Advanced Pedestrian Legform Impactor (aPLI)

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Abstract

Pedestrian protection aims to reduce injuries in car-to-pedestrian impacts. It is the subject of increasingly stringent worldwide statutory and consumer rating requirements and is thus increasingly important in current vehicle development. With electric vehicles, which are not always readily noticed by pedestrians, there is an even higher risk of pedestrian injury. Passive pedestrian protection is, active safety systems notwithstanding, the final countermeasure to reduce serious and fatal pedestrian injury.
The current test assessment for pedestrian protection uses three "impactors" in different loading scenarios designed to represent injuries to specific parts of the human body, such as the head, the upper leg and the lower leg. Recent development of the Advanced Pedestrian Legform Impactor (aPLI) focuses on enhanced biofidelity of the lower extremities to address long-bone fractures, knee ligament injuries and pelvis fractures in a single impactor instead of the separate, independent, lower leg and upper leg impactors.
To date, the requirements for the aPLI are applied to the EuroNCAP 2022 regulations. But as seen with the previous development of the FlexPLI, it is to be expected that the global statutory requirements will be influenced by global consumer rating requirements.
The CAE development process focuses on high accuracy simulations within the vehicle development process, using reliable and robust FEM vehicle and impactor models. The aPLI-FE models represent the Cellbond aPLI SBL-A hardware and have been developed in close cooperation with the hardware manufacturer.
Utilizing many years of experience in the field of occupant protection with HIII models, the FE model ATD-aPLI was also developed with extensive feedback from partners in the German automotive industry. Special modelling techniques were developed and applied in LS-DYNA®. The ATD-aPLI model was validated by material and component investigations and by experiments in generic test rigs. Models for future hardware versions will be released regularly in preproduction and final versions.
Automotive manufacturers face new challenges in the CAE process and hardware tests using the new aPLI. Despite similarities with the previous FlexPLI, the attached upper body mass of the aPLI has a strong influence on the impactor kinematics and particularly the femur load. This paper highlights some characteristics of the aPLI and describes a sensitivity analysis using LS-DYNA within the framework of a typical CAE development process.

Introduction

The global consumer-rating schemes, such as the European New Car Assessment Programme (Euro NCAP), with stringent requirements in addition to the statutory requirements, have led to a reduction in serious injuries for all road users. Therefore, the safety requirements are continually enhanced. Within the category of "Vulnerable Road Users" (VRU) the Euro NCAP assesses, in the case of a car-to-pedestrian accident, potential injuries to the pedestrian head, pelvis and leg by means of subsystem tests on the vehicle front. For every assessed vehicle, the Euro NCAP regulations prescribe pelvis impact to the bonnet leading edge, while statutory regulations UN-R127 Add. 126 Rev. 2 specify only tests with the upper leg impacting the bumper area for a specific vehicle height above ground.
These subsystem tests are performed with individual impactors representing different, simplified components of the human body and provide an assessment of possible injuries in case of a car-to-pedestrian accident.
With representation of the lower extremities of the human body by the individual lower leg and upper leg impactors, reliable assessment of potential injury is questionable, given that the kinematics of the complete human body is not taken into account owing to the absence of a human torso [1]. Therefore, the development of a leg impactor with upper body mass has resulted in a higher biofidelity and a more realistic modelling of the actual kinematic behavior of the human body in car-to-pedestrian accidents [2]. In February 2019 the Euro NCAP committee adopted the use of the recent advanced Pedestrian Legform Impactor as leg form

impactor for the Euro NCAP rating from 2022. Being complemented by an upper body mass and hip, the aPLI, incorporates the enhanced kinematic behavior of upper and lower leg joint [3].

From 2022, the Euro NCAP rating scheme for VRU protection will no longer allow separate upper and lower legform tests with 6 assessment points in each legform but will require the use of the aPLI leg form impactor and at least 18 assessment points for VRU protection [4]. This new point allocation for the aPLI leg form test represents 28.6 % of the total available points used in VRU protection. For a five star Euro NCAP rating in 2022, and eligibility for scoring in the AEB assessment, the criteria must be satisfied for at least 70% of total available points of VRU protection and at least 22 points in the subsystems, such as head form and leg form [5].

This paper will describe geometrical differences in the FE models for LS-DYNA for the ATD-FlexPLI FE model and the newly developed ATD-aPLI FE model. A sensitivity study of the ATD-aPLI leg form impactor within the range of typical CAE vehicle development parameters with varying impact speed and vehicle ride height will be presented.

Although, the new aPLI leg form impactor is required for the Euro NCAP vehicle assessment from 2022, the mandatory conditions for the hardware tests and thresholds for the criteria will be fixed in the course of 2020. Therefore, in analogy with the recently used FlexPLI hardware tests by Euro NCAP, the sensitivity study adopts assumptions such as a ground clearance of 25 mm and an impact velocity of 11 m/s with a tolerance of ± 0.2 m/s. A generic vehicle model of a sedan is used for this basic assessment of the ATD-aPLI FE impactor model, which was primarily developed to compare kinematics of human body models for pedestrian simulations [6].

Advanced Pedestrian Legform Impactor

The new developed aPLI appears quite similar to the currently used FlexPLI but is supplemented with an upper body mass (UBM) to represent the human pelvis. This UBM is connected by a rotational joint with one degree of freedom and, with a mass of 11.5 kg, shows a significant influence on the leg's kinematic behavior. The main components for the vehicle assessment tests in both leg form impactors are the femur and tibia bones and the knee joint with its ligaments. These are the medial collateral ligament (MCL), anterior cruciate ligaments (ACL) and posterior cruciate ligament (PCL). To obtain good agreement with the human body model of the leg form impactor extensive adjustments are made to all components [2]. In the following some geometrical differences between the aPLI and the FlexPLI are described.

