Investigating the Use of Adhesively-Coated External Airbag to Reduce Post-Impact Kinematics.

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Abstract Ground or secondary impact is a known source of injuries to vulnerable road users. Efforts to meet/exceed existing pedestrian protection standards have been shown to reduce injuries due to primary impact, but the secondary impact problem remains significant and unaddressed. Using computational and experimental methods, we investigated the efficacy of adhesive coated pedestrian airbags in reducing secondary impact severity. The impact scenario of a 50^{th} %ile male with a sedan front surface and adhesively-coated airbag was modelled. The human body was comprised of rigid bodies with freely rotating joints. Adhesive properties were calibrated based on ball drop tests. Results indicate an adhesively-coated airbag may prevent flight, or reduce rebound velocity, resulting in reduced secondary injuries. Manufacturing challenges, including tack time, packaging, deployment, laminating onto fabric and release layers, were addressed by experiments. These experiments have shown that overcoming many of the challenges, including deployment, is possible. Modelling and prototyping demonstrated that adhesively coated airbags could be helpful in reducing exit velocity from primary impact, thus reducing secondary injuries.

Keywords adhesive, airbag, kinematics, pedestrian, secondary impact

I. INTRODUCTION

The sources of injuries to vulnerable road users (VRUs), e.g., pedestrians, cyclists, powered two wheelers, in vehicle-to-VRU accidents have historically been separated between primary impacts with the vehicle and subsequent secondary impacts with the ground or environment [1]. The efforts to mitigate pedestrian injuries have focused on changes to vehicle geometry and stiffness to reduce the severity of primary impact injuries, independent of secondary impact. These efforts have been well-placed as 1) the majority of life-threatening injuries can be attributed to primary impact [2-4], 2) the dynamics of the VRU in primary impact is more predictable than the subsequent secondary impact, and 3) it is relatively easier to implement countermeasures to mitigate injuries from primary vehicle impact vs. secondary ground contact. Through GTR regulations and Euro NCAP programmes, the focus on primary impact has been shown to be effective in reducing pedestrian injury severity [5-7]. However, the injuries that can be attributed to secondary impact remain significant and unaddressed.

[2] reported 65% of pedestrians in vehicle-to-pedestrian crashes sustained at least one injury induced by the ground. [4] reported 20% of AIS3+ injuries to pedestrians were a result of ground contact. At lower injury severities (AIS2+), field studies by [8] and [9] showed an increase in role (26% and 28%, respectively) of the ground in contribution to injury. The latter study also suggests that the relative contribution of ground contact injuries is likely to increase as vehicle impact speeds decrease, as more than half (57%) of AIS2+ injuries in their study could be attributed to the ground for vehicle speeds below 30 km/h [9]. The contribution of secondary impact has been reported to be more pronounced for cyclists than pedestrians, with the majority of AIS2+ injuries being attributed to ground contact [3][8].

For serious injuries (AIS3+) sustained in secondary ground impacts, it is well-established that the head is the body region with the highest injury frequency and severity [2-4][10]; consequently, characterization of ground impacts in literature have focused on body orientations that give rise to high head-ground velocities. Computational studies suggest that a more optimal scenario for reduced head-to-ground impact severity occurs when the lower extremities are first to make contact with the ground [11]. While it is difficult to predict the exact injury pattern to a pedestrian stemming from ground impact, reducing throw distance (via lower vehicle

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impact speed and lower primary impact rebound velocity) has been shown to correlate to lower head injury rates in ground impacts [9].

There have been very few prototypes tested for reducing the severity of secondary ground impact. Jehu *et. al.* [12] lowered the bonnet leading edge of a vehicle and installed a catching mechanism that retained un-instrumented adult and child dummies at vehicle speeds up to 24 km/h [12]. Students at the Technical University Berlin approached the problem by deploying an airbag from underneath the front of a slowly-braking vehicle, to cover the ground, and demonstrated effectiveness with a 50^{th} %ile ATD struck at 20 km/h [13]. A seemingly straightforward solution is to extend the duration of the vehicle-to-VRU momentum transfer, by reduced braking at impact, relying on friction to retain the VRU on the vehicle. Two main obstacles to this solution are 1) cases of forward projection (when pedestrian CG height is lower than the bonnet leading edge) whereby the pedestrian would be at risk of being run over, and 2) the difficulty in switching braking schemes (whether it is human behaviour or sensing/algorithmic) from full braking up through the beginning of primary impact, to light braking (~0.4g's) for the duration of the event.

