Investigating the Effects of Inflating a Wearable Airbag Under a Motorcycle Jacket

Oscar Cherta-Ballester, Maxime Llari, Valentin Honoré, Catherine Masson, Pierre-Jean Arnoux

Abstract The effects of wearing an airbag vest, under a motorcycle jacket, on injury risk during inflation and protection against impacts were investigated. An existing finite element airbag model was inflated under a motorcycle jacket model and the risk of rib fractures was evaluated by measuring chest deflection of the HUMOS2 model. Three inflators were used to increase the amount of gas injected into the airbag. Once inflated, linear frontal thoracic impacts centred over the 4th costal interspace were performed based on previous crash simulations. Ribcage and internal organ injury risk reduction were assessed by chest deflection and Viscous Criterion from simulations with protector and reference simulations without protection. No injury risk was noted due to the inflation of the airbag under the jacket for the three injected masses. Blunt impact simulations demonstrated that the level of protection was maintained or even improved wearing the airbag under the jacket. The benefits of the airbag were more significant for impacts against obstacles with larger contact surfaces and increased with mass injection. Coupling airbags and garments could improve the effectiveness of inflatable protectors and should be optimised to minimise injury occurrence and severity. The method proposed in this work could be used for future evaluations of other rider morphologies as well as garment types and sizes.

Keywords Finite element modelling, injury mitigation, motorcycle jacket, safety assessment, thorax, wearable airbag.

I. INTRODUCTION

Over the last few decades, wearable airbag protectors have been developed to mitigate motorcyclist trauma. The aim of these safety devices is to shape an air cushion around the human body to absorb impact energy and thus protect the motorcyclist. The covering areas vary from one manufacturer to another, but protecting the thorax remains the main challenge for these safety devices due to the severity of the injuries sustained on this body segment and the associated haemorrhagic and respiratory risks for the motorcyclist [1-2].

These inflatable devices are generally fitted in a vest worn by the motorcyclist outside or inside a motorcycle jacket or a leather suit. In terms of airbag design, the main advantage of integrating an airbag into a motorcycle garment is the abrasion resistance provided by the garment, enabling the development of lighter and more breathable airbag protectors. However, the garment represents an additional layer that could reduce the space to inflate the airbag, depending on the rider's morphology as well as on the size of the garment and its fabric's mechanical properties. Thus, the inflation of the airbag could pose a risk to the rider during inflation and could modify the effectiveness of the device in mitigating injuries during the accident. For safety reasons, manufacturers recommend wearing the airbag protector with specific compatible garments or under garments that conform to their sizing compatibility recommendations [3-4]. So far, airbag design has not been supported by any studies evaluating the interaction between airbag protectors and motorcycle garments and its influence on motorcyclists' safety. This work aims to investigate the effects of inflating an airbag protector under a motorcycle jacket in terms of:

1. The risk of injury related to the inflation of the airbag.
2. The effectiveness of the airbag in mitigating injuries.

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II. METHODS

Finite element (FE) modelling was used to inflate an airbag under a motorcycle jacket and simulate blunt impacts to the thorax of a human body model (HBM), with and without protection. The software used in this study was the solver Radioss V2017 (ALTAIR, Troy, MI, USA).

The present work is divided into three main parts:

1. The first part dealt with the modelling of the motorcycle jacket and its validation based on experimental data obtained from drop impact tests.
2. The second part focused on the evaluation of injury risk during the inflation of the airbag alone and under the motorcycle jacket.
3. The third part consisted of the simulation of blunt thoracic impacts and the evaluation of the protection capacity of the fully inflated airbag (alone and under the jacket) compared to reference simulations without protection.

Human Body, Airbag and Jacket Modelling

The HUman MOdel for Safety (HUMOS2) representing the 50th percentile adult male was chosen to evaluate the risk of injury. This HBM includes the description of compact and trabecular bones, internal organs, ligaments, muscles, tendons and skin [5]. The thoracic response against frontal impacts was improved in previous research [6] and this updated version was used in the present work.

