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ANALYSIS AND EVALUATION OF THE EURO-NCAP UPPER LEGFORM TO WAD 775 MM TEST

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ABSTRACT−Recently, governments around the world are seeking to reduce pedestrian mortality by strengthening pedestrian safety regulations such as Euro-NCAP (European New Car Assessment Program). In 2015, the Euro-NCAP revised the upper leg assessment for the upper legform to WAD (Wrap Around Distance) 775 mm test. The methods and procedures of the revised upper legform to WAD 775 mm test are analyzed and evaluated. Experimental tests are carried out to comprehend the test procedures, and the aspects to be supplemented are observed. A car-to-human model simulation, which reproduces the pedestrian accident, is performed, and the data on the thigh and femur are computed. It is assumed that the car-to-human simulation can represent a real accident. Comparison is conducted between the results of the Euro-NCAP test and the car-to-human simulation, and the problems of the Euro-NCAP test are identified. The car-to-upper legform simulation is carried out to improve the costly repeated Euro-NCAP tests. Also, it is shown that the newly proposed car-to-upper legform simulation can be used to follow the path of the car-to-human model simulation. The upper legform to WAD 775 mm test is discussed based on the results of the experimental tests and the simulations.

KEY WORDS : Pedestrian protection, Upper legform, Human model

1. INTRODUCTION

As the mortality rate of pedestrian accidents increases, governments around the world perceive the need to protect pedestrians. They added pedestrian safety protocols to the new car assessment and steadily strengthened it. In 2008, the UN Global Technical Regulations (GTR) for the protection of pedestrians have established GTR No. 9 for pedestrian safety, and major countries are obliged to comply with GTR No. 9. Therefore, various studies have been carried out to improve pedestrian safety (Chang, 2008; Schuster, 2001).

An upper legform model has been made to evaluate the injury of the human upper leg in an accident, and it is utilized in an experimental crash test (Teng and Nguyen, 2008). Euro-NCAP (European New Car Assessment Program) and ANCAP (Australasian New Car Assessment Program) are car safety performance assessment programs, and employ upper leg assessment for pedestrian safety (ANCAP, 2018; EuroNCAP, 2016). Upper leg assessment of Euro-NCAP was performed based on the pedestrian testing protocol version 7.1.1 until 2014 by impacting the upper legform to the bonnet leading edge. In this test, the conditions are determined according to only the geometrical dimensions of the front bumper (EuroNCAP, 2013). From 2015, the upper legform to WAD (wrap around distance) 775 mm test was used for the pedestrian testing protocol version 8.0 (EuroNCAP, 2014). In this test, the internal structure of the bumper also affects the determination of the test conditions. The test is still valid in the current version 8.3 (EuroNCAP, 2016; EuroNCAP, 2013; EuroNCAP, 2014; EuroNCAP, 2015b).

There are some studies on the test conditions such as the impact angle and velocity of the upper legform to bonnet leading edge test. The upper legform to bonnet leading edge test is a Euro-NCAP test where an upper legform is impacted to the bonnet leading edge (Konosu *et al.*, 1998; Okamoto *et al.*, 2001; Lawrence, 2005). The test can be conducted by simulation or actual experiments. Lubbe *et al.* (2011) conducted a study on the relationship between the upper legform to bonnet leading edge test and real-life injury of the femur by using a human model called THUMS. The EEVC (European Enhanced Vehicle Safety Committee) working group 17 report shows that there is a limit to express the sliding effect in the upper legform to bonnet leading edge test (European Enhanced Vehicle-safety Committee, 1998; Teng and Nguyen, 2010). Pedestrian leg injuries are studied by human model simulation for an accident, and the influence of the pedestrian position to leg injuries is investigated (Baviskar *et al.*, 2014; Funk *et al.*, 2004, Moon *et al.*, 2012, Liers and

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Hannawald, 2009). Baviskar *et al*. (2014) studied the femur injuries of the human model, upper leg impactor and FlexPLI. Funk *et al.* (2004) studied the structural tolerance and material properties of the human femur in dynamic bending. Moon *et al.* (2012) conducted a design of a crumple zone that reduces the bending moment in the upper legform. A study shows the effect of pedestrian safety assessment of Euro-NCAP on pedestrian protection in real life (Liers and Hannawald, 2009).

Although there are many studies related to the upper legform test, they are the ones before the revision of the upper legform to bonnet leading edge test. After the revision, the structure inside the bumper is taken into account, whereas only the outer shape of the front part of the vehicle is considered in the original test. The results after the revision are rarely reported. It is desirable to enhance pedestrian protection by strengthening various pedestrian protection assessments such as the upper leg assessment. However, much controversy exists regarding whether it can exactly represent the injury of a pedestrian in a pedestrian accident. The upper legform to WAD 775 mm test is a test for pedestrian safety evaluation. The purpose of this article is to analyze and evaluate the validity of the upper legform to WAD 775 mm test in Euro-NCAP.

The purpose of this study is that the procedure and regulations of the upper legform to WAD 775 mm test are analyzed for a passenger sedan and a sport utility vehicle (SUV). Experimental tests of Euro-NCAP are performed first. And a pedestrian accident is simulated using a human model to evaluate the pedestrian injury and the test conditions. The results of the two cases are precisely compared. The advantages and drawbacks of the Euro-NCAP test are mentioned and the improvement of the test is specified. Generally, the experimental tests should be repeatedly performed to find the average values of the responses, and it is extremely costly. A simulation model with an upper legform is developed to save the cost. It is shown that the repeated tests can be simulated by perturbation of some parameters in the upper legform. Also, a new simulation procedure is defined to match the results of the human model simulation.

2. EURO-NCAP UPPER LEGFORM TO WAD 775 MM TEST

2.1. Process of the Euro-NCAP Upper Legform to WAD 775 mm Test

The Euro-NCAP upper legform to WAD 775 mm test is an upper leg assessment test that has been used since 2015. Experimental tests are carried out based on the regulations using a passenger sedan and an SUV. The test location (impact point) should be selected and marked on the vehicle for testing. The test area is an area within less than 50 mm of the left and right corner reference points. The corner reference point is the intersection of the bonnet leading edge reference line and the bonnet side reference line. As illustrated in Figure 1, the bonnet leading edge reference line is formed by a point where the front side of the bonnet meets a straight line at an angle of 50° from the normal line on the ground. The bonnet side reference line is a point at which a straight line forms as illustrated in Figure 2 (EuroNCAP, 2014).