Our approach to the secondary impact problem involves the use of adhesive to keep the VRU with the vehicle after primary vehicle impact has taken place. We initially considered applying adhesive onto the vehicle front structure, but deemed this implementation unfeasible for multiple reasons, chief among them being the difficulty in fabricating a vehicle coating that would expose an adhesive under-layer upon impact. Our current concept involves an externally mounted pedestrian airbag, with adhesive applied on the impact surface. The use of external airbags for pedestrian protection in primary impact has precedent in the form of cowl-mounted systems [14] and bumper-mounted systems [15]. The system would ultimately rely on autonomous sensing to trigger airbag deployment. This study investigates the efficacy of a pedestrian airbag that could deploy with an adhesively-coated surface that could ultimately reduce the severity of head-to-ground contact.

II. METHODS

To evaluate the effectiveness of an adhesively coated airbag, five main areas needed to be investigated.

- Feasibility of applying adhesive onto an airbag surface
- Determining the degree of stickiness that the adhesive can provide
- Ensuring that the airbag could properly deploy when it has an adhesive surface
- Calibrating computational models to the adhesive stickiness experiments
- Using the computational models to simulate pedestrian impacts onto an adhesive airbag

This section covers the methods used in each of these areas.

Applying Adhesive onto an Airbag Surface

In order to assess ease and feasibility of manufacturing an adhesively coated airbag, we performed liner release force tests, using the silicone coated side of the airbag as a release liner. The fabric used was Nylon 66, and the adhesive was applied to the uncoated side. This *self-contained release liner* would allow for a simple cylindrical roll packaging technique that is commonly used in side curtain airbags. A liner release test machine was used to characterise release forces.

Determining the Degree of Stickiness that the Adhesive can Provide

In order to provide basic data to calibrate our computational models, we developed a simple *ball drop* experimental test (Fig. 1). This test used a soft foam component (0.315 m x 0.315 m x 0.490 m) to simulate the stiffness of an inflated airbag, underneath an adhesively coated airbag fabric, using a hard polyurethane rubber ball of known mass (0.6 kg) and diameter (0.1 m), from a set of predetermined heights. It was assumed that the smooth surface of a polyurethane ball would result in lower adhesion as a worst case scenario compared to human skin or clothing fabric. Drop, impact and rebound were captured using high speed camera to determine speeds and distances. Several adhesive samples were acquired from a supplier and tests were run on each to determine the best candidate.

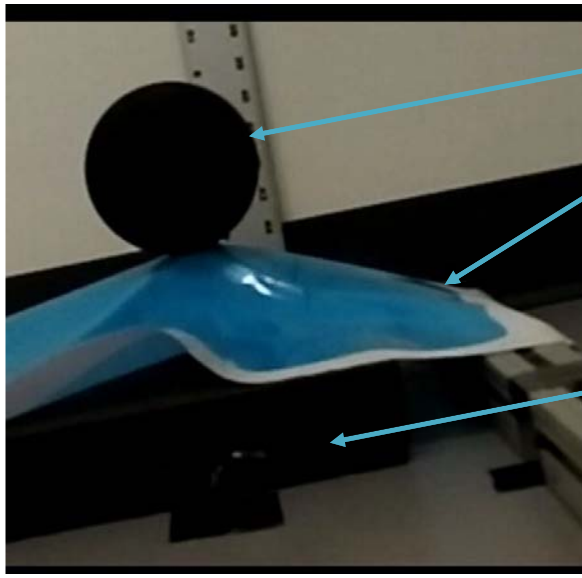

Fig. 1. Ball Drop Experimental Test: Ball rebounding after contact with (blue) adhesive.