The cruciate ligaments in the knee joint of the aPLI are arranged in parallel, as opposed to the crossed arrangement in the FlexPLI. The ankle of the aPLI does not allow bending between the two lowest tibia segments. The flesh tissue of the aPLI is represented by a specially developed rubber part and outer neoprene skin leading to an improved mass distribution of bone and flesh tissue. Furthermore, the front contour of the aPLI reveals a slight gradient of the tibia and femur segments in reference to the knee joint, while the FlexPLI shows the same level for knee joint, tibia and femur segments, as shown in Figure 1.

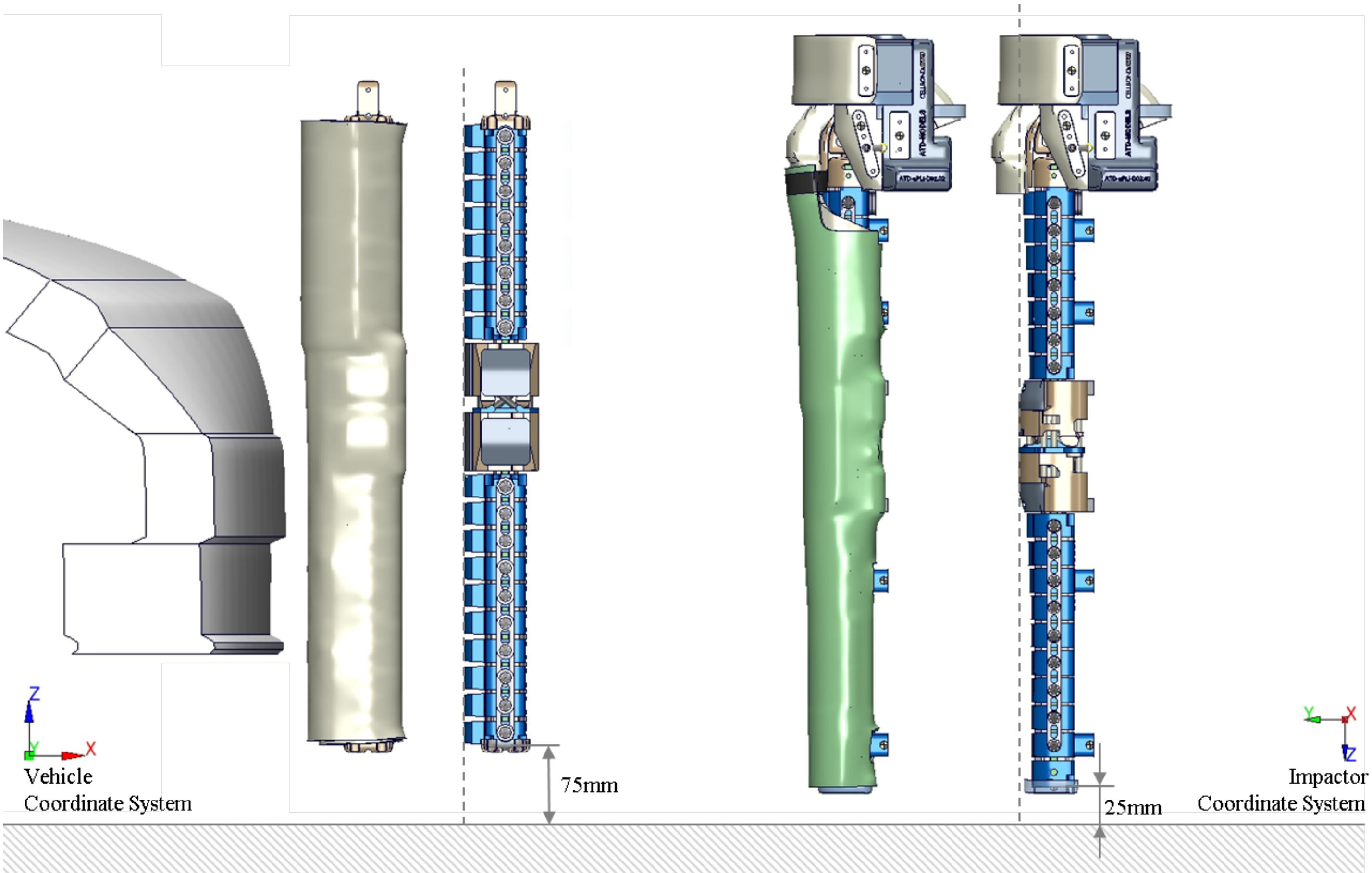

Figure 1: Comparison of FE models of FlexPLI (left – with flesh and without flesh) and aPLI (right – with flesh and without flesh) from ATD models GmbH, Germany, in side view in front of the generic vehicle model of a sedan, developed by Vehicle Safety Institute of Graz University of Technology and Euro NCAP.

The (assumed) positioning of the leg form impactors in front of the vehicle also differs in terms of ground clearance. The FlexPLI has an offset of 75 mm to the ground level, while the aPLI will probably be positioned 25 mm above ground level. The ground level is based on the vehicle's ride height. This summarizes some significant differences in components between the current leg form impactor FlexPLI and the newly developed aPLI.