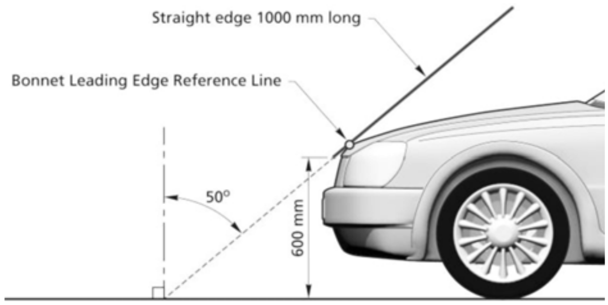


Figure 1. The determination of the bonnet leading edge reference line.

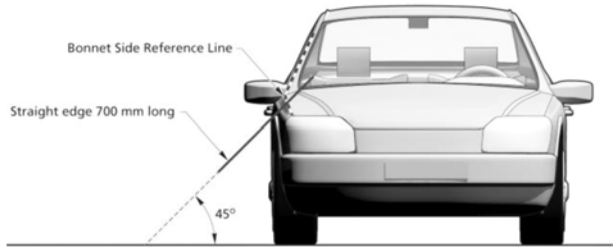


Figure 2. The determination of the bonnet side reference line.

The test location is the point presented in Figure 3. The wrap around distance is measured from the ground along with outer structure of the vehicle to the pedestrian contact point. The test angle is illustrated in Figure 3. The internal bumper reference line (IBRL) is depicted in Figure 4. There is an impact beam (back beam) behind the bumper and the top points of the beam make the IBRL. A straight

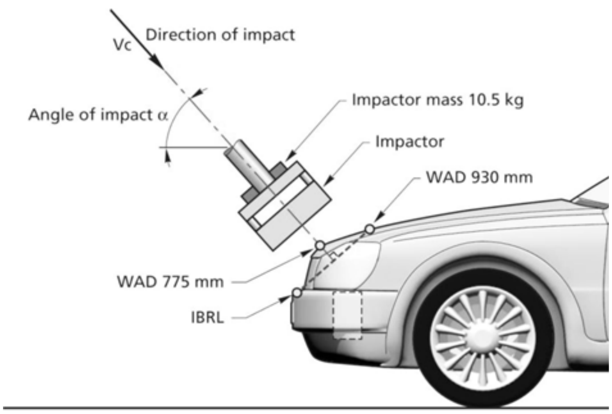


Figure 3. The upper legform to WAD 775 mm test.

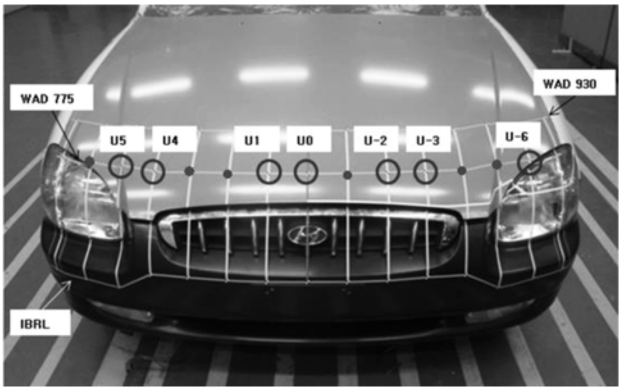


Figure 4. The location of the impact points (sedan).

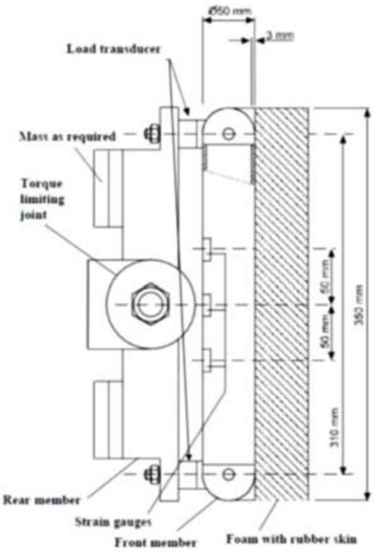


Figure 5. TRL upper legform.

line is defined between a point of the IBRL and the WAD 930 mm, and the direction of the impact line is perpendicular to the straight line. The testing velocity is calculated from the nominal energy of the impactor as follows:

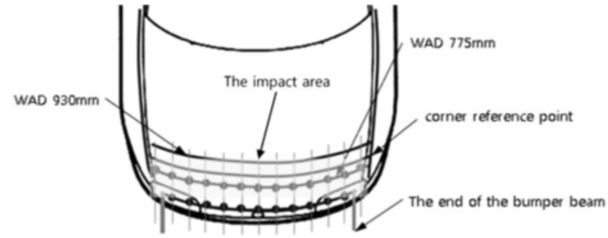


Figure 6. An example of the marked vehicle.

$$\begin{aligned} E_{\mathrm{n}} &= 0.5 m_{\mathrm{n}} v_{\mathrm{c}}^{2} \\ m_{\mathrm{n}} &= 7.4 \text{ kg} \\ v_{\mathrm{c}} &= v_0 \cos(1.2\alpha) \\ v_0 &= 11.11 \text{ m/s} \\ v_{\mathrm{t}} &= \sqrt{\frac{2E_{\mathrm{n}}}{10.5 \text{ kg}}} \end{aligned} \tag{1}$$

where E_{n} is the nominal energy of the impactor and α is the coefficient for the angle of impact considering various vehicle geometries. v_{c} is the nominal velocity, m_{n} and v_0 are the constants and v_{t} is the test velocity.

As illustrated in Figure 5, the upper legform of the Transport Research Laboratory (TRL) is employed (Carroll *et al*., 2014). The mass of the original upper legform is 7.4 kg, and the mass of the upper legform is increased to 10.5 kg due to additional parts. The upper legform is impacted to the bonnet with the velocity in Eq. (1) as illustrated in Figure 3. The force and moment are measured in two load transducers and three strain gauges of the upper legform. The force is the sum of the forces measured in the two load transducers, and the moment is the maximum moment evaluated from the three strain gauges.

2.2. Results of the Euro-NCAP Upper Legform to WAD 775 mm Test

The upper legform to WAD 775 mm test described in Section 2.1 is performed on a passenger sedan and an SUV, and then the injury values are calculated. In the Euro-

Table 1. The results of the upper legform to WAD 775 mm test (sedan).