Ensuring that the Airbag could Properly Deploy when it has an Adhesive Surface

The complexity of airbag deployment and the unknown effects of the adhesive on the deployment led us to set up several experiments to assess the performance. Prototype airbags 0.3 m wide x 0.9 m long were built for the purpose of testing the following:

1. Effects of adhesive on airbag deployment times
2. Shape and trajectory of deployment changes
3. Time rate dependencies of airbag release when adhesively coated

We constructed adhesively coated prototype airbags with a rolled packaging approach (Fig. 2) to test live deployment.

Fig. 2. Prototype Adhesively Coated Airbag: extended and rolled.

In order to test deployment, we built a custom pressure tank with a dump valve to simulate inflator deployment.

Calibrating Computational Models to the Adhesive Stickiness Experiments

Computational modelling was used to evaluate the effectiveness of adhesive on the airbag surface. The first step in the process was adhesive material model calibration. The strength of each adhesive tested was quantified using rebound height from ball drop tests (described in the previous section). In these tests, a hard polyurethane rubber ball of a known mass (0.6 kg) and diameter (0.1 m) was dropped on a soft polyurethane foam block (0.315 m x 0.315 m x 0.490 m) without adhesive coating and with three separate adhesive coatings. The ball was dropped from a height of 1.0 m (impact velocity 4.43 m/s) on the foam block and the rebound height was captured using high speed video for all the experiments. The ball drop based calibration method was selected because adhesive behaviour could be different with different impact speeds and a quasi-static test may not be relevant for adhesives with target use case of high speed impacts. A sample size of 3 was used for each experiment. The experimental setup was then simulated using Abaqus (commercially available Finite Element Analysis software). First, the experiment without adhesive on the foam surface was used to calibrate the base foam material properties. Then three separate adhesives were simulated using cohesive behaviour capability inside Abaqus, where a *sticky* response could be defined between two contacting surfaces using an energy dissipation function applied at contact. The value of dissipated energy was calibrated such that the rebound displacement of the ball from simulations matches that from the experiments with corresponding adhesives. The strongest of these adhesives, i.e., the one which resulted in lowest rebound height, was selected for two additional ball drop tests from heights of 1.8 m (impact velocity 6.0 m/s) and 6.4 m (impact velocity 11.2 m/s). Dissipation energy model in Abaqus was calibrated based on these tests and it was found that for the same adhesive, dissipation energy, i.e., adhesive bond strength, increased with higher impact velocities. In addition, some of the ball-drop experiments were repeated with ball covered with fabric which resulted in lower rebound height indicating that adhesion would be higher for a fabric surface.

Simulate Pedestrian Impacts onto an Adhesive Airbag

For the next step, the impact scenario of a 50th %ile male model with a representative medium sedan front surface and a large pedestrian protection airbag mounted on the front of the vehicle was modelled (Fig. 3). The vehicle front surface was modelled as a rigid surface with 1500 kg mass applied at the vehicle reference point. The 50th %ile male human body model was modelled using rigid bodies each representing the mass and inertia of individual regions of the body with freely rotating joints. The mesh, mass and inertia properties for the body regions for this model were based on the Madymo faceted pedestrian model [16].This simplified human body model was used for the ease of implementation. The human body model was positioned laterally at the middle of the vehicle in a walking stance for all the impact scenarios. The airbag was modelled with 30 kPa internal pressure and was mounted on the front of the bumper as shown in Fig. 3. It should be noted that the feasibility and effectiveness in reducing primary injuries of such a large airbag was not studied in this investigation. It was used in this model to purely investigate the effectiveness of adhesive on the surface. Several simulations were conducted first without adhesively-coated airbag surface and then with adhesively-coated airbag front surface at an impact speeds of 40 km/h (11.2 m/s). The first set of simulations was run with no braking. Another set of simulations were run with hard braking (0.8G constant deceleration) applied right after pedestrian airbag inflation and just before the pedestrian impact. For the adhesively-coated airbag front surface simulation, the model was run with adhesive properties determined from 6.4 metres ball-drop test. Then, the adhesive strength was increased for each subsequent model to determine the threshold at which the human model would remain stuck to the airbag surface. The simulations were run up to 450-500 msec which was a sufficient duration to complete the primary impact and allow separation from the airbag surface. Secondary impact was not modelled with the ground surface since the human body model is not biomechanically validated and joint rotations may not be realistic during impact with the ground surface. It was assumed that reduction in exit velocity would result in lower injury risk for the secondary impact.