For the creation of the ATD-aPLI FE model based on the physical hardware impactor and its physics, some specific features have been taken into account. In representing the flesh tissue, neoprene skin and structure of lower leg, upper leg and knee joint, prestress has been included to obtain a more realistic material behavior. Velcro straps holding the aPLI together are also implemented as in the hardware and can be further adjusted to reflect different levels of tightness. Springs in the knee joint are also loaded with prestress, which can be adjusted using special parameters. This allows great potential for the validation of the ATD-aPLI FE model using hardware test results, given that all hardware impactors could exhibit some deviation during a hardware testing cycle, although the impactor's calibration bounds show its integrity. Other options for adjustment are the overload cables present in both Femur and Tibia assemblies and the friction of the UBM rotational joint. These adjustable parameters also facilitate a worst-case analysis at boundary limits to cover every possible variation in boundary conditions to support a robust vehicle development.
The visual crash markers, located at different hard points of the ATD-aPLI FE model, are not implemented or required for the hardware model of the aPLI. Owing to their location on hard points without coverage by the

neoprene skin or flesh tissue, these markers allow, due to a reference to the underlying structure, ready visual comparison of the impactor's kinematic behavior between hardware tests and simulation.
The center point of the visual marker in the foot of the ATD-aPLI FE model is the origin of the impactor's coordinate system and is used as the reference point to position the leg form impactor's height above ground. The lower protection cap is not taken into account for the position of the ATD-aPLI FE model. All positioning orientations in the ATD-aPLI FE model follow the guidelines of the SAE sign convention "SAE J211-1 Revised DEC2003" which is the same orientation of the impactor fixed coordinate system of the leg of the ATD-H350 dummy. Therefore, the impactor specific x axis represents the rotational axis of the UBM, while the impactor specific z axis points into the direction of the impactor's foot. The positive rotations adhere to the "right-hand rule" [7].
Currently, the aPLI LS-DYNA model comprises 260k elements, 215k of nodes, 493 property entities and 389 materials. Several different material definitions are included in the model. These include Ogden rubbers, Fu Chang foams, elastic springs and rigid materials. One of the most important aspects of the model is the contact definition. For the inner aPLI contacts, such as the contact in the knee joint and the contact between the flesh tissue and bones, all have significant impact on the aPLI's kinematic behavior. Contact group definitions allow for quick adaption for different car environments. All of the hardware sensors and outputs are echoed in the FEA model. Cross-sections, accelerometers, angular rate sensors and more are present in the model and are described by ISO codes. This allows for easy comparison of test and FEA results.
The current release of SBL-A revealed issues with the UBM rotation in negative "x" rotation, see Figure 1. In order to overcome this issue a new bumper was introduced to decrease the rotation of the UBM by providing a rotational inertia. Another change was the reduction of the amount of ballast in the flesh tissue assembly.

The generic vehicle model shown in Figure 1, represents a typical sedan contour developed along with Roadster, Multi-purpose vehicles and Sport Utility Vehicle (SUV) by the Vehicle Safety Institute of Graz University of Technology and the Euro NCAP to compare kinematics of human body models for pedestrian simulations, shown in Figure 2 [6]. These generic vehicle models are based on European vehicle designs, reduced to 120 parameters, and represent the median vehicle shape. All relevant subassemblies, like spoiler, bumper, grill, bonnet lead and bonnet, are simplified and reproduced with different layers such as an elastic-plastic interface layer, a foam layer and a compaction layer on a rigid bottom layer. Their properties and material parameters vary to emulate representative structural behavior.

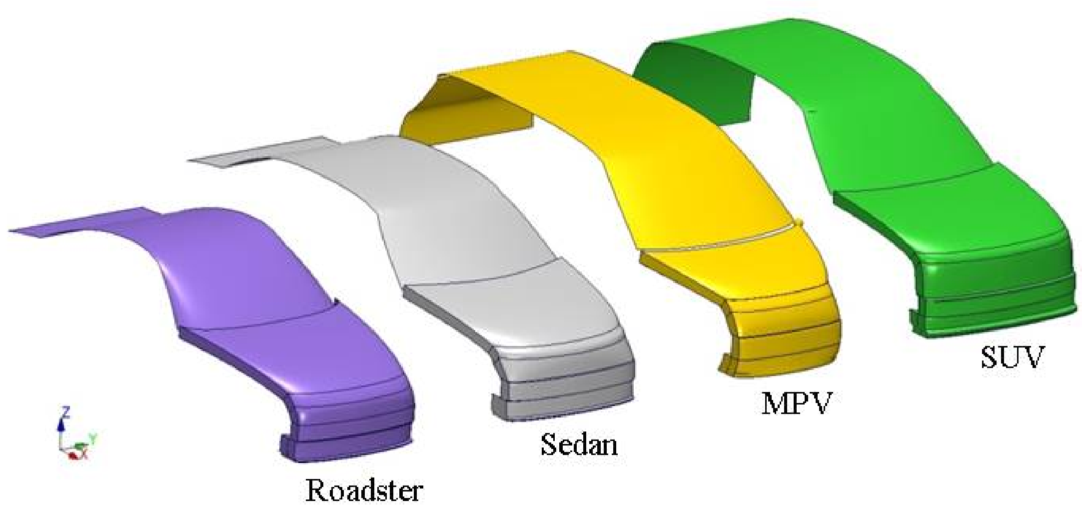

Figure 2: Generic vehicle models for Roadster, Family car/Sedan, Multi-purpose vehicles (MPV) and Sport Utility Vehicle (SUV) developed by Vehicle Safety Institute of Graz University of Technology and Euro NCAP

Based on the common objectives of the generic vehicle development for human body simulations and the improved biofidelity of aPLI, the generic sedan model was used in a sensitivity study of the newly developed ATD-aPLI FE model by varying the impact velocity by ± 0,2 m/s and vehicle's ride height by ± 10 mm and ± 20 mm. The sensitivity study is described in the following sections.