	U5	U4	U1	U0	U-2	U-3	U-6
Sum of forces (kN)	2.89	3.17	2.99	2.79	3.12	3.09	3.28
Bending moment (N-m)	179.78	157.79	206.36	172.78	194.20	174.41	213.33

Table 2. The results of the upper legform to WAD 775 mm test (SUV).

	U6	U3	U1	U0	U-2	U-4	U-5
Sum of forces (kN)	3.97	4.11	3.05	4.15	3.03	5.13	5.06
Bending moment (N-m)	269.44	201.72	147.14	139.90	161.24	239.97	363.32

NCAP, the vehicle is evaluated based on the sum of the forces and maximum bending moment (EuroNCAP, 2015a). The calculated values represent the force and moment that the femur receives during an accident. As presented in Figure 4, the test is carried out for seven impact points assuming vehicle symmetry.

Table 1 shows the results of the test for a sedan. In this research, kN and mm units are employed to match the unit system used in Euro-NCAP. Since the unit of the moment is N-m and the unit of the force is kN, the value of the moment is greater than the value of the sum of forces. The maximum injury value occurs at the test location U-6 near the headlight. The results of the SUV case are listed in Table 2. The highest injury value of the SUV case also occurs at the point adjacent to the headlight. In both cases, the maximum injury is found at the point where the secondary impact with the headlight occurs immediately. Moreover, the injury value is affected by the test angle and speed depending on the vehicle shape and the internal structure of the bumper.

The hood height of the SUV is higher than that of the sedan. When the hood height is raised, the WAD 930mm line moves forward. Then the impact angle is reduced and the impact velocity and impact energy are increased. In this experiment, the average load at all the impact points for the SUV case is higher than that of the sedan case by 33.6 %, and the average moment is 17.3 % higher.

As illustrated in Figure 6, if the end of the bumper beam is located inside the impact area, the angle cannot be determined because the internal bumper reference line cannot be set. Thus, the regulation should define the angle of this case. One suggestion is that the angle should be defined by an extrapolation method.

Figure 7. The finite element model of a sedan.

Figure 8. The finite element model of an SUV.

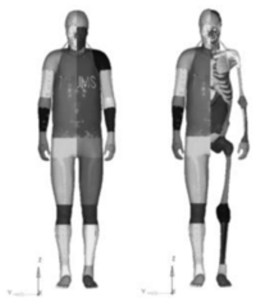


Figure 9. The finite element model of THUMS (Total Human Model for Safety).

3. CAR-TO-HUMAN MODEL SIMULATION

3.1. The Finite Element Model and the Conditions of the Simulation Ubheading

Car-to-human model simulation is conducted to reenact actual car-to-pedestrian accidents. The purpose of the simulation is to observe the speed and load of the upper leg of a pedestrian during a collision process. The simulation is performed for the passenger sedan and SUV that are the same as the ones for Euro-NCAP test in the previous section. LS-DYNA, which is a nonlinear dynamic finite element analysis program, is chosen for the simulation (Hallquist, 2007) and a commercial system named Hypermesh is utilized for FE modeling (HyperWorks, 2009).

The finite element model of a sedan is presented in Figure 7. The model has 108,213 nodes and 108,231 finite elements. The finite element model of the SUV is illustrated in Figure 8. The model has 226,697 nodes and 221,824 finite elements. In both vehicle models, the average size of the mesh is 5 mm. Only the frontal structures are modeled in detail for both models. A mass element is also added at the rear part of each model. Boundary conditions are set at the rear parts for both cases.

The pedestrian model is the Total Human Model for Safety (THUMS) AM50 Pedestrian Model Academic Version 4.02 developed by Toyota as illustrated in Figure 9 (Toyota Motors Corporation, 2015). THUMS has 1,975,422 finite elements, and the bones, joints, tissues, and organs are modeled. THUMS can simulate organ injuries inside the human body at the tissue level. THUMS AM50 used in the simulation represents an average male adult, 173 cm tall and 77.3 kg weight. THUMS has two models such as an occupant model in the vehicle and a pedestrian model. In this study, the pedestrian model is utilized to simulate car-to-pedestrian accidents.

The impact velocity of the car-to-human model collision is set by 40 km/h (11.11 m/s) according to the pedestrian safety evaluation criteria of Euro-NCAP (EuroNCAP, 2014). The positioning of the human model is set as Gait-40 % as presented in Figure 10. The left leg is forward and

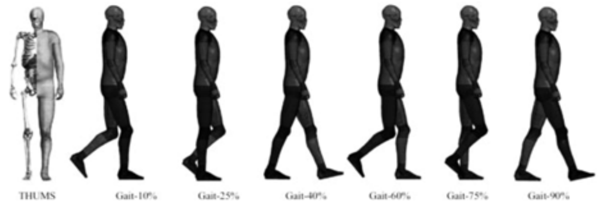


Figure 10. The gait-40 % stance of THUMS.

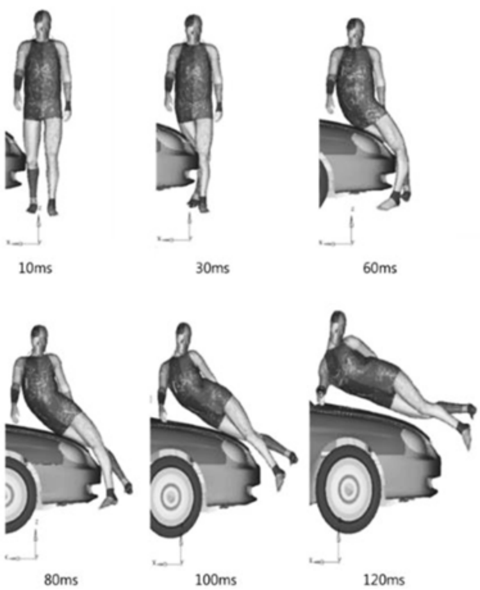


Figure 11. Car-to-human model simulation (sedan).

the right leg collides with the car (Li *et al*., 2015).

3.2. The Results of the Car-to-human Model Simulation

The car-to-human model simulation is carried out up to the full contact of the vehicle and the head. Figures 11 and 12

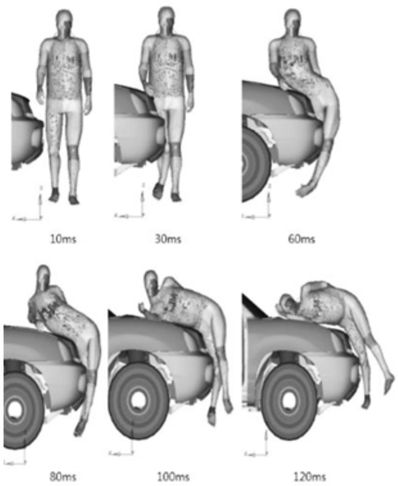


Figure 12. Car-to-human model simulation (SUV).