The airbag model was created and validated by [6] based on a prototype version of an airbag vest designed by the manufacturer In&motion (Annecy, France). The mechanical properties of the fabrics were obtained from tensile tests, while the dynamic response of the model was calibrated based on experimental drop impact tests.

A conceptual motorcycle jacket model was developed to impose an inflation constraint to the airbag model. For this purpose, the jacket was modelled without sleeves by scaling the trunk of the HBM. Data from experimental tests performed on two motorcycle jackets were used to calibrate the model. The compatibility recommendations offered by the airbag manufacturer based on human morphology and jacket dimensions were considered in choosing the size of the jackets representing well-fitting garments. One of the jackets was made of leather and the other one was a textile garment. Both jackets had the same chest and waist girth dimensions, but the fabrics had different thickness and mechanical properties. The jacket model was meshed using quad and tria elements with an average size of 10 mm and 2 mm thickness (average of the 2 jackets). An elastic orthotropic material law (Radioss law 19) was used for the fabric, the parameters of which were defined to obtain the final thickness of the frontal air chamber, the operating pressure inside the airbag as well as realistic responses against impacts. The impact response of the airbag jacket (airbag protector worn under the motorcycle jacket) was calibrated based on drop impact experimental data. Frontal thoracic impacts were performed with the airbag positioned on a rigid torso and worn under the leather or the textile jacket (Figure 1a). A support was used to raise the torso avoiding the contact of the rear part of the airbag and the ground. The airbag was manually inflated by an air compressor and a dropping apparatus was used to release a falling mass along a guided vertical path. The pressure of the airbag was defined from previous inflation tests with the airbag positioned on the rigid torso and worn under the leather or the textile jacket. The impactor was rectangular with dimensions of 5 cm*46 cm, a mass of 7 kg and made of steel. Impact energies of 30, 40 and 50 J were evaluated. The tests were simulated (Figure 1b), blocking all degrees of freedom of the torso, and the acceleration measured on the impactor was compared to the experimental results in order to correlate the behaviour of the airbag jacket model.

Airbag Inflation

The airbag was positioned and inflated on the human model, alone or under the jacket. The airbag was pulled towards the HBM by spring elements and pressure loads were used to embed the airbag under the jacket. Maximum chest deflection was measured when the airbag was perfectly positioned and inflated to evaluate the risk of injury. Chest deflection was measured as the change in length between a node on the mid-sternum and a node on T9 vertebrae which were aligned to the 4th costal interspace of the HBM. The final pressure and volume of the airbag were altered by changing the mass of gas injected into the bag. Three inflators, I1, I2 (1.2*I1) and I3 (1.5*I1) were used.

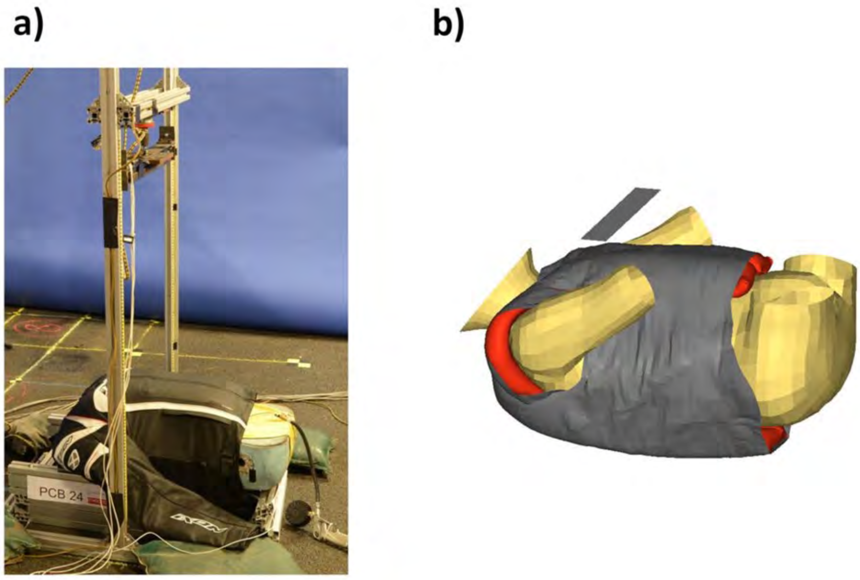

Fig. 1. Airbag jacket drop impact test. a) Experimental; and b) Simulation.