Figure 3 shows a time sequence of the ATD-aPLI FE model. With a ground clearance of 25mm and an impact speed of 11 m/s, the aPLI strikes at the vehicle center line of the generic sedan model, positioned at specific sedan ride height. This configuration provides the nominal setting and baseline result for the evaluation of the following variations. Various measured variables are available for the analysis of the ATD-aPLI FE model and can be divided into two categories. Firstly, measured variables to assess the integrity of the numerical simulation, such as the model's kinetic energy, time step, added mass, hourglass energy, etc. and secondly, measured variables to monitor the impactor's kinematics and its physical loads, like angular velocity of joints, bending moments, ligament elongation, forces, etc. Figure 4 shows the progression over time of the rotational angle of the pelvis relative to the leg, elongation of the knee ligaments, femur and tibia bending moments. The assessment interval was set to 80 ms capturing the last zero crossing of all femur and tibia segments following their first local maximum at around t = 68 ms, simulations were carried out to a time of 100 ms. The elongation of knee ligaments almost crossed zero at 70 ms.
The knee joint steadily intrudes the front contour of the generic sedan model without any significant reaction to knee ligaments until t = 10 ms. While the tibia and femur are still intruding, the knee joint reaches its point of maximum intrusion and its rebound pushes the knee joint out of the vehicle front contour, shown by the unloading of the bumper and grill area at t = 15 ms,

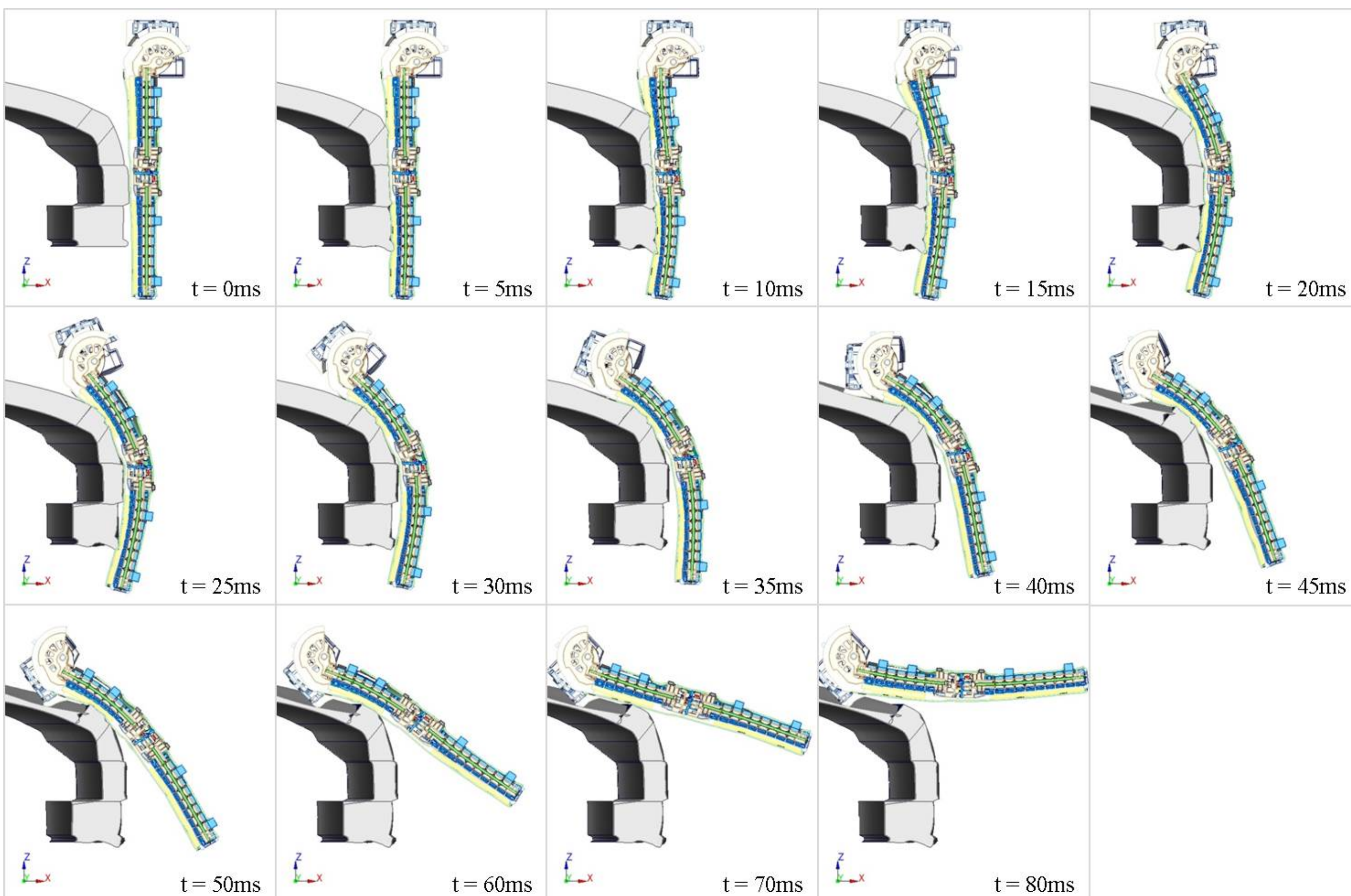

Figure 3: Kinematic behavior of the ATD-aPLI FE model for LS-DYNA at the vehicle centerline of generic sedan front

