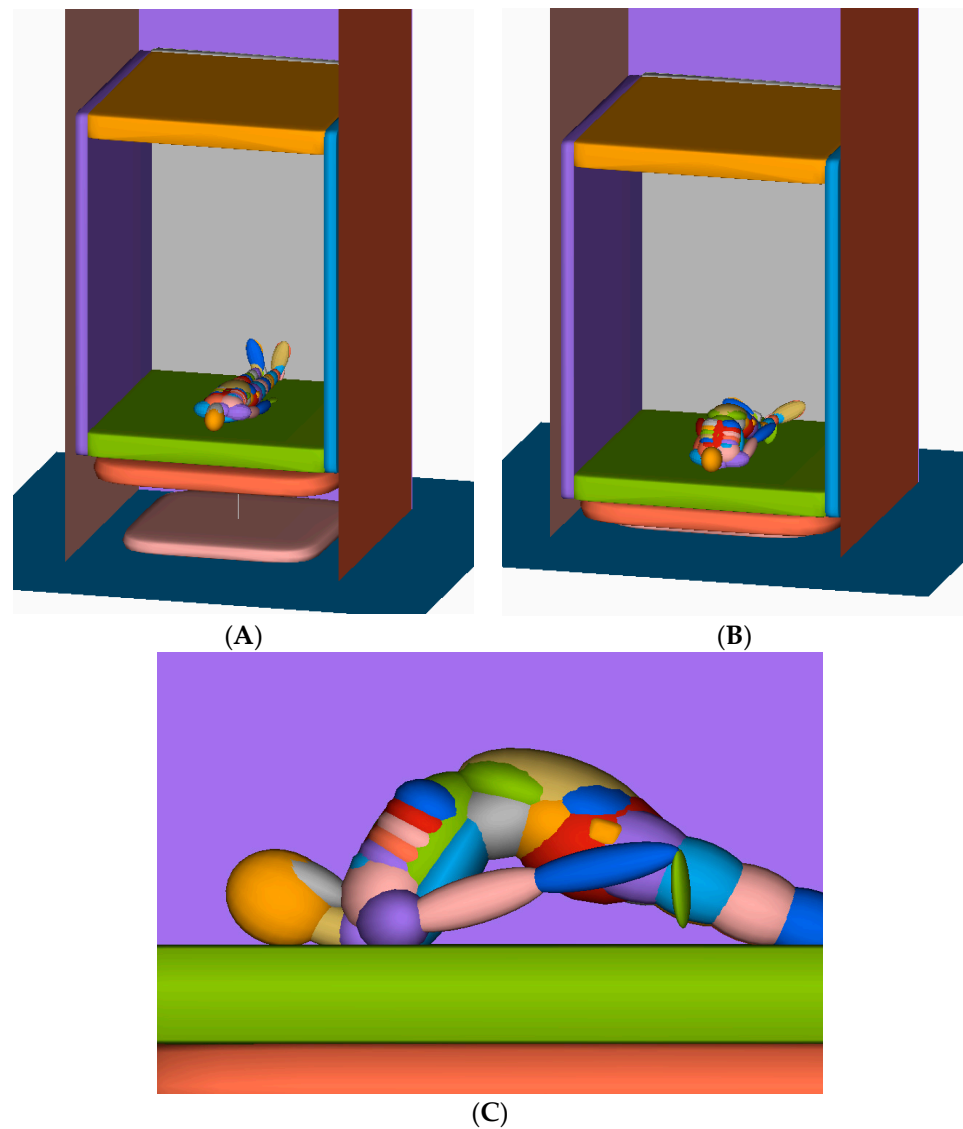


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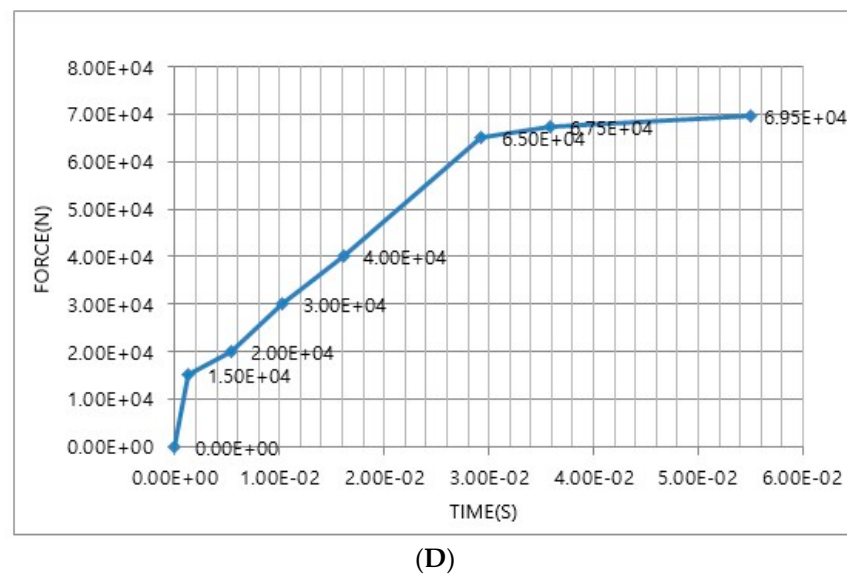


Figure 3. The result of body injury analysis in case of free fall. (A) Before shock absorber. (B) After shock absorber. (C) Degree of injury in the human body model. (D) The graph of momentum for the human body model ($F - \Delta t$) in the fall from the fifth floor.

3.2. Safety Device Operation

Based on the above findings, comparing the amount of impact and degree of injury according to the occupant's behavior and air mat usage during a free fall due to a cut elevator wire rope from the 5th floor or higher can be inconsequential. Therefore, we performed human injury analysis according to the passenger's posture and the use of air mats, limited to instances where the governor safety device was operational (1.4 m/s constant velocity motion). To compare and analyze the cushion effect according to the occupant behavior while the governor safety device was operating, as shown in Table 2, we analyzed fall-induced human body injuries to determine the force and torque values of the injured part, considering cases where one individual was standing, two individuals were standing, one individual was lying down, and two individuals were lying down, respectively. Finally, to compare and analyze the cushioning effect according to the use of air mats while the governor safety device was operational, the force and torque values of the injured part were derived by analyzing the fall-induced human body injury caused while one individual was lying down on an air mat. Figures 4–8 represent the analysis results for the major injured parts immediately after the impact of the shock absorber in each case, in the order of momentum for the human body, force and torque values at the major injured part, and impact posture. In case 5, to analyze the buffering effect according to the use of the air mat, we additionally derived the change in the volume and pressure values of the air mat. Tables 3 and 4 present the results of the above analysis that compares and analyzes the buffering effect according to the passenger's posture and the use of an air mat. However, in the case of the two individuals standing state, the human body model hugged and the human body model lying on top in the case of the two-individuals lying down state are considered as objects to be protected, and the value for the human body is indicated for the amount of impact. In the case of two human bodies in the elevator, the shock can be transmitted to both, but from the point of view of security, one of the two human bodies, that is, the human body that is hugged when two people are standing or lying down, is considered to be the object to be protected. This means that injury is determined only by considering the analysis result of this human body model. The act of being hugged constrains the arm of the human body hugging and the upper body of the human body being hugged, and this is given as a boundary condition for the analysis. In the case of standing with one or two persons, there was a high possibility of fracture in the ankle area, given that values exceeded the limit of force and torque at the ankle