Impact simulations

The human model was coupled with the airbag and the jacket models to obtain three main modelling configurations (Figure 2):

1. Without protection (NO PPE)
2. With airbag (AB)
3. With airbag jacket (AB+J)

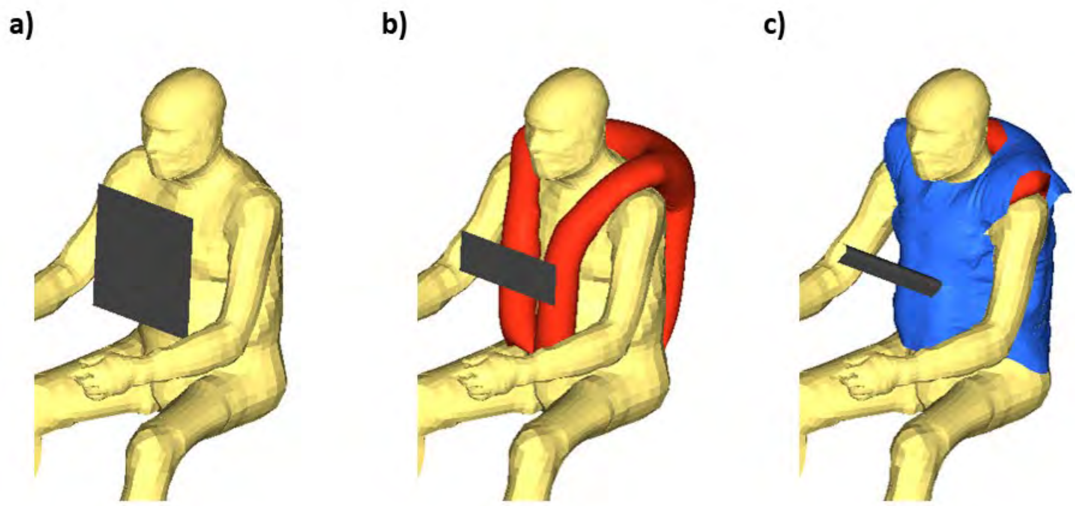

Fig. 2. Frontal thoracic impact simulations. a) Without protection; b) With airbag; and c) With airbag jacket.

Frontal thoracic impacts were simulated with 23.4 kg impactors centred over the 4th costal interspace and therefore over the chest deflection measurement. Three impactor shapes (Plate, Pillar and Kerbstone), already used in a previous work [6], were defined to consider penetrant and flat obstacles with larger contact surfaces. The plate was a square with a side of 30 cm (Figure 2a). The pillar was rectangular with dimensions of 10 cm*30 cm (Figure 2b). The kerbstone was rectangular on top with a length of 30 cm and a width of 5 cm. The impact face was a cylindrical face with a radius of 1.25 cm (Figure 2c). Impactors were meshed with 2D shell elements and modelled as rigid bodies with only one degree of freedom corresponding to the direction of the impact. Linear normal impacts were performed at 7 and 9 m/s. The movements of the human model were not constrained, i.e., it was not seated on any support and gravity acceleration was not considered. The airbag was perfectly inflated at the instant when the impactor touched the protector. The details of the parametric study carried out in this work are summarised in Table I. A total of 54 simulations were performed: 18 without protector, 18 with the airbag and 18 with the airbag jacket. The numerical simulation analysis addressed both skeletal and soft tissue injury risks. Thoracic injury severity caused by blunt impacts was evaluated with chest deflection [7] and the Viscous Criterion (VC) [8].