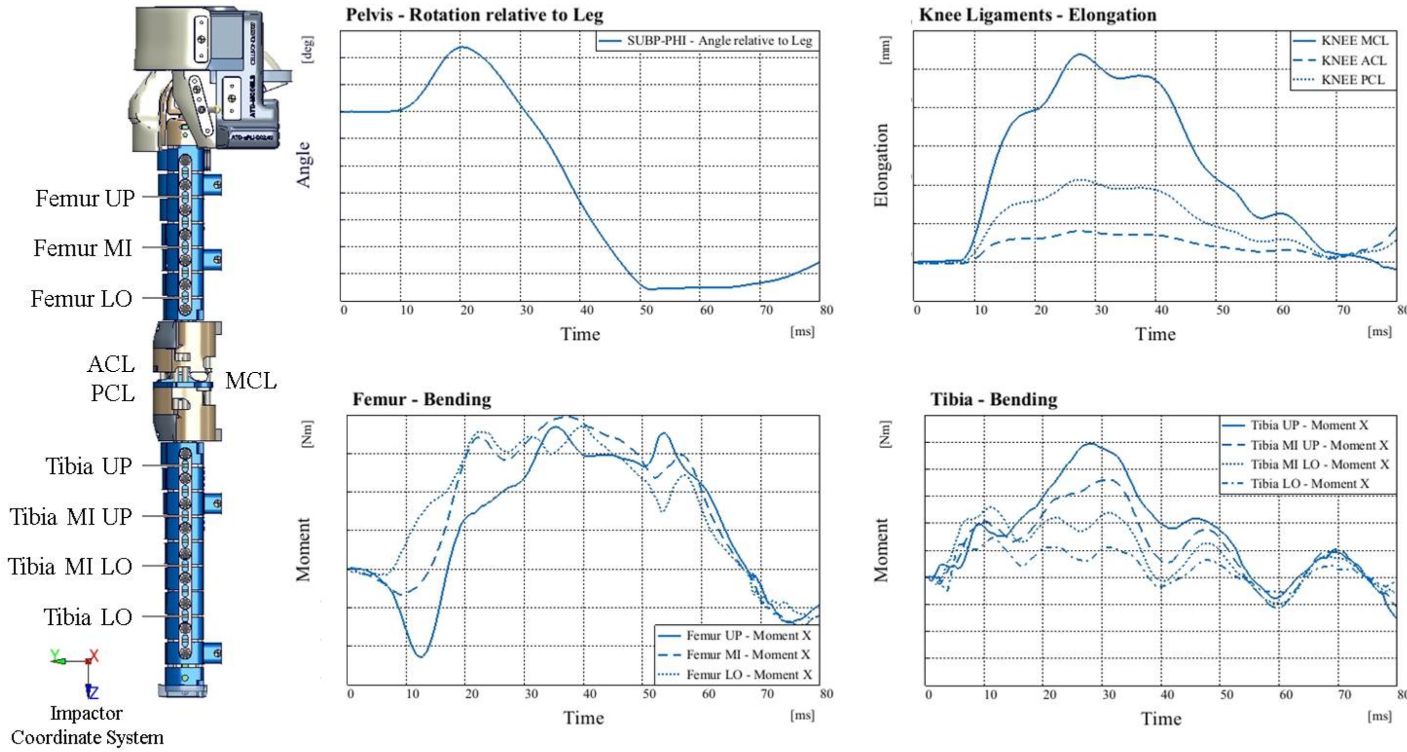

Figure 4: Measures variables of the ATD-aPLI FE model for LS-DYNA at the vehicle centerline of generic sedan front to describe the impactor's kinematic behavior and loading

The tibia and femur bending are already influenced by the rebound of the knee joint. Between t = 15 ms and t = 17.5 ms the rebound of tibia begins, shown by unloading of the spoiler area, while the femur pitches towards the bonnet. This kinematic behavior corresponds to the first inflexion point in the MCL elongation. The further increasing MCL elongation is caused by alignment of the femur onto the vehicle contour, while the rebound of the tibia can not reduce the MCL elongation effectively. This culminates in the maximum MCL elongation at t = 27.5 ms and illustrates the opposing effect of the upper leg and lower leg on the elongation of the knee ligaments.
The tibia bending moments “Tibia MI LO” and “Tibia LO” induced by the missing support of the spoiler reach their maximum value at around t = 11.4 ms. The overall maximum tibia bending moment is measured by the gauge of “Tibia UP” at t = 28.3 ms just below the knee joint and illustrates also the effect of different rebound phases of different components. From t = 40 ms the curve progression in Figure 4 shows only the oscillation of tibia in its free flight phase.
The femur bending moment “Femur UP” shows a peak of negative bending at t = 12.5 ms due to the pelvis' mass inertia, while the remaining leg form impactor is supported by the vehicle front contour. The overall maximum femur bending moment is achieved at the gauge of “Femur MI” at t = 37.2 ms and corresponds to the time of full contact of the pelvis with the bonnet. All femur bending moments show different local peaks from t = 22.6 ms to t = 53.6 ms with comparable peak magnitudes, while the magnitudes of the tibia peak values are clearly different. The rotation of the pelvis towards the vehicle contour starts at t = 20 ms.

The variation of the impact speed within its tolerance range of ± 0.2 m/s shows no significant influence on the impactor's kinematic behavior and loading, given that the deviation of peak values is less than ± 2 % in relation to the reference simulation with nominal velocity of 11.1 m/s. Curve progressions of evaluation criteria, like bending moments and ligament elongation, in Figure 5, also show no significant deviation in qualitative progression until reaching the peak value.