area. The impact force was reduced by approximately one-half in the case of the two people lying down when compared with that observed in the single individual lying down scenario, with a nearly doubled buffering effect. In the case of a single person lying down, a high possibility of fracture can be expected, given that the values exceeded the limit of force and torque at the neck joint. However, the impact force was buffered in the case of individuals lying down, and the buffering effect was approximately one-third the limit value for neck joint fractures. The buffering effect in the case of one individual lying down using an air mat was similar to that observed in the case of two individuals lying down, based on the force and torque values of the injured area. Nevertheless, it is meaningless to directly compare the impact data in the standing and lying states because the impact force and impact values in these states differ considerably. However, comparing the degree of cushioning in the same position was possible.

Table 2. The condition of case according to the passenger's posture and the use of air mats.

Case No.	Case 1	Case 2	Case 3	Case 4	Case 5
Condition	Single individual standing	Two individuals standing	Single individual lying down	Two individuals lying down	Single individual lying down using air mat

Table 3. The result of the body impact analysis in case of operation for the governor safety device.

Case No.	Impact Force (N)	Impact Time (s)	Momentum (kg m/s)
1	15,000	0.014	54,000
2	2000	0.035	14,000
3	1153	0.090	50,000
4	570	0.100	18,000
5	-	-	-

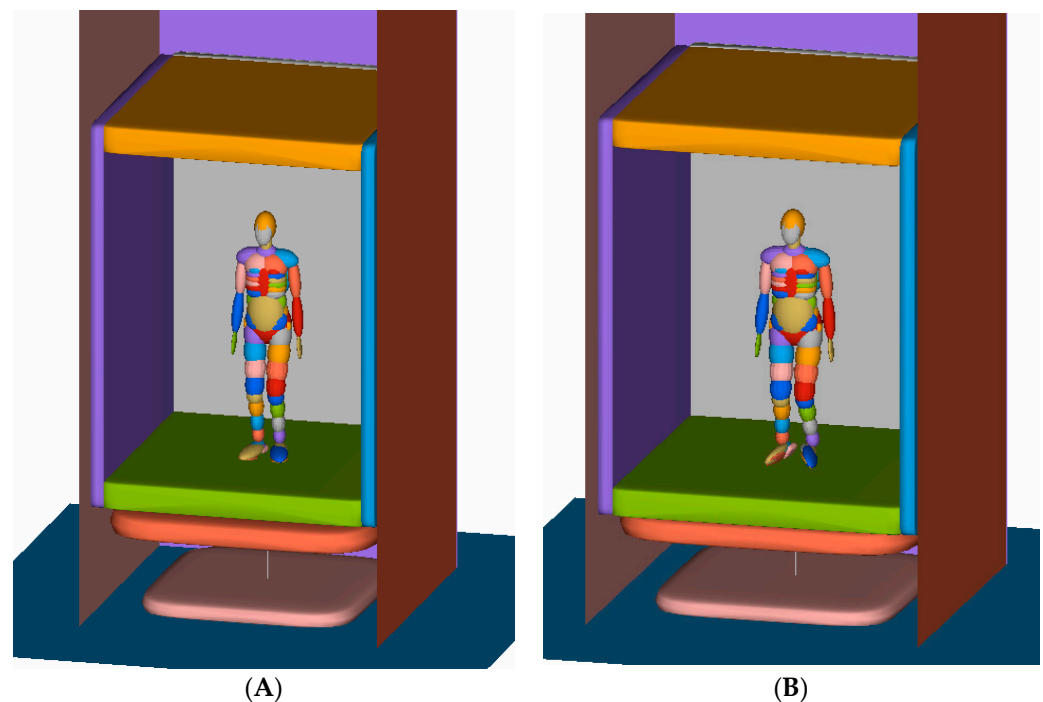
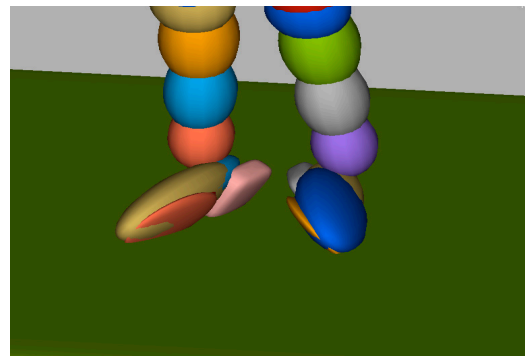
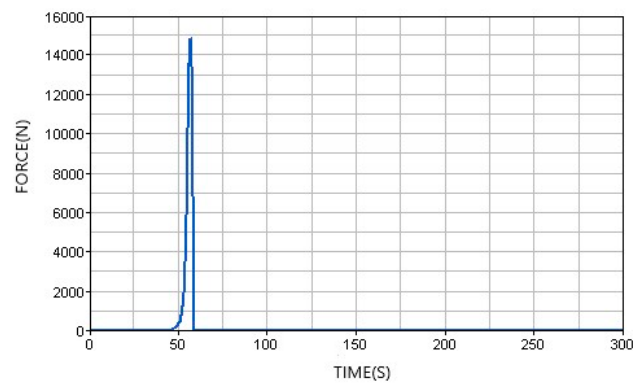