TABLE I
DESIGN VARIABLES OF THE PARAMETRIC STUDY

Variables	Tested values/categories
3 configurations	No protection (NO PPE), Airbag (AB) and Airbag Jacket (AB+J)
1 impact location	Frontal thorax
3 impactor shapes	Plate, Pillar and Kerbstone
2 impact velocities	7 and 9 m/s
1 impactor mass	23.4 kg
3 inflators	I1, I2 and I3

III. RESULTS

Airbag Jacket Model Validation

Resultant impactor accelerations obtained from experimental drop impact tests and the corresponding numerical simulations are depicted in Figure 3. The contact between the impactor and the protector defined the t=0ms. Focusing on experimental data, equivalent responses in terms of trend and range of the curves were observed by testing the airbag under textile and leather jackets. For the impact at 30 J, the bag was not completely compressed and no contact was noted between the impactor and the rigid trunk. The duration of both compression and rebound phases was around 20 ms (Figure 3a). For impact energies of 40 and 50 J, the airbag was unable to absorb all the impact energy and it was fully compressed. The contact between the impactor and the rigid trunk led to a high increase of the acceleration pulse at 17 ms for the impact at 40 J (Figure 3b). At 50 J, the impactor hit the trunk between 13 and 15 ms after contact with the jacket (Figure 3c). Only the airbag compression phase was evaluated for the model validation at 40 and 50 J because of the impactor rebound phase was disrupted by the contact between the impactor and the trunk.

The response of the numerical model was consistent with the behaviour of the real protector, which was found to be similar between both experimental configurations. The trend of the numerical acceleration curves was consistent with experimental data for all impact energies. The computed impactor rebound phase was 3 ms longer at 30 J than the experimental results. For simulations at 40 and 50 J, contact between the impactor and the trunk occurred between 1 and 3 ms earlier than in the experimental tests.

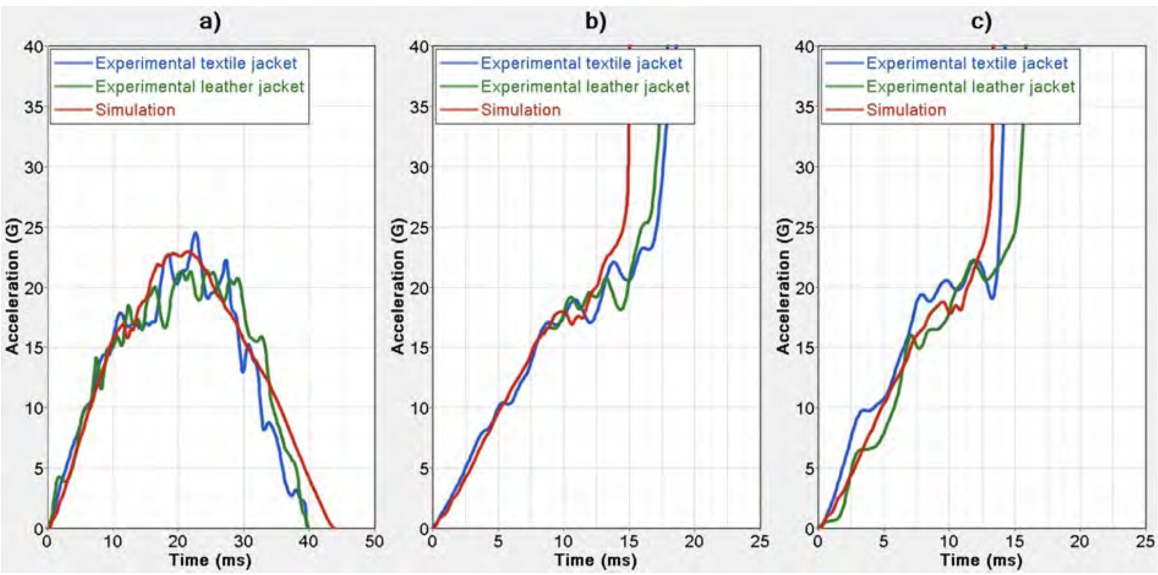

Fig. 3. Drop impact accelerations. a) Impact energy of 30 J; b) Impact energy of 40 J; and c) Impact energy of 50 J.