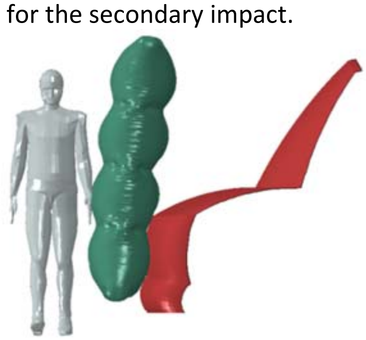

Fig. 3: 50th %ile male human body model positioned in front of the rigid car surface with airbag mounted in front of the bumper at t=0 msec.

III. RESULTS

Applying Adhesive onto an Airbag Surface

Using the coated side of an airbag as release liner yielded loads on average of 4 g/mm (2 g/mm is typical for common release liner materials). No apparent rate dependent loading was observed as we varied the speed from 1 m/s to 5 m/s (max speed test the machine can achieve). Only peak initial load varied but that is expected. The adhesive remained on the (uncoated) bag fabric.

Determining the Degree of Stickiness that the Adhesive can Provide

Ball drop tests on our leading adhesive candidate are shown in Table I:

TABLE I
RESULTS FOR LEADING CANDIDATE ADHESIVE IN BALL DROP TESTING

Drop Height (m)	*Velocity (kph)*	*Rebound (m)*	*Coefficient of Restitution*	*Notes*
1	16	.05	.22	Ball stuck to fabric
1.8	21.6	.1	.24	Ball stuck to fabric
6.4	40	2.1	.57	Ball did not stick
1	16	.48	.69	No Adhesive
6.4	40	3.3	.72	No Adhesive

These values, and values from other adhesives tested, were used to calibrate our computational models material properties. Results pointed us to dive deeper into deployment at speed, given the positive trend in reduction of rebound due to the adhesive.

Ensuring that the Airbag could Properly Deploy when it has an Adhesive Surface

Deployment tests showed favourable results, as inflation times for coated and uncoated bags under similar pressure settings were similar (~0.18 sec at 0.55 MPa, note that the pressure tank approach is not as fast as an actual airbag inflator would be). Unfolding during deployment was slightly different, as bags with adhesive deployed at a higher angle from horizontal than uncoated bags (Fig. 4).

Fig. 4. Mid-deployment adhesively coated airbag.

Adhesive remained intact after each deployment, even with some samples used for multiple deployments. There was negligible difference in deployment between the non-coated and adhesively coated airbags.

Simulate Pedestrian Impacts onto an Adhesive Airbag

The car impact models were run without adhesive and with increasingly stronger adhesives with damage energy of 630 J (Adhesive-630, this corresponds to the strongest adhesive we tried in the ball drop test), 5000 J (Adhesive-5000), 6000 J (Adhesive-6000) and 8000 J (Adhesive-8000), respectively. Note that Adhesives 5000+ are artificial for now, and would have to be developed. The rationale for modelling artificial adhesives is to find out how sticky we would need to be to actually stay stuck to the car. The results for each of these cases at 40 km/h impact velocities with no braking (Figs. 5 and 6) and hard (0.8G) braking (Figs. 7 and 8) are shown below. Simulations at other speeds were run as well, but not included here for brevity - similar trends were observed. Relative velocity of pedestrian pelvis with respect to the car was calculated from the following equation:

$$V_{relative} = \sqrt{(V_x - V_{car})^2 + V_y^2 + V_z^2} \tag{1}$$

where, V_x, V_y, V_z are pelvis velocities in X, Y and Z directions, respectively and V_{car} is the car velocity in X direction.

The simulation results showed that the Adhesive-630 was not strong enough to change the relative velocity of a pedestrian compared to the simulation without adhesive. With increasingly stronger adhesive, higher energy dissipation occurred due to breaking of adhesive bonds which resulted in lower relative velocities. For the no-braking cases with the two strongest adhesives, Adhesive-6000 and Adhesive-8000, there was significant reduction in pelvis velocity, rebound height, and angular velocity (Figs. 5 and 6). It can be hypothesized that by preventing separation of arm, shoulder, and head from the airbag surface in these two instances (Fig. 5), a less injurious ground contact could result.