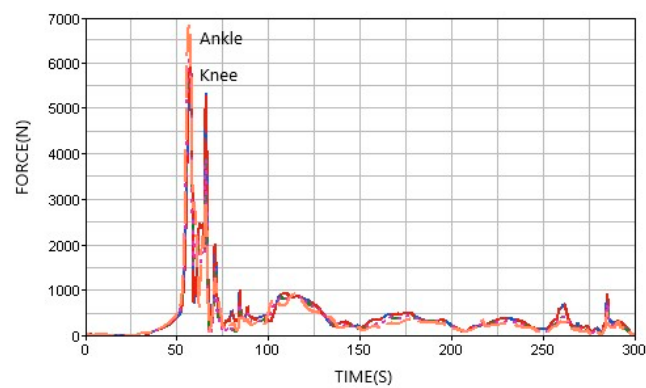
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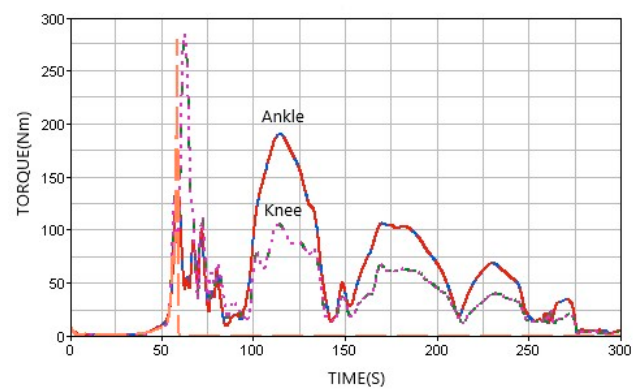
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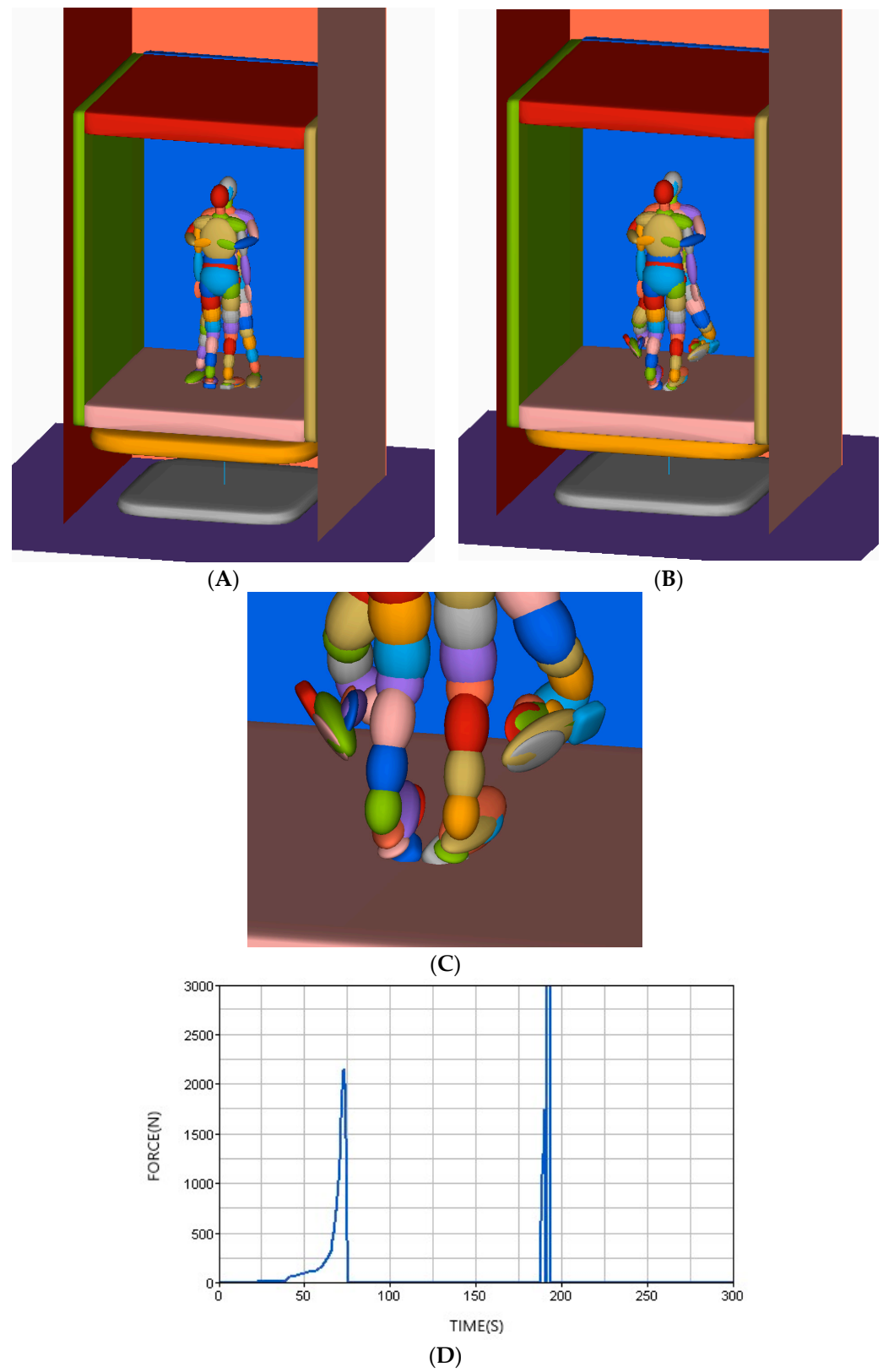


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(F)

Figure 4. The result of the body injury analysis in case of 1. (A) The condition of case 1 (before the impact of the shock absorber). (B) The condition of case 1 (after the impact of the shock absorber). (C) Major Injury part and Injury types (ankle). (D) The graph of momentum for human body ($F - \Delta t$). (E) The graph of force value at major injury part. (F) The graph of torque value at major injury part.