Airbag Inflation Injury Risk

Inflating the airbag alone, lower chest deflections (0.33-0.74 mm) than wearing the airbag under the jacket (6.16-10.58 mm) were computed as detailed in Table II. In the former case, the airbag tended to straighten up and detach from the human body. This phenomenon increased with mass injection and thoracic compression decreased by increasing the amount of gas injected into the bag. On the contrary, when the device was worn under the jacket, inflation was blocked by the garment and chest deflection increased with mass injection. When wearing the jacket, an increase in the bag's pressure and a corresponding reduction in volume were observed.

TABLE II
MAXIMUM CHEST DEFLECTION DURING AIRBAG INFLATION (PRESSURE AND VOLUME COEFFICIENTS IN BRACKETS)

Inflator	AB	AB+J
I1	0.74 mm (P, V)	6.16 mm (1.37*P, 0.92*V)
*I2=1.2*I1*	0.71 mm (1.57*P, 1.14*V)	8.42 mm (2.03*P, 1.03*V)
*I3=1.5*I1*	0.33 mm (2.17*P, 1.28*V)	10.58 mm (2.78*P, 1.15*V)

Mitigation of Blunt Impact Injuries

A comparative analysis was performed based on simulations with and without protector to quantify the benefits of wearing the airbag alone and under the jacket. Computed values of maximum chest deflection (D_{max}) and maximum Viscous Criterion (VC_{max}) are reported in Figure 4.

Regarding impacts without protection (NO PPE), D_{max} and VC_{max} tend to increase with impact velocity as well as for penetrant impactor shapes. The highest D_{max} (105.46 mm) and VC_{max} (1.70 m/s) were computed for the impact with the kerbstone impactor at 9 m/s, while the lowest ones (63.59 mm and 0.74 m/s) were observed for the impact with the plate impactor at 7 m/s. Average D_{max} and VC_{max} were 84.66 mm and 1.20 m/s, respectively.

Focusing on cases with the airbag alone (AB), the use of the protector reduced D_{max} and VC_{max} for all simulated impacts. The effectiveness of the airbag increased with mass injection and impactor surface, but decreased by increasing impact velocity. The maximum reduction of D_{max} (-37.58%) and VC_{max} (-48.65%) were obtained for the impact with the plate impactor at 7 m/s and I3, while the lowest gains were calculated for the impacts at 9 m/s and I1 with the kerbstone (-4.13% of D_{max}) and pillar (-5.47% of VC_{max}) impactors.

Considering simulations with the airbag under the jacket (AB+J), the highest mitigations of D_{max} (-31.76%) and VC_{max} (-52.70%) were computed for the impact with the plate impactor at 7 m/s and I3, while the lowest reductions were observed for the impacts with the kerbstone (-7.21% of D_{max}) and plate (-10.62% of VC_{max}) impactors at 9 m/s and I1. The gain of the airbag worn under the jacket, compared to the airbag alone, was more significant or at least equal for all the impacts at 9 m/s. Regarding impacts at 7m/s, the reduction wearing the airbag under the jacket was higher or equal than benefits obtained wearing the airbag alone except for kerbstone I1 (-10.62% vs. -10.53% of D_{max}), kerbstone I2 (-20.69% vs. -18.97% of VC_{max}), kerbstone I3 (-20.30% vs. -19.85% of D_{max}), pillar I3 (-25.80% vs. -25.49% of D_{max}) and plate I3 (-37.58% vs. -31.76% of D_{max}).

Raising mass injection improved the performance of the protectors for all impact configurations. The use of the airbag alone (D_{max}=76.21 mm and VC_{max}=1.07 m/s on average) or under the jacket (D_{max}=73.86 mm and VC_{max}=1.01 m/s on average), inflated with I1, attenuated impact severity. For I2, the combination of the airbag with the jacket (D_{max}=68.93 mm and VC_{max}=0.91 m/s on average) provided higher protection than the airbag vest (D_{max}=72.35 mm and VC_{max}=0.97 m/s on average). The maximum injury severity reduction was found with the airbag integrated into the jacket using I3 (D_{max}=66.25 mm and VC_{max}=0.77 m/s on average), while the benefit of the airbag alone was also significant (D_{max}=67.07 mm and VC_{max}=0.88 m/s on average).