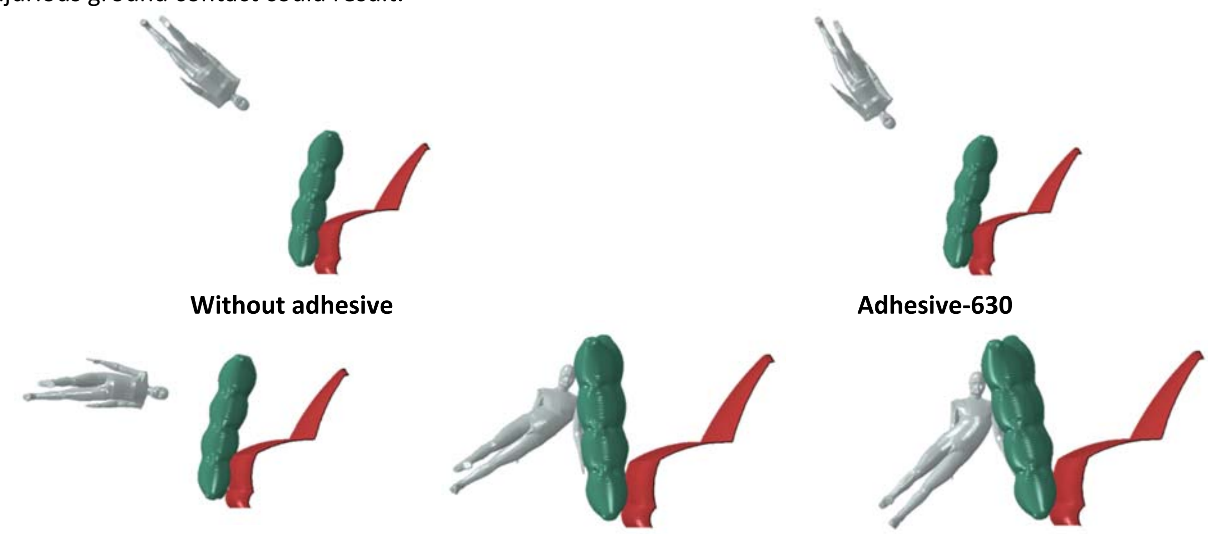

Fig. 5: Pedestrian orientation after impact for car impact velocity of 40 km/h and no braking at t=500 msec.

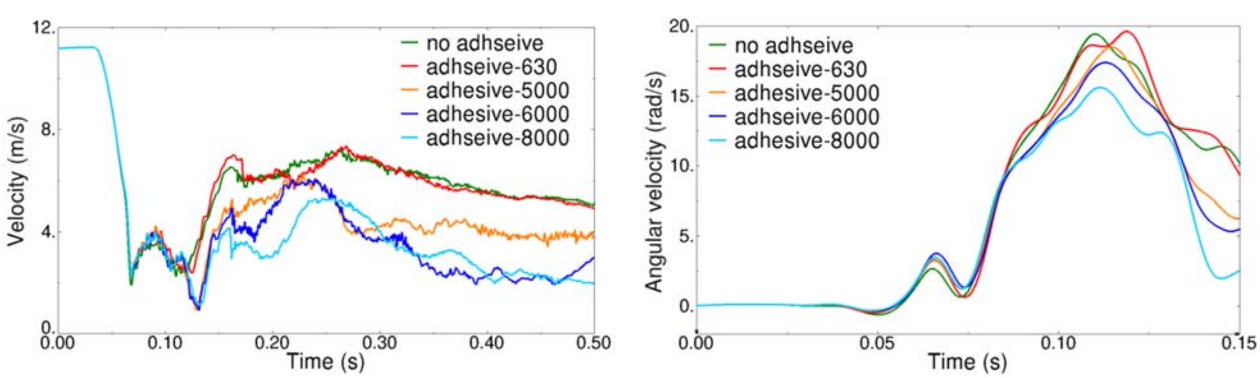

Fig. 6: Relative Velocity derived using eqn. 1 of pelvis with respect to car (left) and Angular Velocity of pelvis in the out-of-plane direction (right) for impact velocity of 40 km/h and no braking.