**Figure 5.** *Cont.*

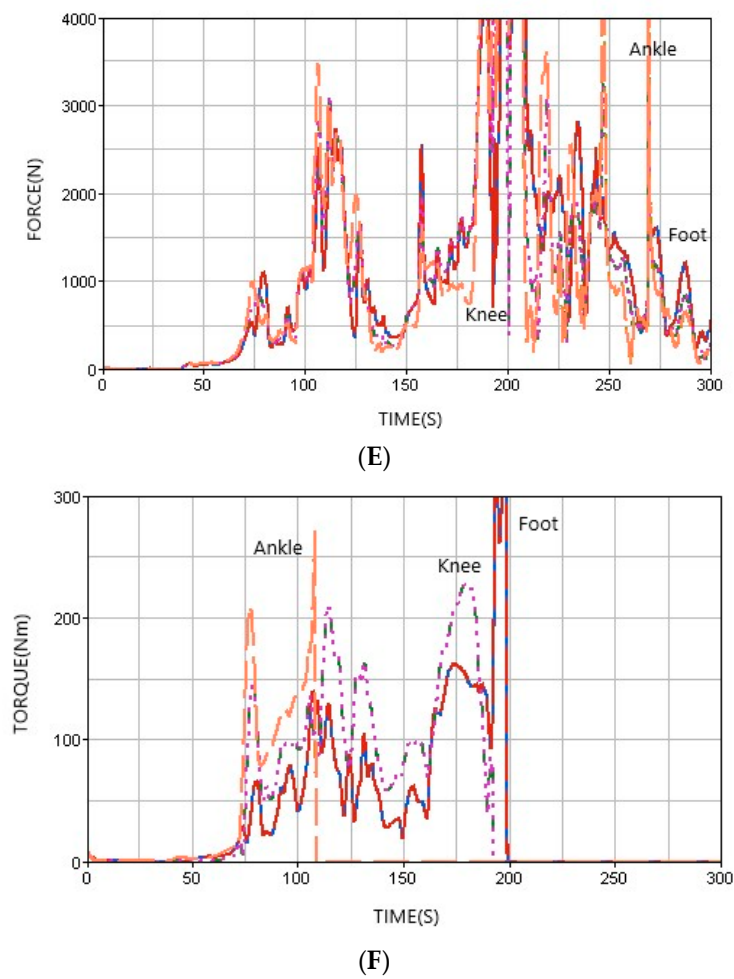


Figure 5. The result of the body injury analysis in case of 2. (A) The condition of case 2 (before the impact of the shock absorber). (B) The condition of case 2 (before the impact of the shock absorber). (C) Major Injury part and Injury types (ankle). (D) The graph of momentum for human body ($F - \Delta t$). (E) The graph of force value at major injury part. (F) The graph of torque value at major injury part.

Table 4. The result of the body injury analysis in case of operation for the governor safety device.

Case No.	Injury Part	Maximum Force (N)	Maximum Torque (Nm)	Criteria (by EuroNCAP)
1	Ankle	7000	285	Limit Force: 4000 N
2	Ankle	3400	270	Limit Torque: 285 Nm
3	Neck	1103	220	Limit Force: 845 N
4	Neck	340	50	Limit Torque: 88.1 Nm
5	Neck	390	56	(AIS 1 Level)

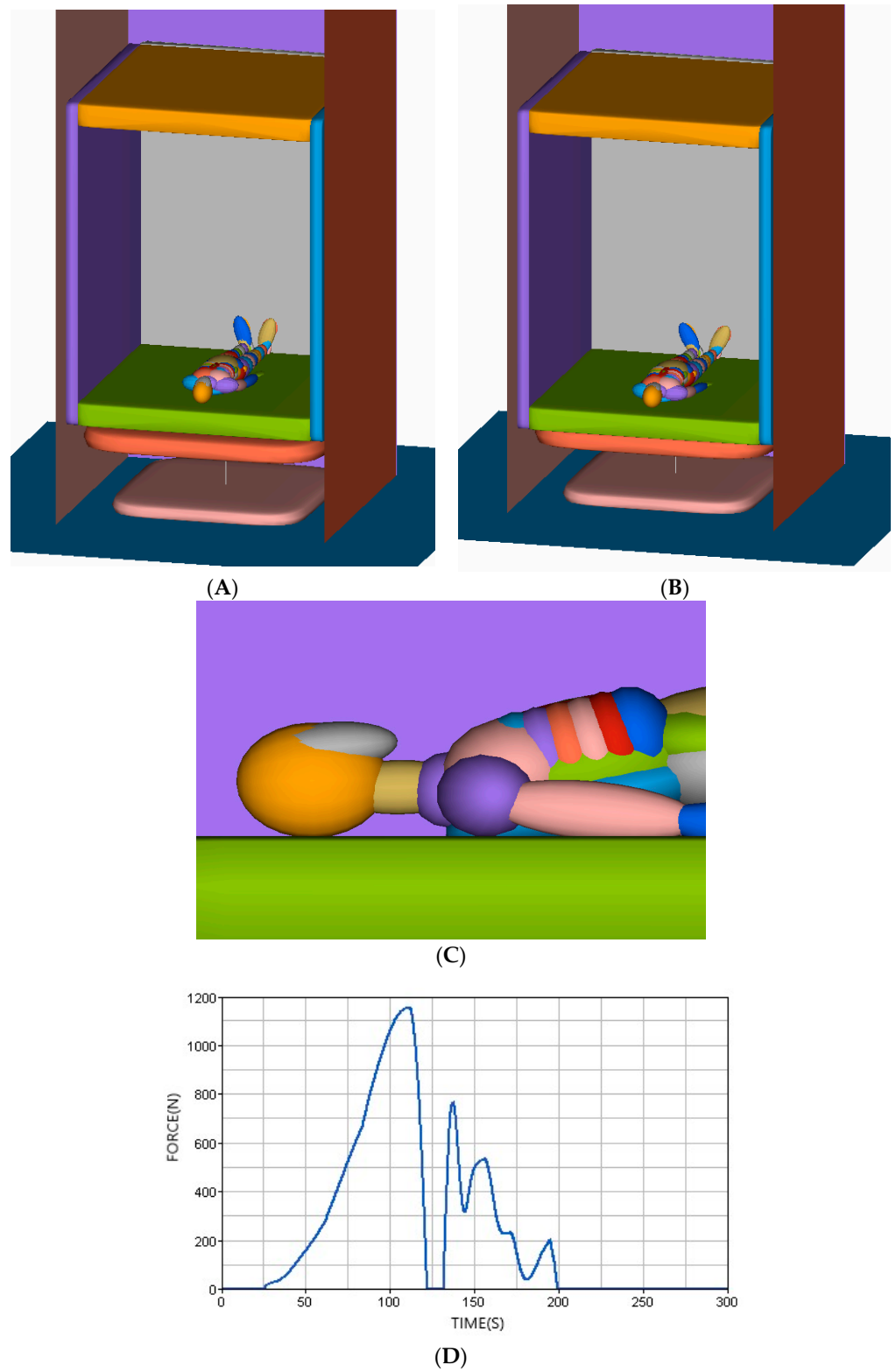


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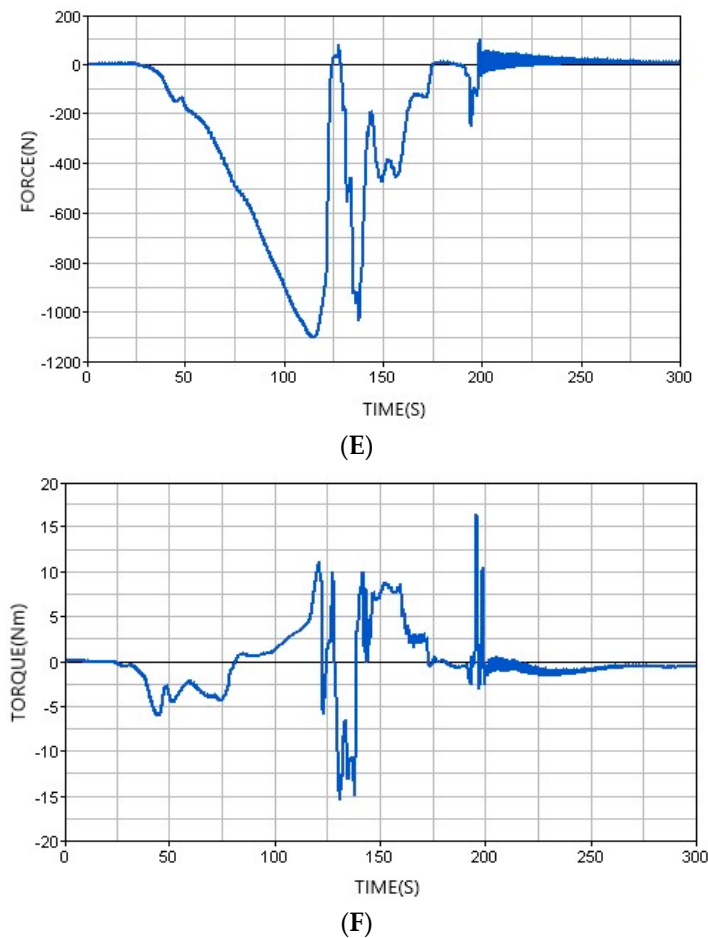