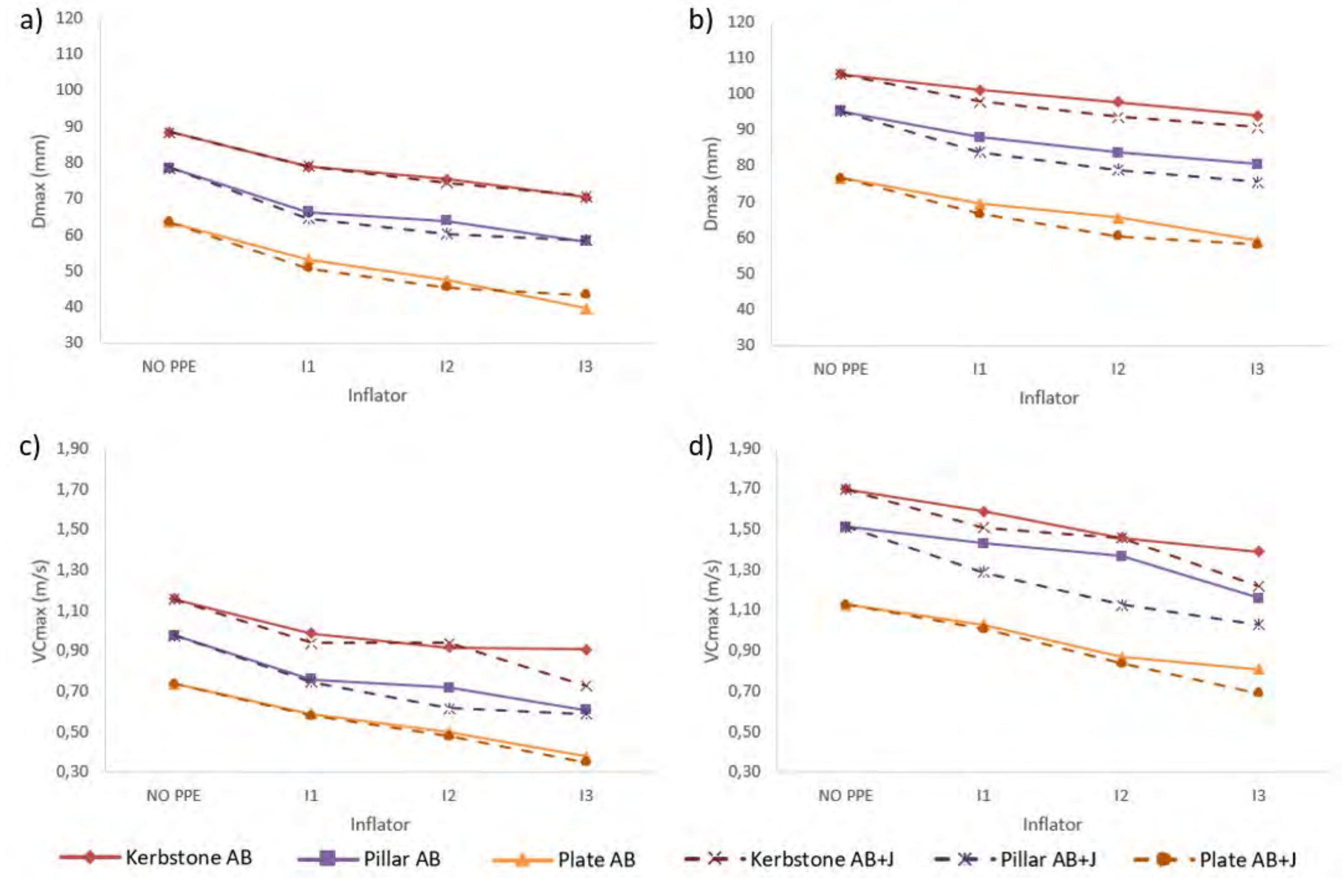

Fig. 4. Maximum chest deflection (D_{max}) and Viscous Criterion (VC_{max}) vs. mass injection. a) D_{max} at 7 m/s; b) D_{max} at 9 m/s; c) VC_{max} at 7 m/s; and d) VC_{max} at 9 m/s.