For 40 km/h impact velocity with hard (0.8G) braking, similar reduction in vertical velocity was observed as compared to without braking case for the three strongest adhesives, namely Adhesive-5000, Adhesive-6000 and Adhesive-8000. These results were worse than the 40 km/h impact without braking because braking resulted in higher relative velocity between the car surface and pedestrian after primary impact as shown in the relative velocity plots.

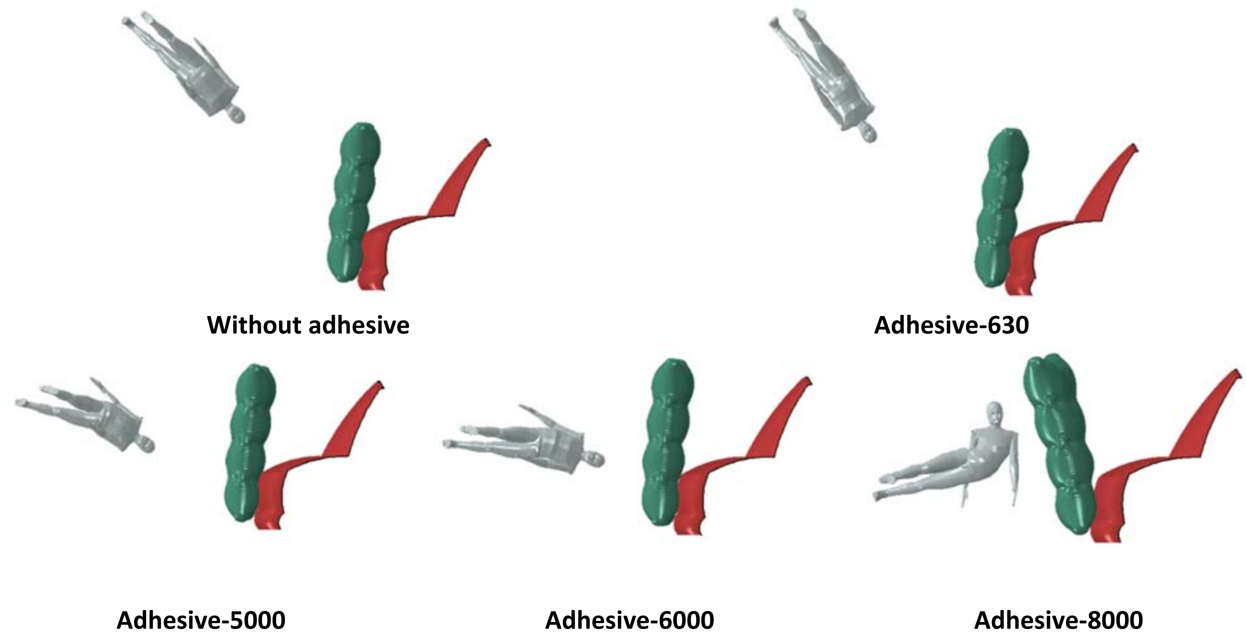

Fig. 7: Pedestrian orientation at t=450 msec after impact, for car impact velocity of 40 km/h and 0.8G braking.