Figure 6. The result of the body injury analysis in case of 3. (A) The condition of case 3 (before the impact of the shock absorber). (B) The condition of case 3 (after the impact of the shock absorber). (C) Major Injury part and Injury types (neck). (D) The graph of momentum for human body ($F - \Delta t$). (E) The graph of force value at major injury part. (F) The graph of torque value at major injury part.

3.3. NICs during Safety Device Operation

Although the human injury standard table suggests injury standards for six parts of the human body, the cervical spine is critical for human activity; therefore, it is necessary to determine the degree of human injury from the perspective of neck injury. Kaneko et al. (2004) calculated the NIC in a collision using Equations (1) and (2) [14–17].

$$NIC = 0.2 \times a_{rel}(t) + (v_{rel}(t))^2 \quad (1)$$

$$a_{rel}(t) = a^{T1} - a^{Head}, v_{rel}(t) = v^{T1} - v^{Head} \quad (2)$$

where a^{T1} is the acceleration–time curve measured in the anterior posterior (x) direction at the level of the first thoracic vertebra in units of g. Likewise, a^{Head} is the acceleration–time curve measured in the anterior to posterior (x) direction at the location of the center of gravity of the head in units of g. The integration of the acceleration (converted to m/s^2) of the head center of gravity in the time domain, giving the velocity in the x-direction (resulting in units of m/s), is expressed by v^{T1} . The integration of the acceleration (converted to m/s^2) at the level of the first thoracic vertebra in the time domain, giving the velocity in the x-direction (resulting in units of m/s), is expressed by v^{Head} [18].