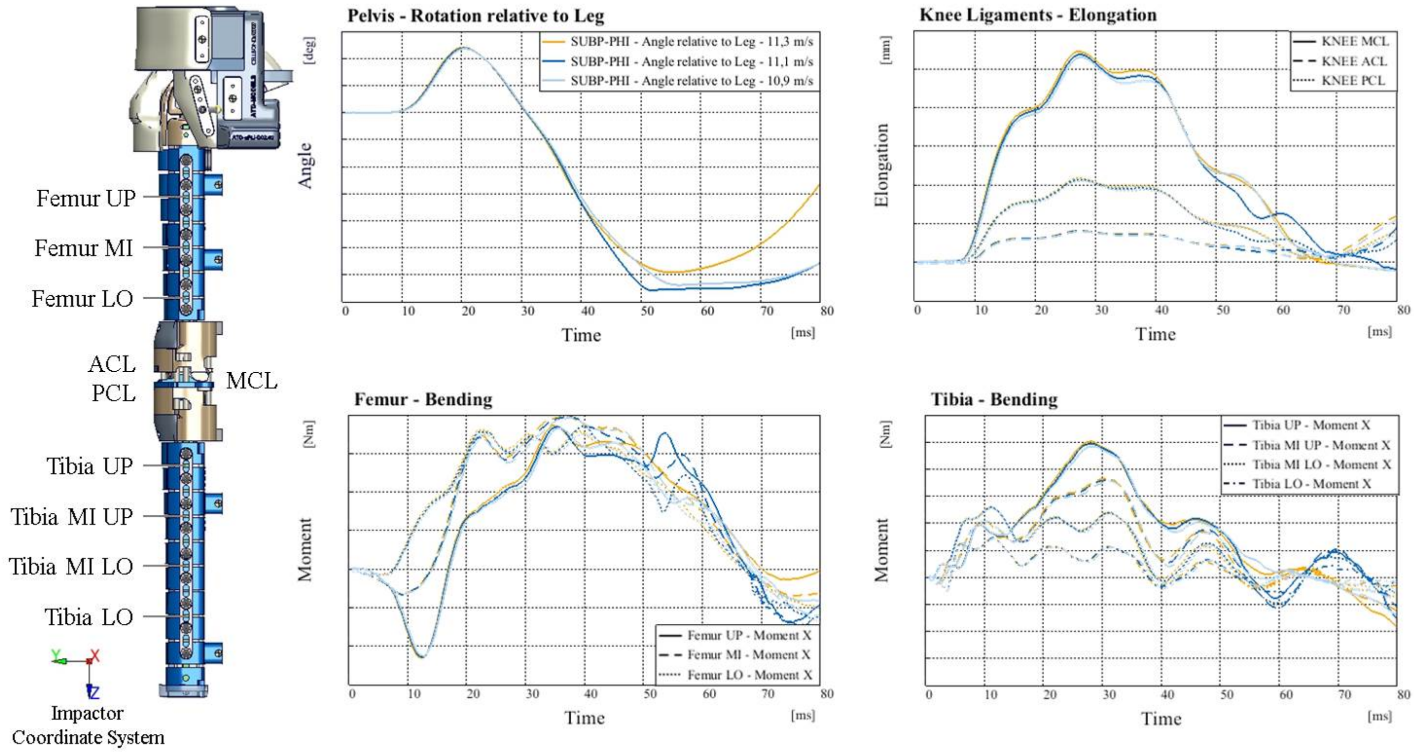

Figure 5: Variation of impact speed

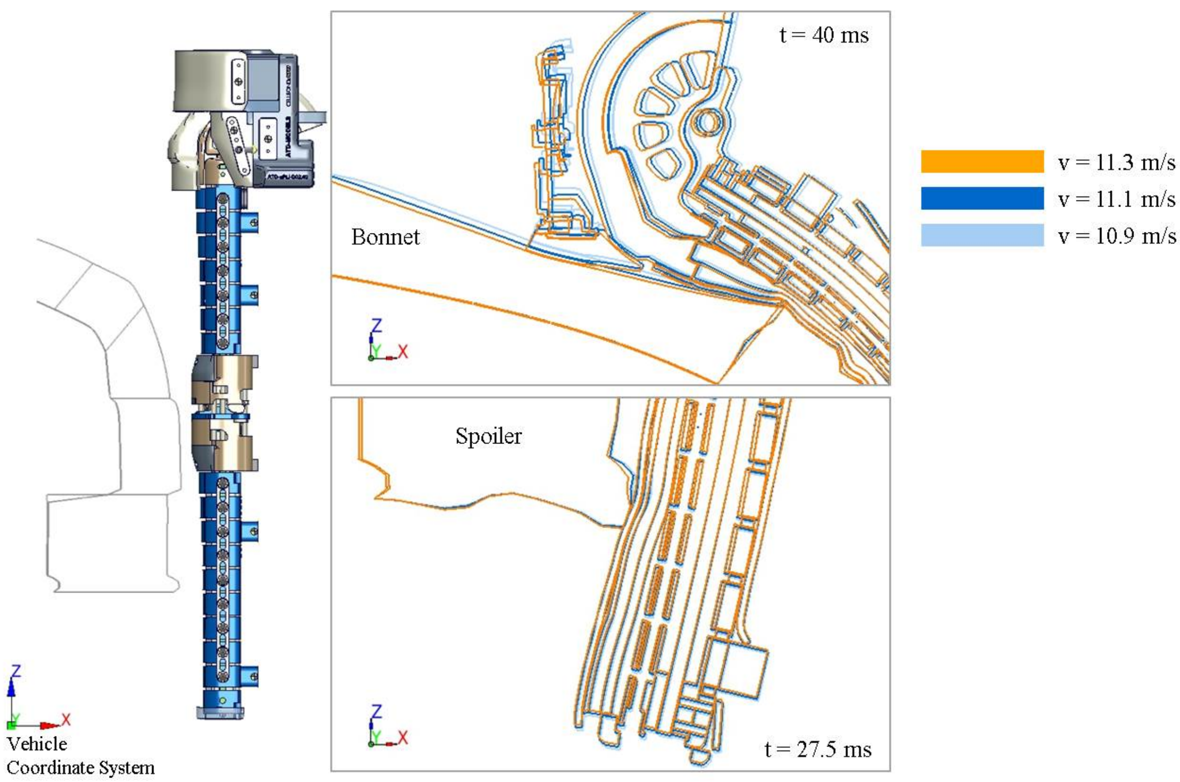

Figure 6: Kinematic differences by variation of impact speed

From t = 50 ms, knee ligament elongations and tibia bending moments show some differences compared to the reference simulation. This is probably caused by the different rebound and oscillation at the free flight phase of