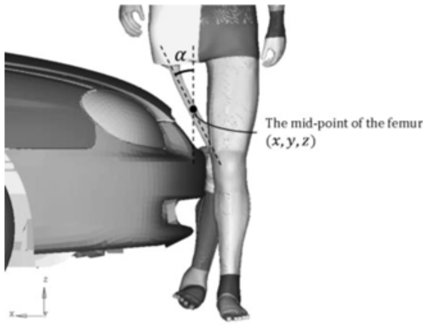
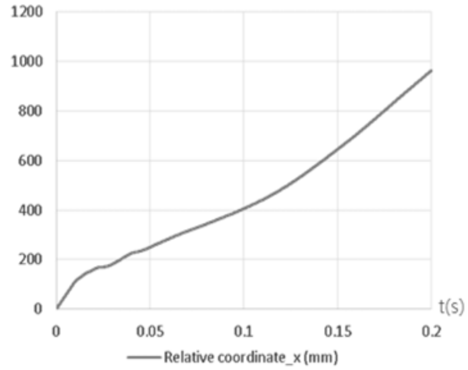
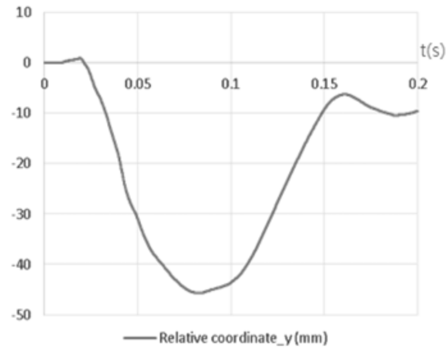


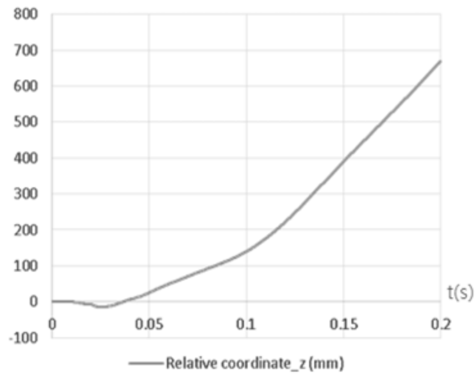
Figure 13. Schematic for trajectory calculation.



(a) Relative x-coordinate (mm)

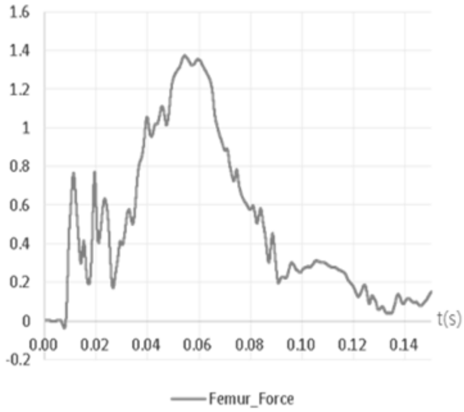


(b) Relative y-coordinate (mm)

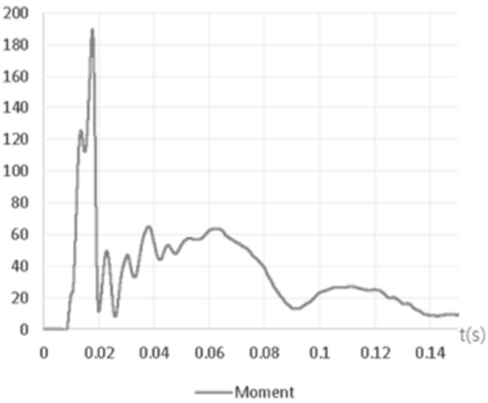


(c) Relative z-coordinate z (mm)

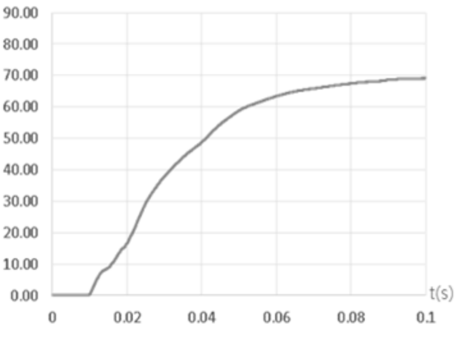
Figure 14. The relative coordinates of the middle point of the femur (sedan).



(a) Femur force (kN)



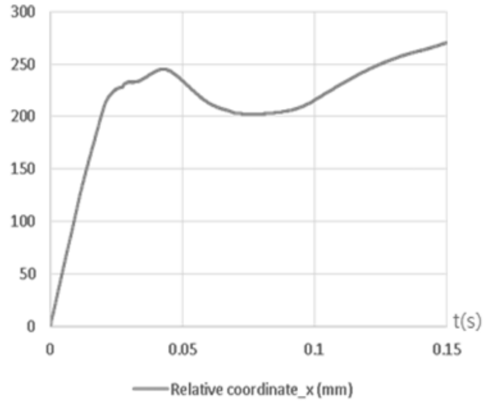
(b) Moment (N-m)



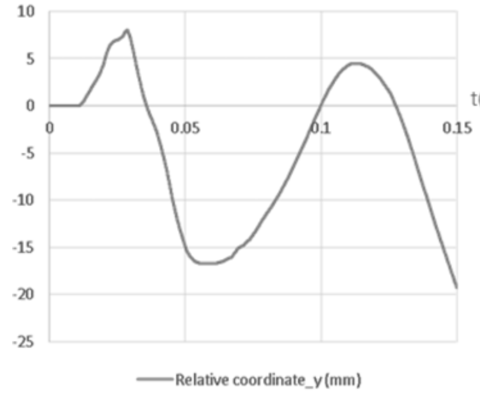
(c) Alpha (◦)

Figure 15. The responses of the human model (sedan).