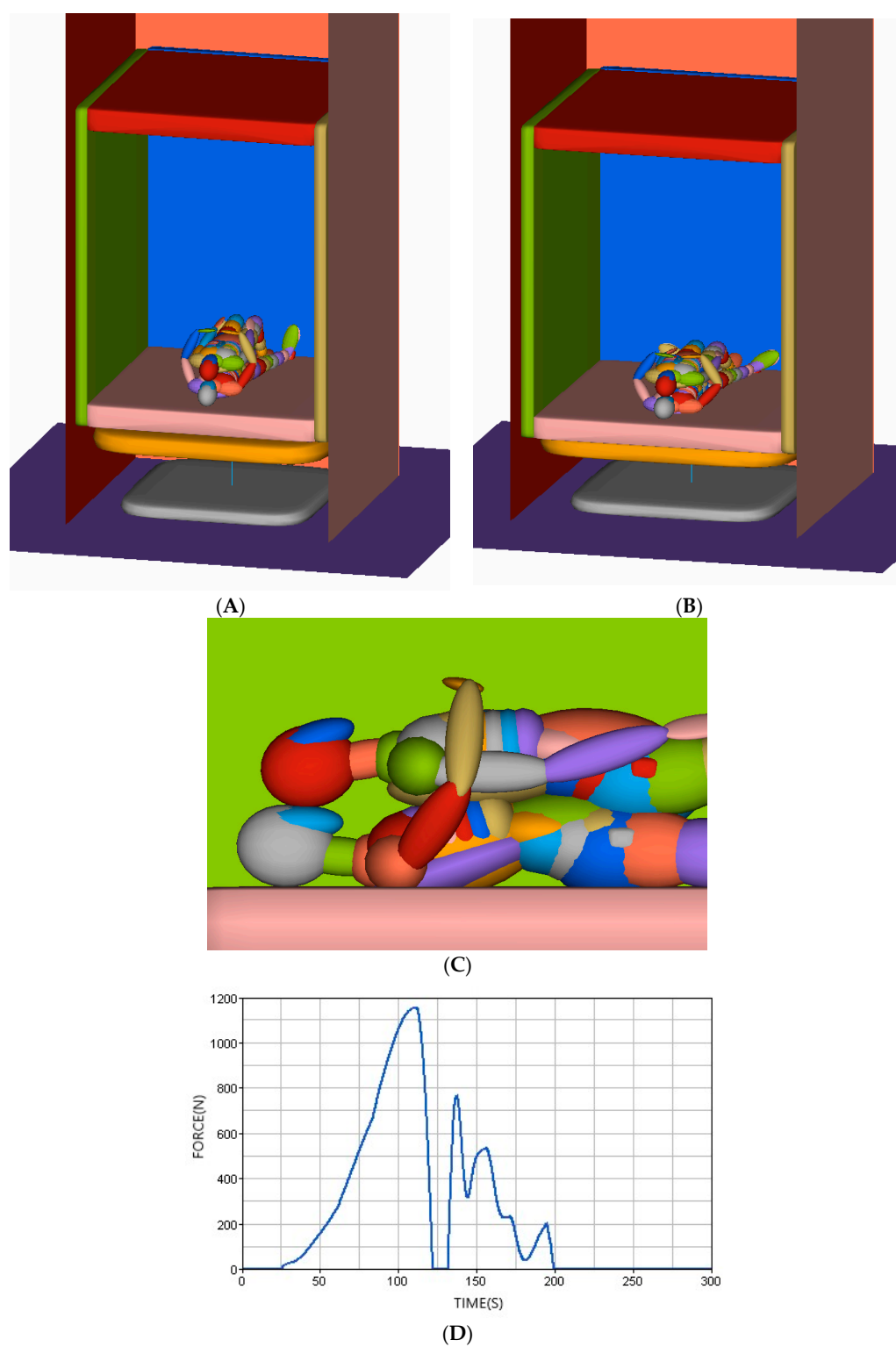


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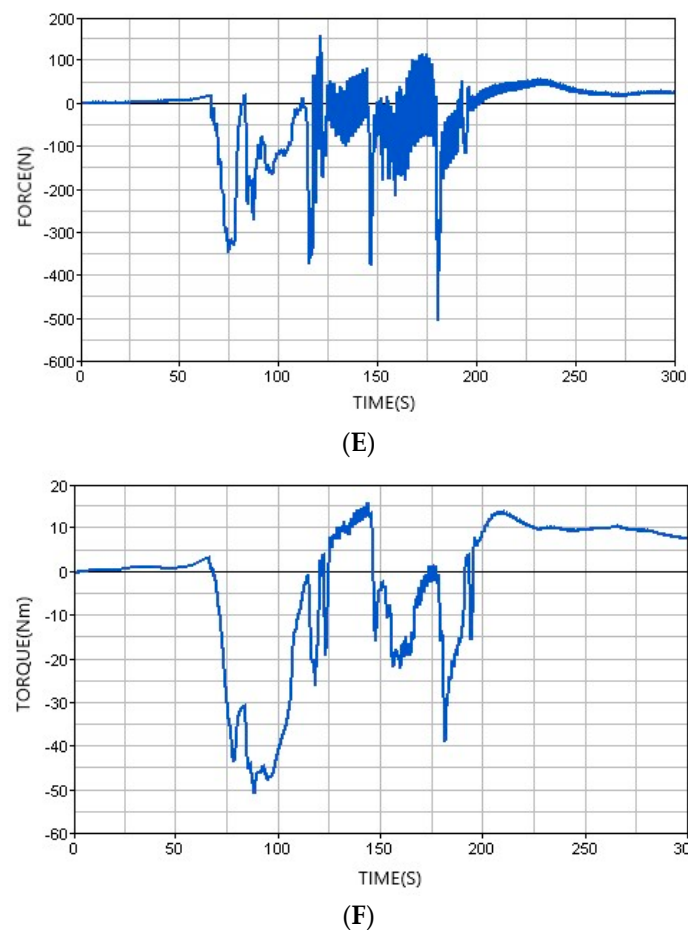


Figure 7. The result of the body injury analysis in case of 4. **(A)** The condition of case 4 (before the impact of the shock absorber). **(B)** The condition of case 4 (after the impact of the shock absorber). **(C)** Major Injury part and Injury types (neck). **(D)** The graph of momentum for human body ($F - \Delta t$). **(E)** The graph of force value at major injury part. **(F)** The graph of torque value at major injury part.

The authors referred to NIC as the square of the difference in velocity and acceleration between the head and torso, reporting that neck fracture would result when the NIC value > 15 [9]. In the current study, to compare and analyze the degree of cervical spine injury according to the occupant's posture when the governor safety device was activated (1.4 m/s constant velocity motion), NIC values were derived by assuming that one individual was lying down (case 1), two individuals were lying down with constraint (case 2), and two individuals were lying down without constraint (case 3), as shown in Table 5 and Figure 9. As shown in Figure 10, changes in NIC values according to time for each case were compared and analyzed based on the AIS; cervical spine injuries, such as skin, muscle, abrasions, contusion (hematoma), and minor lacerations, were found to occur. Based on the findings, the overall degree of cervical spine injury would be low because of relatively low collision speeds in both cases, i.e., when a single individual and two individuals were lying down. In the case of two individuals lying down, it was confirmed that the cushioning effect of the individual lying at the bottom was advantageous for reducing injuries. Moreover, inadequate mutual restraint was more likely to result in cervical injury than adequate restraint, owing to relative movement.

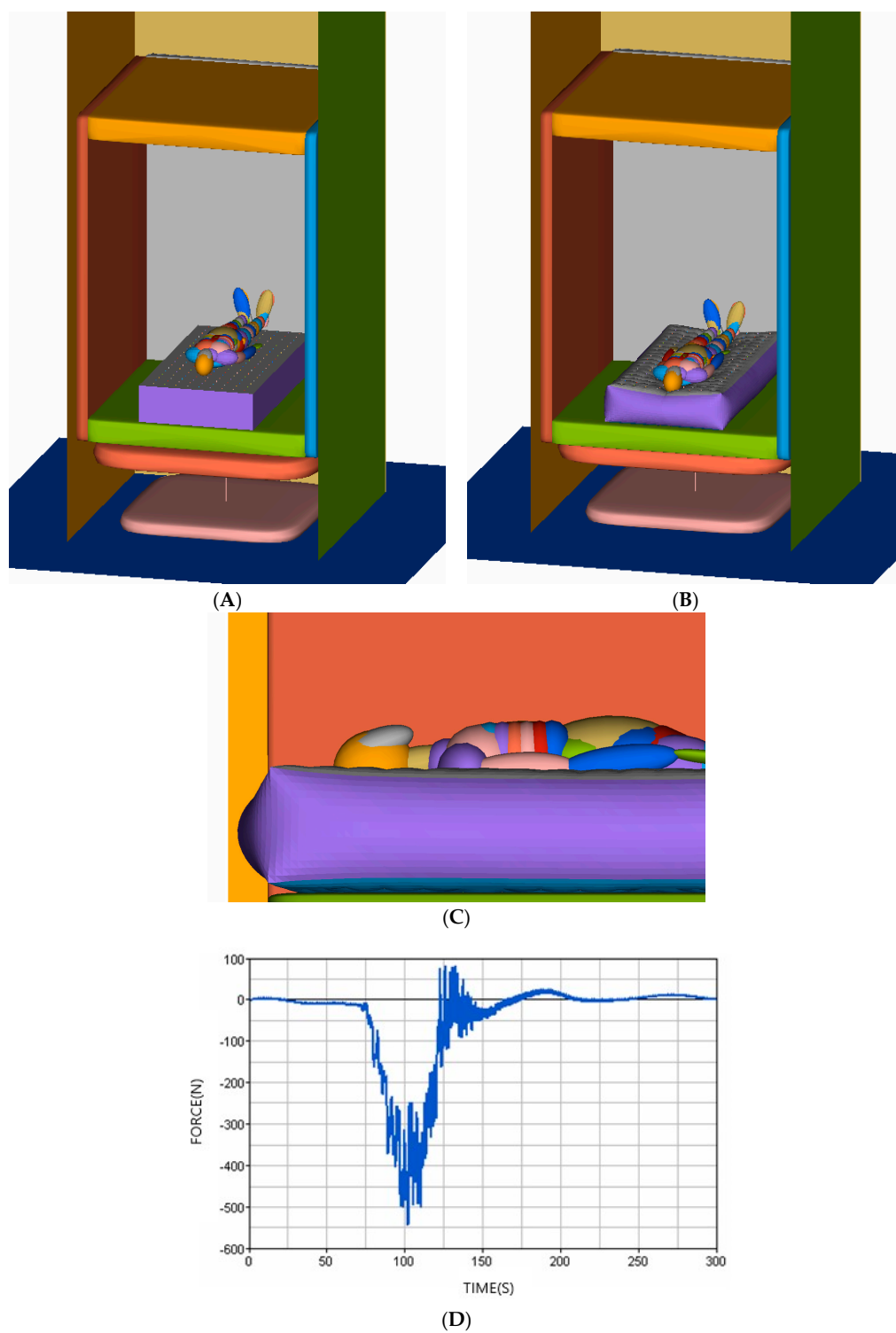
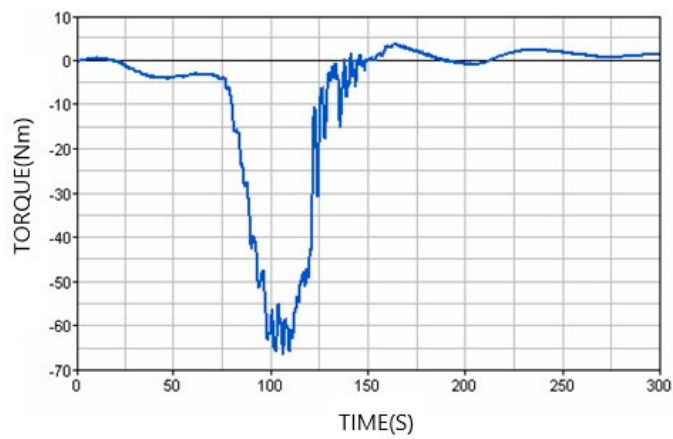
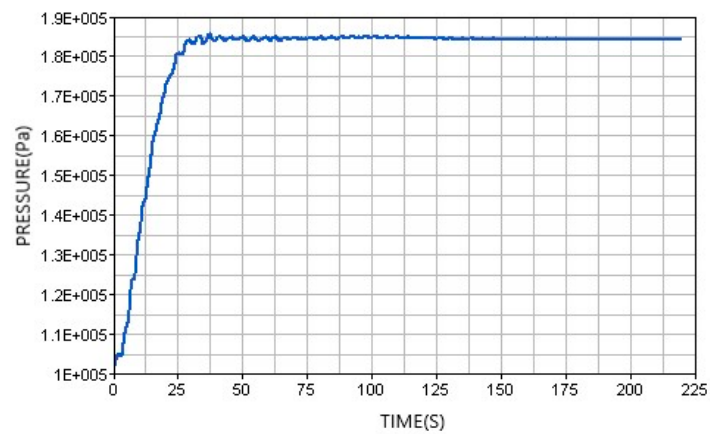