the tibia and the knee joint with no contact to the vehicle front. Nevertheless, pelvis and femur make contact with the vehicle front at t = 50 ms.
Femur bending moments already show a slight variation at t = 40 ms, after the maximum peak value occurred at "Femur MI". But the femur bending moment "Femur UP" of the nominal reference simulation shows an additional local peak at t = 53.5 ms, owing to the different rotation and intrusion of the UBM into the bonnet as shown in Figure 6. This different behavior of the pelvis is also visible in its angle relative to the leg.
In addition to the different behavior of the pelvis in conjunction with the different rebound of knee joint, there is also a time shift in the maximum load of "Femur LO" from the third local peak value at t = 39.8 ms, within an impact speed of v = 10.9 m/s and v = 11.1 m/s, to the first local peak value at t = 22.7 ms at the impact speed of v = 11.3 m/s. This shifting of maximum peak value of "Femur LO" lies within a range of 20 Nm and has no influence on the overall maximum femur bending and all remaining femur bending moments show a linear increase with increasing impact velocity.
All in all, owing to the increased kinetic energy of the aPLI, the intrusion into the vehicle front and the resultant rebound differ slightly for the different load paths of the vehicle, as shown in Figure 6. Maximum peak values of measured variables show a linear increase within a maximum deviation of ± 2 %, except for the rotation of the pelvis in relation to the leg. But within this small range of variation of ± 0.2 m/s the kinematics of the pelvis and its influence on the femur bending is visible.

Variation of vehicle ride height by ± 10 mm and ± 20 mm generates a corridor for the measured variables of the ATD-aPLI FE model as shown in Figure 7.
The maximum elongation of knee ligaments shows an increase of + 2,3 mm of MCL elongation with increasing vehicle ride height and development of a second local peak between t = 30 ms and t = 40 ms while the inflexion point at t = 17.5 ms is reduced.
By comparing both limiting cases of "z + 20 mm" and "z – 20 mm" in Figure 8, the elongation of knee ligaments is influenced by opposing trends. The rebound of the lower load path is positively influenced by a lower contact point at the aPLI within a vehicle ride height at z – 20 mm, while the opening of the knee joint is induced by the alignment of the femur and pelvis with the bonnet. Therefore, the rebound of the lower load path at the vehicle ride height of z + 20 mm shows a delay due to the higher contact point. Despite the higher support of the femur and pelvis by the vehicle contour, this in conjunction with the rebound of the knee joint, leads to the second local peak in the MCL elongation. The remaining knee ligaments, the anterior and posterior cruciate ligaments, show a related behavior between t = 30 ms and t = 40 ms owing to their location at the knee joint.
With increasing vehicle ride height, all tibia bending moments show an increase in their maximum load up to + 65 Nm, particularly around t = 30 ms. This increase corresponds to the different rebound of the lower load path in conjunction with the rebound of the knee joint. The tibia bending moments "Tibia MI LO" and "Tibia LO" show an intensification of their local peaks at t = 10 ms and t = 30 ms which also leads to a shifting of maximum peak value from t = 10 ms to t = 30 ms. Owing to the different magnitudes of the tibia bending moments this behavior does not influence the overall maximum tibia bending moment.
Also, the maximum load of femur bending moments increased to + 49.7 Nm with the higher vehicle ride, although the overall maximum femur bending moment of all vehicle ride heights at "Femur MI" increased by + 30.8 Nm only. Furthermore, with increasing vehicle ride height, the higher support of the femur and pelvis results in a decreased local negative bending moment of "Femur UP" between t =11.5 ms and t = 13.2 ms. The femur bending moments for the vehicle ride heights of nominal "z" and "z + 20mm" show an additional local peak at t = 50 ms. This corresponds to the angle of pelvis rotation relative to the leg but does not affect the overall maximum femur bending.