IV. DISCUSSION

Based on the evaluation method for wearable airbag protectors developed in previous work [6], FE simulations were performed to investigate the influence of wearing an airbag vest under a motorcycle jacket. The pertinence of this work was supported by the calibration of the AB+J model based on drop experimental test data leading to a good correlation of its response against frontal thoracic impacts.

Regarding injury risk related to the inflation of the protector, no ribcage injuries were noticed for either of the two modelling configurations (AB and AB+J) which is coherent with airbag users experience. The chest was compressed by up to 10.58 mm (3.94% chest compression), which is much smaller than the AIS1 ribcage injury threshold of 24% [7]. This preliminary analysis should be strengthened by modifying the geometry of the models to be able to inflate the airbag directly inside the jacket, allowing the application of the Viscous Criterion. According to the injury mechanisms and tolerances described in the work of [8], chest compressions measured when the airbag was perfectly positioned and inflated (0-4%) could not have caused severe soft tissue injuries. In fact, for chest compressions of up to 5% chest wall velocities above 30 m/s are necessary to induce blast injuries. For velocities lower than 3 m/s, which are coherent with those related to airbag inflation, the injury mechanism is the compression of the thorax and injury is sustained at 40% of chest compression by crushing of the tissue. Additional experimental data would be necessary to integrate minor and moderate soft tissue injuries, that could hypothetically be caused by the inflation of a wearable airbag. Another perspective could be the evaluation of injury severity on specific organs by applying local injury criteria based on pressures, stresses or strains as carried out in the work of [9]. Other human body morphologies and jacket sizes should also be considered to evaluate a wider range of inflation situations and provide recommendations for the safest airbag-garment combination as well as cases to be avoided. Complementary research could be performed to evaluate tighter jackets or one-piece suits. The main difference between jackets and suits lies in the blocking of the suit's vertical movement by the groin of the rider. When an airbag is worn under a jacket, the device can push the jacket upwards in order to increase the space for inflation. The effect of maintaining the airbag inflated during a long period of time on breathing couldn't be studied by chest compression. Static inflation tests by an air compressor could be done to address this point, while ergonomics and dynamic inflation tests are performed during certification process to avoid any issue for the user [10-11]. The study of injury risks related to the inflation on other body regions such as the shoulders or the back could be another future work, but modelling the sleeves of the garment seems necessary for a pertinent assessment on these areas.

In relation to protection against impacts, realistic impact conditions leading to D_{max} from 63.59 mm to 105.49 mm (AIS1-AIS4 for the ribcage [7]) and VC_{max} from 0.74 to 1.70 m/s (13-77% of AIS4+ soft tissue injury risk [8]) were simulated. The use of the airbag reduced injury risk for all simulated impacts, while similar or higher injury mitigation performance was observed with the airbag integrated into the jacket, especially for impacts at 9 m/s. This could be explained by the variation of the airbag's characteristics and by the enveloping effect of the garment. The jacket modified the inflation of the airbag, reducing the volume and the thickness of the air chamber and increasing internal pressure. Worn under the jacket, the shape of the airbag was more flattened, leading to a wider covered area of the human body, increasing the initial contact surface between the impactor and the airbag. The inflation conditions of the protector under the garment contributed to a higher reduction of impactor velocity during airbag compression. Further studies including sensitivity analysis should be performed to quantify injury mitigation capacity within various pressure and thickness ranges in order to optimise the effectiveness of the airbag. An excessive increase in pressure exceeding the optimal one would reduce the absorption capacity of the protector, avoiding the contact between the human body and the obstacle, while transmitting the energy of the impact. In order to improve the global protection capacity of the protector, other body regions such as the shoulders, abdomen or the spine should also be considered as injury tolerance differs from one body region to another. In this respect, the development of garments with the capacity to locally adjust the volume and shape of the airbag, to optimise the protection of each body region, could be one of the potential improvements concerning airbag jacket design. For future studies, a review of the validation process of the current HBM or the use of other models more suitable for injury risk assessment on specific body regions should be considered.