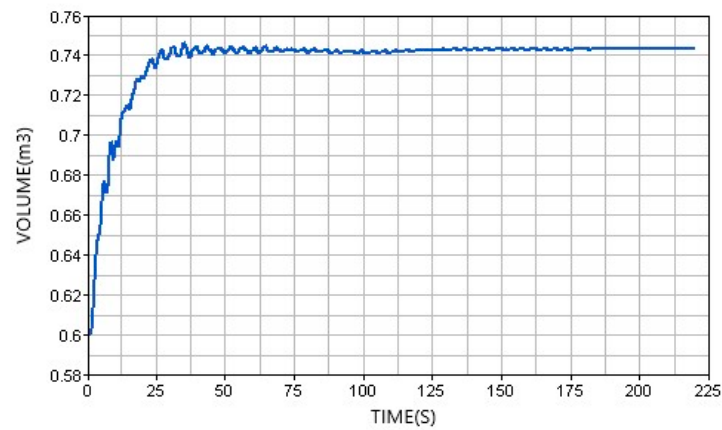
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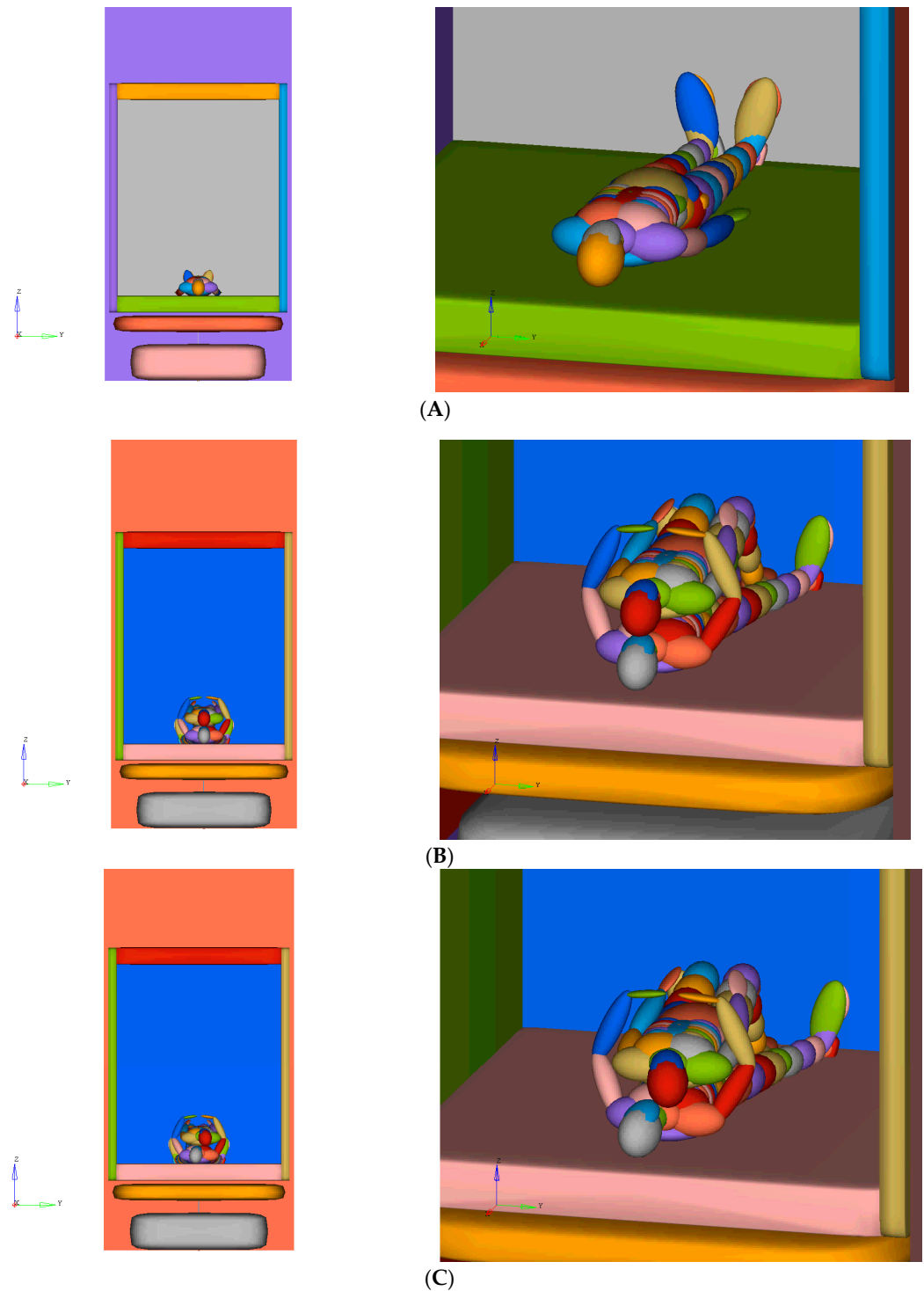


(G)

Figure 8. The result of the body injury analysis in case of 5. (A) The condition of case 5 (before the impact of the shock absorber). (B) The condition of case 5 (after the impact of the shock absorber). (C) The type of Impact motion with air mat (neck). (D) The graph of force value at major injury part. (E) The graph of torque value at major injury part. (F) The pressure change in the air mat. (G) The volume change in the air mat.