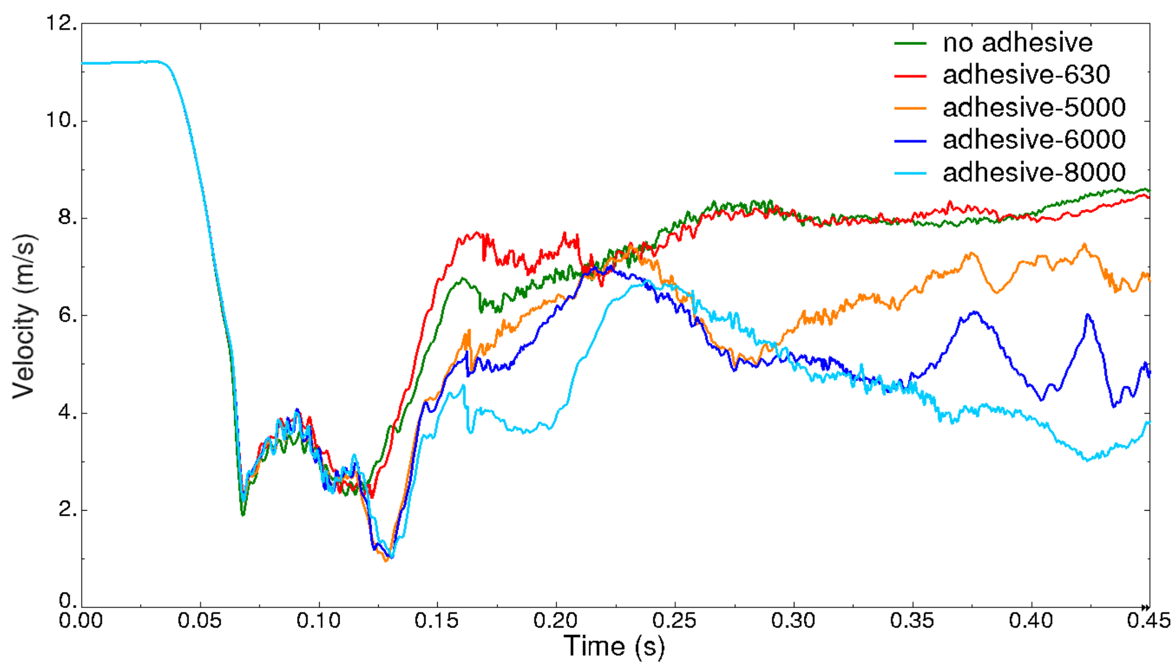

Fig. 8: Relative Velocity derived using eqn. 1 of pelvis with respect to car for impact velocity of 40 km/h and 0.8G braking.

HIC15 values were also calculated for all the cases at primary impact with the airbag (Table II). The HIC15 values were low for all the cases due to the presence of airbag indicating no significant risk of head injury during primary impact. The HIC15 values reduced further for lower strength adhesive and then increased for stronger adhesives.

TABLE II
HIC15 VALUES FOR PEDESTRIAN MODELS DURING PRIMARY IMPACT

Adhesive Energy (J)	*HIC15*	
	40 km/h no brake	*40 km/h*
0 (No Adhesive)	167	186
630	130	118
5000	221	192
6000	214	218
8000	215	218

IV. DISCUSSION

Applying adhesive to the surface of uncoated airbag fabric does not appear to present major challenges, and in the drop tests performed, the adhesive remained stuck to the airbag fabric. Testing with the striking object being of different materials could possibly reveal cases where the adhesive stuck to the object and released from the fabric. However, the energy to pull the adhesive off the fabric in those cases would still be greater than what we observed by the object pulling away from the adhesive in the tests already done, causing an even greater reduction in rebound velocity.

Results of the drop tests illustrate that the adhesive causes a substantial decrease in rebound height as compared to the cases where no adhesive was used. In cases up to 21 km/h, the ball actually stayed stuck to the fabric, and this speed and below accounts for about half of pedestrian vehicle impacts [17]. In the 40 km/h test, a reduction in restitution of 20% was seen, and it is expected that with further research into suitable fast-tack adhesives, this can be improved further. The ball drop experiments were conducted to characterize the adhesive properties assuming that the smooth ball surface would result in lower adhesion as compared to human skin or fabric, resulting in the worst case scenario. Further investigation of impacts with sizes and masses corresponding to different body regions is needed for a complete characterization of adhesive behaviour.

Deployment of an airbag from a folded/packed condition can be addressed with separate release liner materials, but taking that approach could cause difficulties in having the liner getting pulled off during deployment. Testing has shown that our approach of using a silicone coated side of the airbag itself as the release layer is feasible and it greatly simplifies packing. Also, the presence of the adhesive has negligible effect on how the airbag deploys. Further investigation is needed with stronger adhesives. In addition, based on the discussions with the adhesive vendor, the adhesive strength would not deteriorate with aging. The data for the adhesive used in these experiments indicated that there should be no significant performance degradation across the expected environmental temperature range; however, additional investigation is needed to characterize these effects.