The pressure, volume and shape of an airbag are interrelated and depend on the patterns and mechanical properties of the fabrics as well as on the mass injected into the bag. The design of the airbag is restricted by technical limitations, ergonomic constraints and performance requirements in terms of intervention time and covering areas, among others, which make safety improvement difficult. For the specific airbag and jacket designs studied in this work, injury severity tends to decrease as the mass injected into the airbag is increased, thus pointing out the importance of considering airbag inflation for safety assessment. Additional simulations with other inflator characteristics should be carried out to define the optimal configuration that would minimise the risk of injury for the motorcyclist. The effectiveness of protectors also depends on impact conditions, especially on the shape of the impacted obstacle. In the present work, the airbag was more effective in case of flat impacts and the jacket helped to extend the impact on a wider surface for the pillar and kerbstone impactors, increasing the performance of the airbag. The use of a passive chest protector would be the best solution to improve the protection provided by the airbag in case of penetrant impacts as suggested by [12]. The combination of airbags, passive protectors and garments should be further investigated in order to optimise the protection in all impact situations. Current EN1621-4 European standard for mechanical airbags [11], derived from passive body protectors standards, only test airbags against penetrant impacts and does not evaluate the main benefit of airbags, i.e. energy absorption. The development of a specific impact test method for the certification of wearable airbags is required for a pertinent evaluation.

In addition to increasing pressure and contact surface, the jacket also provides an enveloping effect on the airbag, limiting the movement of the device and the redistribution of the air during compression. Inflating the airbag under the jacket also increases the tension of the fabrics' fibres and therefore their bending resistance. The superior restitution capacity obtained by coupling the airbag with the jacket could increase impactor deceleration when the airbag is fully compressed. For the two garments experimentally tested in this work, the impact response of both airbag jackets was equivalent and therefore the impact absorption capacity of motorcycle jackets could be considered insignificant compared to airbag devices. Motorcycle clothing provides additional protection for superficial soft tissue damage such as abrasions, cuts, lacerations, bruises and burns [13-14]. This advantage is also applied to the airbag, if worn under the jacket, and enables the design of lighter and more breathable safety devices. Since motorcycle jackets can improve the effectiveness of airbag protectors, the interaction between airbags and garments should be investigated further. One of the main limits of this study was the use of a conceptual jacket model, developed without performing tests to obtain the mechanical properties of the fabrics as done for the airbag vest in previous research [6]. Additional work, including the development of specific leather and textile jacket models, should be carried out for a more detailed analysis of the enveloping effect of the garment and its influence on airbags energy absorption and restitution capacities.

V. CONCLUSION

The effects of coupling a wearable airbag protector with a motorcycle jacket on injury risk during the inflation and on protection against impacts were investigated. This work was supported by the validation of the airbag jacket model under impacts on the frontal thoracic area.

No ribcage injuries were noticed due to the inflation of the airbag protector alone or under the jacket. The maximum computed chest deflection, 10.58 mm (3.94% chest compression), was significantly lower than the injury threshold for AIS1 ribcage injuries (24%) [7].

The quantitative comparative analysis between simulations with protector and reference simulations without any protection, demonstrated that the effectiveness of the airbag was maintained or even improved when it was worn under the jacket, especially for impacts at 9 m/s. Additional reductions by up to -5.15 mm of D_{max} and -0.24 m/s of VC_{max} were measured with the jacket. Airbag benefits were more significant for impacts against obstacles with larger contact surfaces and increased with mass injection. Interaction between airbags and garments should be optimised to minimise injury occurrence and severity.

VI. ACKNOWLEDGEMENTS

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