Table 5. The condition of case according to the passenger's posture.

Case No.	Case 1	Case 2	Case 3
Condition	Single individual lying down	Two individuals lying down with constraint	Two individuals lying down without constraint

**Figure 9.** The NIC values analysis according to case. (A) The condition of case 1. (B) The condition of case 2 (with constraint). (C) The condition of case 3 (without constraint).

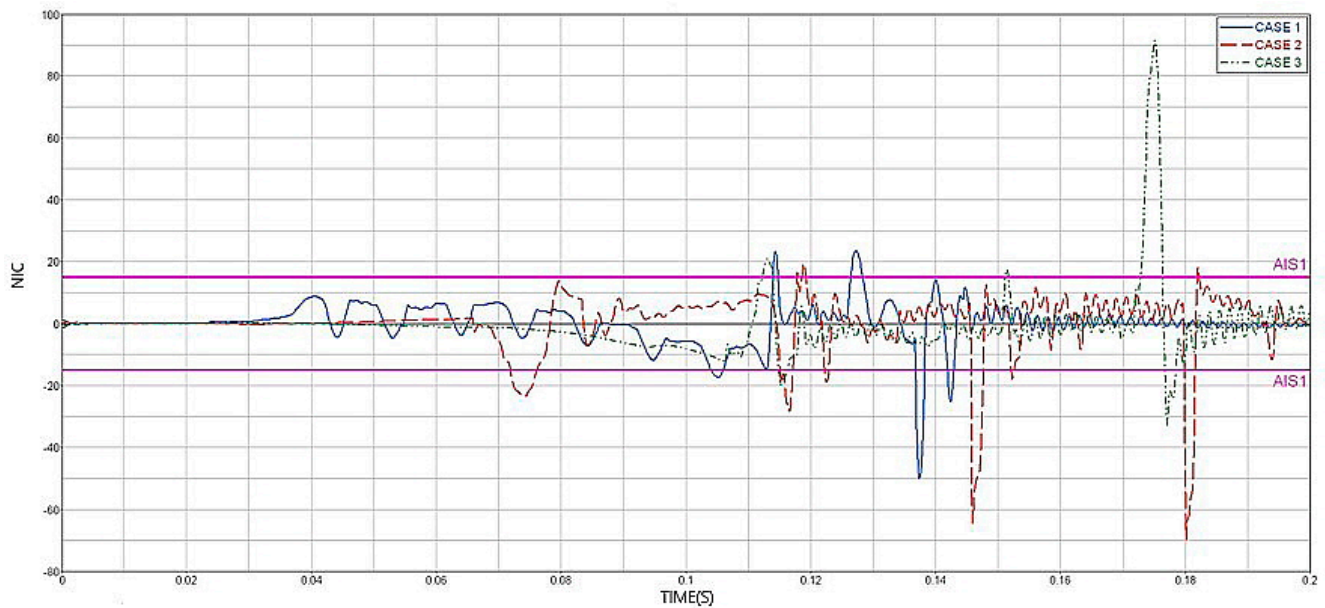


Figure 10. The change graph of NIC values based on AIS1.

4. Conclusions

In this study, through human injury analysis, safety device operations, such as speed governor and buffer when breaking elevator wire rope, occupant's behavior, and air mat usage, were used to derive force and torque values for the injured part, and then determine the amount of impact and degree of injury to the human body. By analyzing the buffering effect of impact, the following conclusions were reached. Subsequently, we determined the amount of impulse and degree of injury to the human body. By analyzing the buffering effect of the impact, we reached the following conclusions:

- (1) On cutting the elevator rope (free fall), the analysis revealed that all human body parts and joints ruptured after falling at 14 m/s from the 5th floor to the lowest floor, confirming that comparing the amount of impact and degree of injury according to the method was insignificant.
- (2) Activating the speed governor safety device (1.4 m/s uniform motion) was associated with a high possibility of fracture in the ankle area in both standing cases, i.e., standing with one or two individuals, respectively.
- (3) Activating the speed governor safety device (1.4 m/s uniform motion) was associated with a high possibility of fracture in the neck joint area in the scenario where a single individual was lying down. However, when two individuals were lying down, there was a high possibility that a neck joint fracture would not occur owing to the buffering action of the lower body.
- (4) If the governor safety device was operational (1.4 m/s constant velocity motion), the air mat afforded a buffering effect to a single individual lying down, similar to that observed when two individuals were lying down.
- (5) In the case of an elevator fall when the governor safety device is operational, the posture of an individual lying on the lower part of the individual to be protected affords a greater buffering effect than the standing position; the use of an air mat would yield a similar buffering effect.
- (6) In the case of a single individual lying down when the speed governor safety device is operational (1.4 m/s uniform motion), the overall degree of cervical spine injury would be low. In addition, inadequate mutual restraints were more likely to cause cervical spine injury than instances of perfect mutual restraint.

Although the standing person breaks his/her ankles first, and it would then be expected that the secondary impact of the body on the floor would be accompanied with

injury risk to other parts, injury evaluation through the program can obtain a meaningful value only for the primary impact behavior, and since the secondary impact behavior cannot be calculated, there is a limit to human injury research through the program. Human injury evaluation using real people is very dangerous and almost impossible, so evaluation and development using analysis are being conducted in most of these areas. In the case of vehicles, since the experimental methods and regulations are standardized, a specially manufactured manikin equipped with various sensors instead of the human body and actual evaluation are being conducted, but in the case of elevators, it is difficult to find research related to this. This study, focusing on this point, can be said to be unique in terms of academic rigor and originality in the study of human injury evaluation in the case of an elevator fall. Since there have been few studies on human injury evaluation in the event of an elevator fall, I believe that the results of this study can be applied to future elevator airbag concepts, and it is expected that it can be used as the basis for various fields such as security aspects and safe work methods.

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