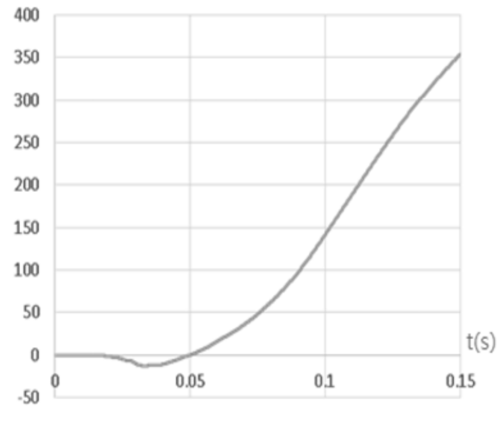
present the car-to-human model simulations for the passenger sedan and SUV, respectively. The trajectory is investigated for the mid-point of the femur in Figure 13. Figures 14 ~ 17 present various responses of the human models such as the angle α in Figure 13, the femur loads, moments, etc. The femur load is defined as the load that occurs between the femur and tissue during the collision, and the femur moment is defined as the moment at a cross-section of the femur. Figures 14 and 16 show the trajectory of the femur midpoint in the case of the sedan and SUV,



(a) Relative x-coordinate (mm)



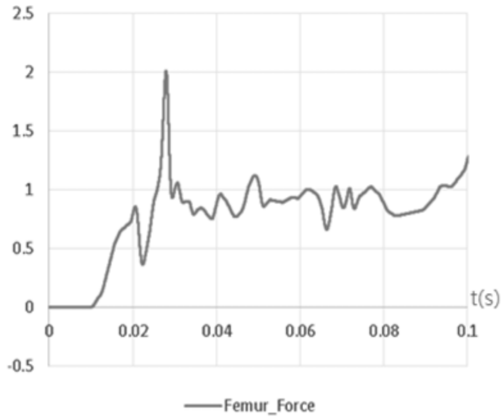
(b) Relative y-coordinate (mm)



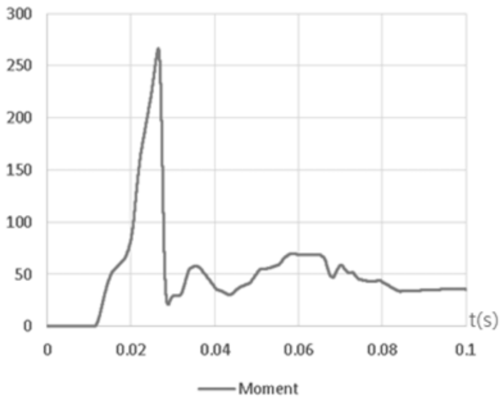
(c) Relative z-coordinate (mm)

Figure 16. The relative coordinates of the middle point of the femur (SUV).

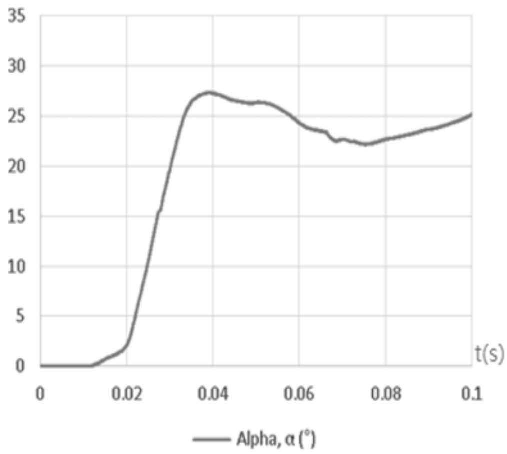
respectively. Figures 15 and 17 present the femur loads, moments and angle α in Figure 13 in the case of the sedan and SUV, respectively. When the upper leg gets the maximum femur load or the maximum moment in Figures 15 and 17, the angles are compared with the test angles of



(a) Femur force (kN)



(b) Moment (N-m)



(c) Alpha (°)

Figure 17. The responses of the human model (SUV).

the upper legform to WAD 775 mm test.

Table 3 shows the results of the car-to-human model simulation. In the case of the sedan-to-human model simulation, the maximum femur load is 1.373 kN at 0.05442 s, and the angle of the femur is 61.13°. The maximum value is 50.73 % lower than that of the Euro-NCAP test in Section 2. The bending moment has a maximum value of 189.763 N-m at 0.01770 s with an angle of 13.19°. The maximum moment is 10.89 % higher than that of the Euro-NCAP test. It is noted that the angle is fixed by 47.8° in the Euro-NCAP test. Comparison is also performed for the SUV-to-human model simulation in the same manner. The maximum femur load is 2.041 kN at 0.02797 s, and the angle of the femur is 15.9°. The maximum value is 50.86 % lower than that of the Euro-NCAP test. The bending moment has a maximum value of 266.7 N-m at 0.02655 s with an angle of 11.4°. The maximum moment is 99.31 % higher than that of the Euro-NCAP test. The angle is fixed by 24.4° in the Euro-NCAP test.

Table 3. The results of the car-to-human model simulation.

	The maximum load			The maximum moment		
	Value (kN)	Time (s)	Angle (°)	Value (N-m)	Time (s)	Angle (°)
Sedan	1.373	0.05442	61.13	189.763	0.01770	13.19
SUV	2.041	0.02797	15.9	266.7	0.02655	11.4

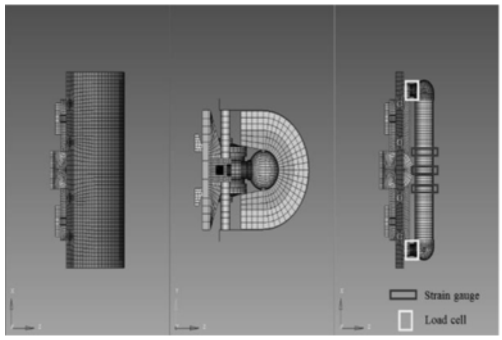


Figure 18. The finite model of LSTC pedestrian upper legform.

The difference in the time points for the maximum load and moment is larger in the sedan case. In the sedan case, the maximum moment occurs first and the load is maximum after 0.03672 s. This is because the bumper height of the sedan is lower, and the knee hits the bumper first and the femur hits the hood second. The maximum moment occurs in the middle of the first and second impacts and the maximum load occurs during the second impact. On the other hand, if the bumper height is higher, the femur hits the bumper first, and the body hits the hood second. Thus, the maximum load and moment occur quite closely.