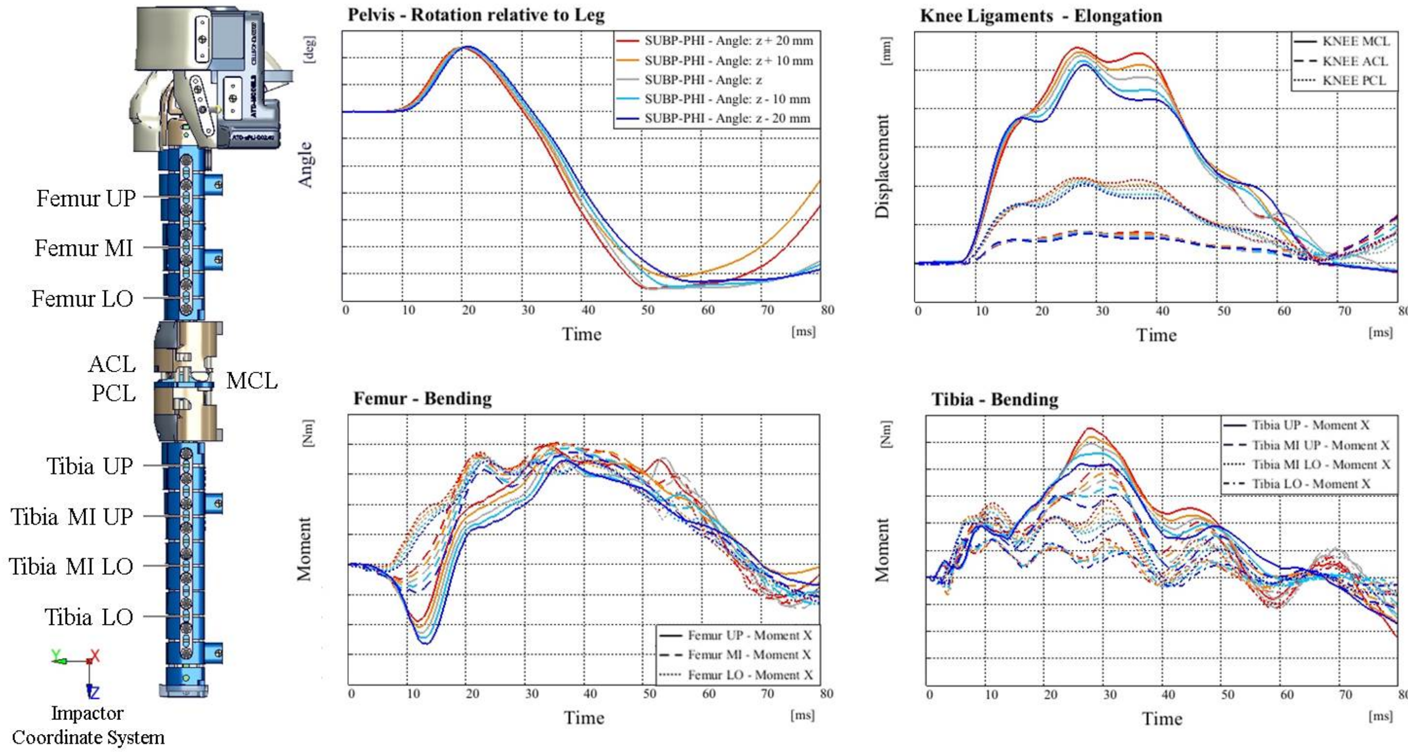

Figure 7: Variation of the vehicle ride height

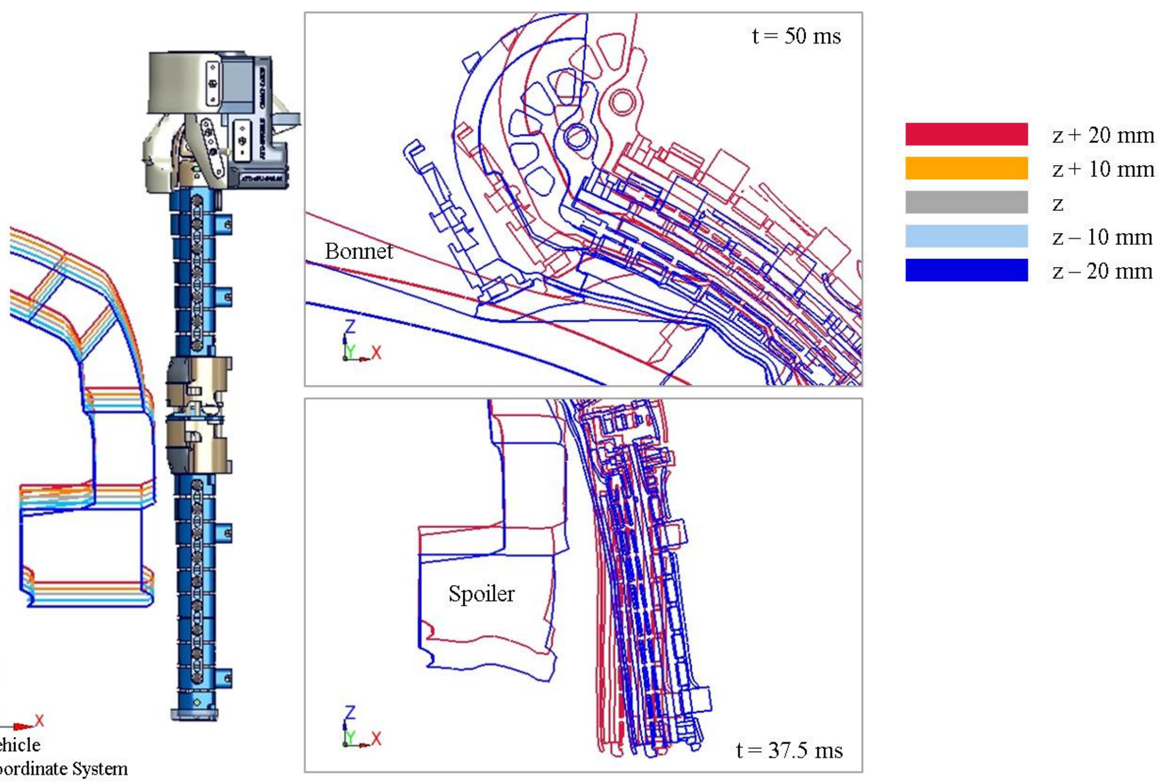

Figure 8: Kinematic differences by variation of vehicle ride height

Conclusions

The newly developed aPLI aims for a higher biofidelity. Therefore, extensive adjustments to all components were made, as well as applying special techniques of modelling for the compilation of a robust FE model by ATD models, Germany.
The strategy adopted in the development of the FE model of the aPLI was step-by-step validation starting from materials and individual parts (bones, cables, springs) to components (tibia, knee, femur, pelvis) and finally the overall model (rig tests). This process allowed the incorporation of validated physical properties into the model. Another main focus was on the pre-simulation of the foam, neoprene and Velcro parts. This pre-simulation is the only way to correctly transfer friction to the FE model.
Owing to the enhanced requirements of Euro NCAP from 2022, ongoing OEM vehicle development must now work with the new aPLI. Given that the mandatory boundary conditions for the hardware tests and thresholds of the evaluation criteria will be fixed in the course of 2020, the sensitivity study described in the paper aims to gain an understanding of the impactor's kinematic behavior with varying impact speed and the vehicle ride height.
The sensitivity study shows the expected opposing effect on the knee ligament elongation by the rebound of the lower leg while the upper leg with the UBM rotates towards the vehicle frontal contour. Therefore, the properties of the bonnet leading edge and the bonnet are of importance for the impactor's kinematic behavior, in particular with regard to the femur bending moments. The parameters which were selected for variation (vehicle ride height and impact speed) are just two of many conditions encountered and must be considered in the vehicle development process. With approved mandatory boundary conditions for the leg form test and thresholds of the evaluation criteria there are more issues to be addressed. For example, the impactor's kinematic behavior at the outer bumper area to evaluate the behavior of the cruciate knee ligaments and the UBM, or, a direct comparison of the FlexPLI and the new aPLI to identify possible conflicting implications for the vehicle development.

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