Simulations show that with increasing levels of adhesion, there is an increasing reduction in the magnitude of the resultant rebound velocity (up to 50 to 60% for the 40 km/h situation for the strongest adhesive). Reductions in the X component of relative velocity were upward of 75% for the strongest adhesive. Of significant note is the change in the rebound Z component, as should be obvious from the orientation images. The pedestrian, at higher levels of adhesion is no longer launched up into the air. Z velocities have changed (for the better, from upward in direction to downward) by about 5 m/sec, and the resulting orientation of the pedestrian appears to be substantially less likely to cause a head impact. The rebound velocities directly influence *projection distance*, and it would be expected that a reduction here would cause a reduction in the secondary impact injury [9]. Another aspect of increasing stickiness is a decrease in angular velocity. This decreased rotational energy should also be favourable toward secondary injury reduction.

It is natural to ask whether the best of the existing adhesives that were tried could provide a benefit in the context of the sticky airbag. Unfortunately, the answer is no, that adhesive would only be effective at sticking the pedestrian when the impact speeds were so low that secondary impact is not much of a concern. A quest for stronger adhesives must be undertaken. There may be some potential chemical changes in the existing adhesives which could help us achieve higher adhesion, but it has not been investigated yet.

The airbag material modelled in this study was based on actual test data from fabric. The airbag mounting point was located close to the bumper region which is a feasible mount location. The strains at the mount regions were well below the failure strains for the material and the forces observed at the mount could be easily dealt with common engineering materials. Therefore, we found no risk of airbag material or mount failure.

Of interest is the role of braking in the simulations of wrap trajectories. As could be expected, with no braking, the adhesive is more effective in reducing launch velocity compared to the full braking scenario, as the separation energy is primarily a function of elastic airbag response, and does not need to overcome separation energies imparted during hard braking. While a strategy of full braking prior to impact followed by delayed braking after impact would be difficult for a human driver to implement, research and testing into the autonomous vehicles sensing/compute capabilities could realise the benefits of this approach. Simultaneously, the implementation of airbag venting needs to be explored so as to lessen the demands placed on stronger adhesives in reducing launch velocity.

The HIC15 values reduced further for lower strength adhesive and then increased for stronger adhesives. This could be due to a combination of reduced body rotation and increased airbag rotation resulting in a slightly larger gap between the head and the airbag surface for higher strength adhesives. The amount of change seen was not large, but it still warrants further investigation with a human body model with realistic joint stiffnesses.

Despite the many beneficial effects of the increased adhesive strength, the fact remains that the higher strength adhesives modelled do not exist yet. This work provides targets for adhesive manufacturers to work toward. In addition, this work has only begun to scratch the surface of all the variables involved in a secondary impact and the variations in countermeasures. The following is a partial list of areas that need further exploration:

- Stronger adhesives
- Effect of clothing/skin
- Friction coefficients
- Airbag venting and pressure variation
- Different airbag configurations and sizes
- Other pedestrian sizes and bicyclists
- Other braking strategies
- Getting unstuck from the adhesive
- Biofidelic human body model

V. CONCLUSIONS

Secondary impact is a serious cause of injuries in pedestrian/vehicle collisions. This study was aimed at determining the feasibility and efficacy of reducing secondary impact dynamics by sticking the pedestrian to a large airbag mounted at the front of the vehicle. We have found that applying adhesive to an airbag surface, and using a silicone coated surface of that same airbag to act as a release layer, to be a viable implementation approach, with no detriment to deployment. It was seen that for certain speeds, existing adhesives could be strong enough to adhere a ball to a target in simple drop tests, and these tests could be used to calibrate computational models of a vehicle to human impact. In the simulation runs for those models, potential secondary impact benefits of an adhesive coated airbag were seen. The benefits included reduction in the magnitude of both translational and rotational rebound velocities, and more *head upward* positioning of the pedestrian. The role of braking strategy in the ability to stick the pedestrian to the bag was investigated and some benefits were found for the act of delaying braking till after impact. By simulating increasingly stickier simulated adhesives, we have identified target areas for adhesive specialists. Further work must be conducted to more thoroughly investigate a number of related variables, but this work indicates that there is merit to the idea of using sticky airbags as a means to mitigate secondary impact injury.

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