The femur loads and moments of the two tests are quite different in both cases of the sedan and SUV. There could be two reasons for these results. The first one is that the structures and materials are different for the impactor and human model. Skin and structure cover around the femur in a human model. However, foam material covers the member, which represents the femur, only for 180° in the impactor. The material of the femur in the impactor is steel while the femur material of the human model is quite different from the impactor. For this reason, there is a study to derive the threshold value of the upper leg impactor (Lubbe *et al.*, 2011), but it is based on the pre-revision protocol and there is no study based on the current test method.

The second reason is the limitation of the Euro-NCAP test. In the Euro-NCAP test, the impactor moves along a straight line. However, the trajectory of the femur is a curve in the car-to-human model simulation as illustrated in Figures 14 and 16. Therefore, the current Euro-NCAP test cannot consider the sliding phenomenon during contact nor the trajectory of the femur. At this moment, we can think of the Euro-NCAP test for the headform (EuroNCAP, 2016). In the test, the headform hits the hood as the upper legform hits the hood in the Euro-NCAP upper legform to WAD 775 mm test. In the case of the headform, the headform hits the hood after the human body slides along the hood. That is, the headform does not slide on the hood and hits the hood in a movement along a straight line. However, as investigated above, the upper leg slides on the hood and hits the hood simultaneously. In the next section, a new test method is proposed by the simulation of the impactor to accommodate the trajectory of the upper leg.

4. CAR-TO-UPPER LEGFORM MODEL SIMULATION

4.1. The Finite Element Model and the Condition of the Simulation

The Euro-NCAP test is simulated by finite element analysis. The vehicle model used the same finite element models for the sedan and SUV used in the car-to-human model simulation. The utilized finite element model of the upper legform is LSTC (Livermore Software Technology Corporation) Pedestrian Upper Legform v2.3.2 (Morten *et al.*, 2014). The model has 20,151 nodes and 34,038 finite elements. The simulation conditions are (1) the ones of the upper legform to WAD 775 mm test for the Euro-NCAP Pedestrian Testing Protocol version 8.0 in Figure 3 (EuroNCAP, 2014). (2) The upper legform in Figure 18 follows the trajectory of the upper leg of the human model illustrated in Figure 13. The simulation is conducted for the passenger sedan and SUV models in the previous sections.

An FE model is made for the experiment in Figure 3. The model is tuned to have the same responses as the ones of the upper legform to WAD 775 mm test. The purpose of this simulation is twofold. First, repeated experiments are required in the upper legform to WAD 775 mm test. When a hood is plastically deformed in a test, a new one should be used in the next test, and this is quite costly. Once the FE model is established for a case, it can be utilized for repeated use at a low cost. In an experimental test, there are some variances on test parameters such as the impact angle, impact point, impact velocities, etc. The parameters of the FE model can be perturbed for repeated use. The perturbations can be determined by some systematic method of the design of experiments.

Second, simulation with the impactor can be conducted by using the trajectory of the upper leg in Figure 13. The simulation has the trajectory of the upper legform of Figure 5, and the trajectory of the legform is the same as the one in Figure 13. In this case, perturbations can be used for repeated tests as well. In this section, the FE model for the first case is established, and the simulation for the upper legform to WAD 775 mm test is performed. Also, simulation that follows the trajectory in Figure 13 is performed as well and analyzed.

4.2. The Results of the Car-to-upper Legform Model Simulation

The sedan-to-upper legform model simulation is performed on a total of 7 points, which are identical to the Euro-NCAP upper legform to WAD 775 mm test. Table 4 shows the injuries and errors of the Euro-NCAP test and sedan-to-upper legform model simulation at the test location U_0. Figures 19 and 20 present the sum of forces and bending moment over time. The sum of forces is defined as the sum

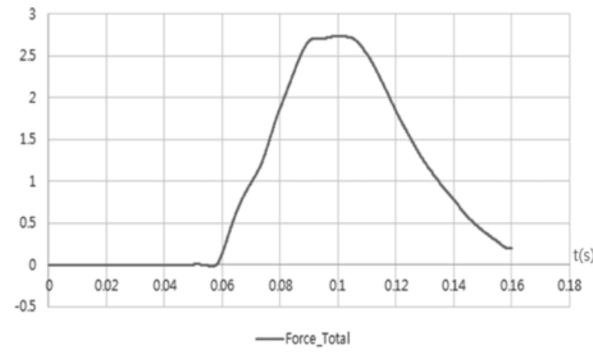


Figure 19. The sum of forces (kN) of the sedan to upper legform simulation (U_0).

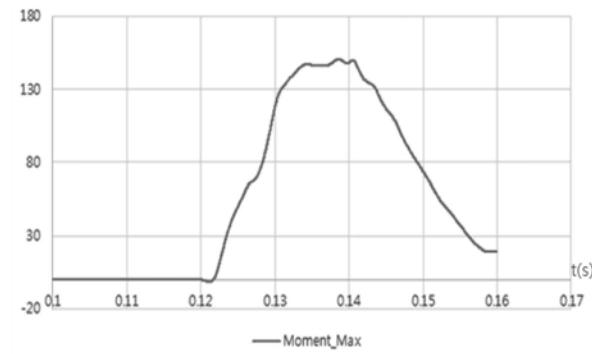


Figure 20. The bending moment (N-m) of the sedan to upper legform simulation (U_0).

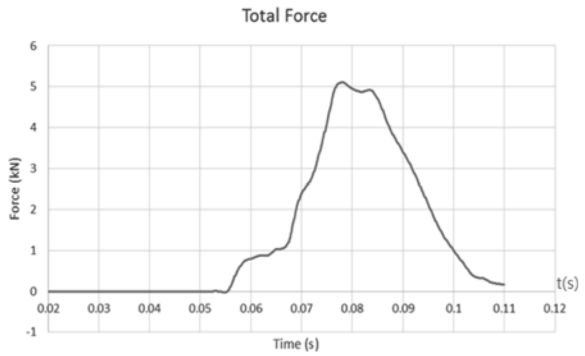


Figure 21. The sum of forces (kN) of the SUV to upper legform simulation (U_0).

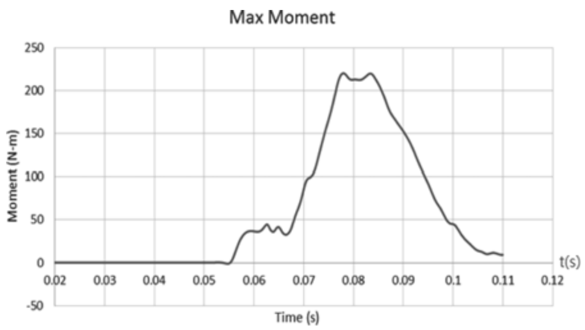
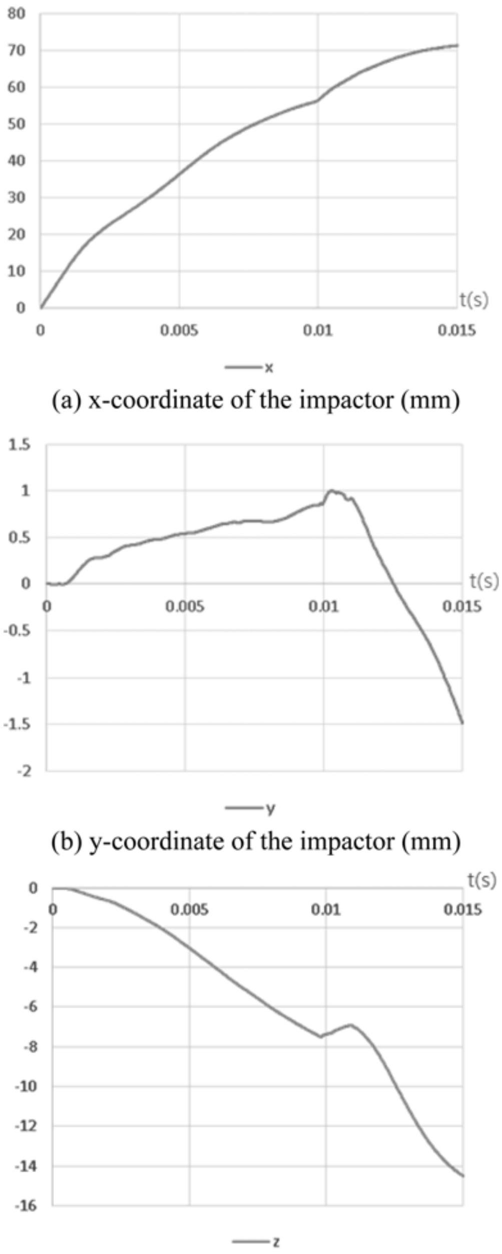


Figure 22. The bending moment (N-m) of the SUV to upper legform simulation (U_0).

of the forces calculated from the upper and lower load cells. The error in U_0 is 6.64 % compared to the Euro-NCAP test. Table 5 shows the errors of the sedan-to-upper legform model simulation at all test positions. The error of the sedan-to-upper legform model simulation is 14.03 % on average. However, the U_-6 point has an error of 34.35 %. This is because since the U_-6 point impact is close to the headlight that is made of plastic material. That is, the larger the nonlinearity exists at the impact point, the greater the error in the simulation and experimental test.

The SUV-to-upper legform model simulation is conducted on a total of 7 points, which are identical to the Euro-NCAP upper legform to WAD 775 mm test. Table 5 shows the injuries and errors of the Euro-NCAP test and SUV-to-upper legform model simulation at the test location U_0. Figures 21 and 22 present the sum of forces and bending moment over time. The error in U_0 is 19.55 % compared with the Euro-NCAP test. Table 6 shows the errors of the SUV-to-upper legform model simulation at all test positions. The error of the SUV-to-upper legform model simulation is 18.39 % on average. From the comparison, the FE models and analyses are considered reliable and the FE models are used in the subsequent simulation.

The analysis is carried out so that the center point of the impactor follows the trajectory of the mid-point in Figure



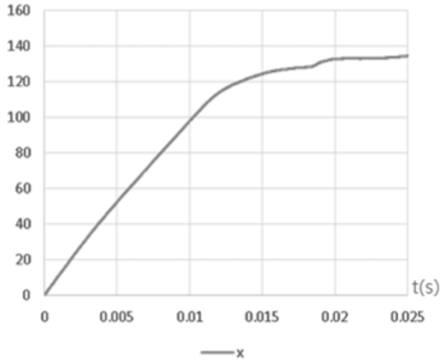
(a) x-coordinate of the impactor (mm)

(b) y-coordinate of the impactor (mm)

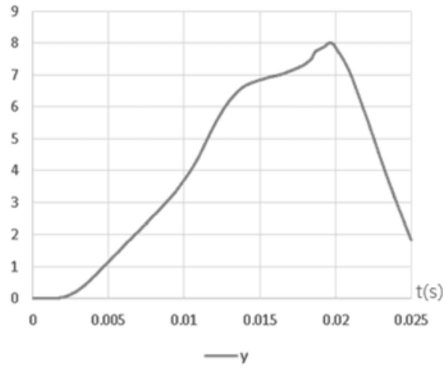
(c) z-coordinate of the impactor (mm)

Figure 23. The coordinates of the upper legform impactor (sedan).

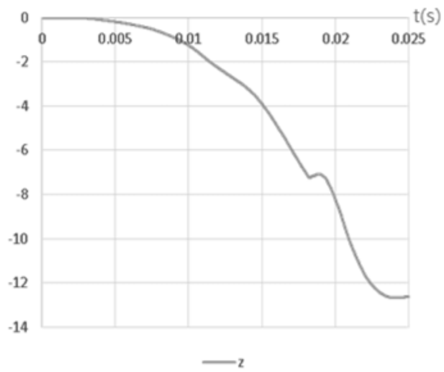
13. The trajectories of the impactor are illustrated in Figures 23 and 24. Figures 25 and 26 represent the sum of the forces (similar to the femur load of the human model) and the moment. In the sedan case, the sum of the forces has a maximum value of 2.1374 kN at 0.008035 s and the maximum moment of 124.8474 N-m at 0.006675 s. The maximum force is 55.6 % higher and the moment is 34.2 % lower than those of the sedan-human model simulation. In the SUV case, the maximum force is 3.982 kN at 0.01950 s and the maximum moment is 190.249 N-m at 0.01975 s.



(a) x-coordinate of the impactor (mm)



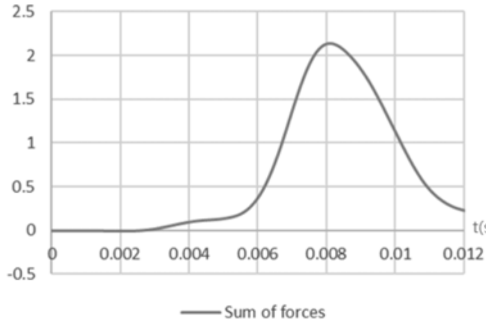
(b) y-coordinate of the impactor (mm)



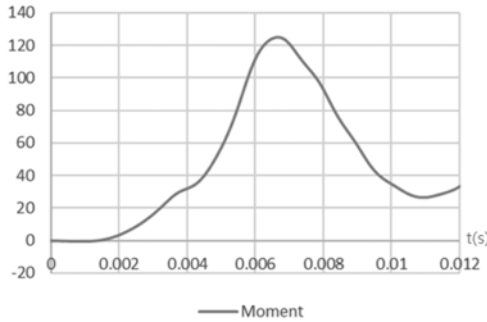
(c) z-coordinate of the impactor (mm)

Figure 24. The coordinates of the upper legform impactor (SUV).

The maximum force is 95.1 % higher and the moment is 28.67 % lower than those of the SUV-human model simulation. However, in both cases, the time points for the maximum forces and moments are similar to those of car-to-human model simulation. The differences in the time points of the maximum forces and moments are similar to the car-human model simulations. In the car to human model simulation, the difference between the maximum force time and the maximum moment time is caused by the collision starting point according to the height of the vehicle.

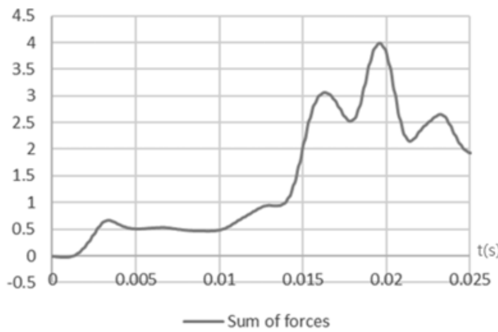


(a) Sum of forces (kN)

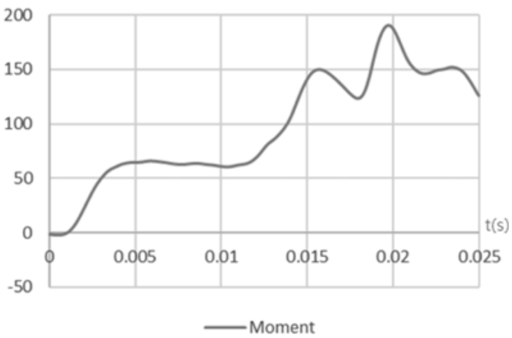


(b) Moment (N-m)

Figure 25. The responses of the upper legform simulation using the trajectory (sedan).



(a) Sum of forces (kN)



(b) Moment (N-m)

Figure 26. The responses of the upper legform simulation using the trajectory (SUV).

Table 4. The results of the car-to-upper legform simulation (Sedan, U_0).

	Sum of force (kN)	Bending moment (N-m)
Upper legform to WAD 775 mm test	2.786	171.121
Car to upper legform simulation	2.755	150.320
Error (%)	1.12 %	12.16 %

Table 5. The results of the car-to-upper legform simulation (sedan).

Test position	Actual test		Sedan to upper leg-form simulation		Error (%)
	Sum of forces (kN)	Bending moment (N-m)	Sum of forces (kN)	Bending moment (N-m)	
U_0	2.786	171.121	2.755	150.320	6.64 %
U_1	2.928	201.177	3.017	171.170	8.97 %
U_-2	3.080	192.064	3.169	168.860	7.48 %
U_-3	3.063	174.069	2.800	132.440	16.25 %
U_4	3.155	156.160	3.137	105.270	16.57 %
U_5	2.880	178.832	3.333	178.530	7.95 %
U_-6	3.281	213.334	4.819	259.889	34.35 %
Average					14.03 %

Table 6. The results of the car-to-upper legform simulation (SUV, U_0).

	Sum of forces (kN)	Bending moment (N-m)
Upper legform to WAD 775 mm test	4.154	133.811
Car to upper legform simulation	3.905	178.122
Error (%)	5.98 %	33.11 %

Additionally, in the sedan case, the maximum force is 22.41 % lower and the maximum moment is 16.94 % lower than the Euro-NCAP upper legform to WAD 775 mm simulation. In the SUV case, the maximum force is 1.97 % and the maximum moment is 6.81 % higher than the SUV-upper legform simulation which follows the Euro-NCAP upper legform to WAD 775 mm test. In the proposed method and the Euro-NCAP upper legform to WAD 775 mm test, the values of maximum force and maximum moment are similar.

In the Euro-NCAP test, since the angle of the impactor is fixed, the maximum load and moment occur at the same time. In the proposed method, the times for the maximum load and maximum moment are similar to those from the human model simulation. The injury value is calculated by considering the height of the vehicle and the shape of the front surface of the vehicle. The newly proposed method, where the impactor follows the trajectory from the car-to-human model simulation, can give injury values closer to a pedestrian accident than the current Euro-NCAP test.

5. CONCLUSIONS

(1) If the impact point is outside the internal bumper reference line, it is difficult to set the test angle because the line connecting with WAD 930 mm cannot be obtained. Therefore, the Euro-NCAP upper legform to WAD 775 mm test needs to give a detailed description of the test angle setting when the impact point is outside the internal bumper reference line. An extrapolation method could be a solution. This is a minor problem that can occur in certain vehicles where the width of the bumper beam is narrower than the width of the vehicle.

(2) A novel test method with an impactor is proposed to accommodate the trajectory of the upper leg. In the proposed test method, the times of the maximum load and the maximum moment are similar to those of a pedestrian accident. That is, the proposed method can consider the shape of the front part of the vehicle and the height of the vehicle. However, the proposed method is only possible in simulation at this time. In the future, it is necessary to develop test equipment to use the proposed method. Currently, the impactor wraps only half of the steel members that represent the femur, but the skin and tissues wrap around the femur in the case of a human. Therefore, structural and material improvement of the impactor is required to obtain a precise value of the injury. An in-depth sophisticated study is required beforehand.

(3) The upper legform to WAD 775 mm test has the limitation that it does not show a sliding effect. Recently, studies on the upper leg assessment method using Flex-PLI have been made steadily to improve the current Euro-NCAP test where the angle of the impactor is fixed. This has the advantage of being able to consider the 'sliding effect' (Isshiki *et al*., 2016; Konosu *et al*., 2016). It is necessary to pay attention to the study on how to perform upper leg evaluation through Flex-PLI in the future.

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