The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1560-6074.htm

An automatic air inflated tubeless safety jacket for motorbike riders

Rameesh Lakshan Bulathsinghala, Sandun Fernando,
Thantirige Sanath Siroshana Jayawardana, Nilanthi Heenkenda,
Sajeeva Jeyakumar, Prathees Packiyarasa, Gamage Hemamala and
Dhananatha Wijesena
*Department of Textile and Clothing Technology, University of Moratuwa,
Moratuwa, Sri Lanka*

Received 5 January 2021
Revised 2 March 2021
Accepted 13 April 2021

Abstract

Purpose – Motorcycle is one of the popular modes of transport in developing countries. However, the statistics related to accidents show that motorcycles are the most vulnerable vehicles. Research studies have revealed that half of all the possible types of motorcycle injuries could be reduced or prevented using effective protective clothing. Facts and figures emphasize that this is high time to develop a safety jacket for motorbike riders. This paper aims to develop an innovative, integrated automatic air-inflated tubeless jacket to prevent major injuries in fatal accidents.

Design/methodology/approach – Two accelerometers integrated near the front axle, an angle sensor and the electronic control unit (ECU) were used to detect the collision or accident. The sensors were fixed on the bike and connected with the ECU via a bluetooth device that was always at the activated stage. The fused sensors were emulated with the ECU under laboratory conditions. The trigger signal generated by the crash discriminant algorithm triggered the chemical reaction to generate N2 gas and inflate the tubeless safety jacket.

Findings – Under laboratory conditions, it was found that the signal generated by the ECU unit ejected approximately 15 litres of N2 gas in volume to fill the jacket within 100 milliseconds, which was less than the approximate estimated falling time of the rider 120 milliseconds.

Originality/value – The existing developments of airbag systems in motorbikes are mounted on the motorbikes' frame, following the airbag systems in automobiles. These developments cannot fully protect the rider due to differentiation in crash dynamics and respective positions of the rider at the point of impact. Though few safety jackets and airbag vests are developed, the airbag deployment is activated when rider and motorbike separated during a collision using a tether-triggering mechanism. The authors designed the jacket so that inflation is activated not only by crash sensors but also on the fusion of multiple sensors based on a crash discriminative algorithm. The airbag deployment mechanism is incorporated with the jacket and acts as a safety jacket during a collision.

Keywords Protective clothing, Tubeless-jacket, Sensor fusion, Automatic activation, Motorbike riders, Textile, Garment, Intelligent system, Woven fabric

Paper type Research paper

1. Introduction

The motorcycle is one of the popular modes of transportation worldwide, especially in developing countries. The reasons for the popularity of these types of vehicles are low in market price, running cost, maintenance cost and less travel time, even on traffic-congested

---

The authors wish to thank HSK Nilmini, HM Seneviratna and Mr Silva of clothing laboratory for the technical assistance in the fabrication of the air jacket and the University of Moratuwa for the facilities provided.

Research Journal of Textile and Apparel
© Emerald Publishing Limited
1560-6074
DOI 10.1108/RJTA-01-2021-0002

roads due to their maneuverability. However, national statistics in Sri Lanka show that motorcycles are the most vulnerable vehicles. According to the National Council for Road Safety, there have been 1,228 fatal crashes involved with motorcycles, killing 1,269 people in 2017. That is 43% of all the vehicle crash fatalities in Sri Lanka for 2017, which is the highest compared to other vehicle types (Dias *et al.*, 2018). Research indicated that half of all possible motorcycle injuries could be reduced or prevented using effective protective clothing (Rome and Stanford, 2006). As the number of motorcycle crashes in Sri Lanka continues to increase with the growing number of motorcycle registrations annually (Dias *et al.*, 2018), the need for a high-performance air jacket is proportionally increased.

There are tethered airbag systems for motorbikes developed in jackets and vests, such as Helite – Built-in Armor, Hit-Air-Wearable airbag and MotoAir-Motorcycle airbag vest. These brands introduced lighter airbag vests and jackets that act as a body splint. The airbag deployment is triggered through a coil wire that pulls a key from the gas releasing system as riders separated from the motorbike and eject gas to inflate the vest. During a collision, crash dynamics are initially and fully absorbed by the vehicle before the occupant (Gabauer and Gabler, 2006). The tethered-triggered airbag systems provide an occupant-responsive decision, which delays response time in response to deploy airbags than vehicle-responsive decisions in crash sensor-mounted vehicles. Therefore, airbag deployment based on vehicle-responsive decisions provide better safety for riders. Moreover, the tethered-triggered airbag systems do not guarantee occupant safety during "roll out" and "slippage" crashes since riders will keep intact with the motorbike for a considerable time in some crashes.

Honda announced the commercial availability of an airbag system with their 1800 cc motorcycle in which airbag deployment decision is based on collision judge logic triggered by sensors ("Honda Gold Wing Motorcycle Airbag System Explained - auto-evolution", 2021; Kuroe *et al.*, 2004; Nayak *et al.*, 2013). Aikyo *et al.* (2015) analyzed the application feasibility of using an airbag system to motorbikes without a sufficient reaction structure based on seven impact configurations specified in ISO 13232. In this study, an upraised airbag with three different functional areas was proposed. The airbag was stored in a retainer box and can absorb the rider's kinetic energy during a collision without a supporting structure. However, one of the limitations perceived in airbag systems mounted on motorbikes is that riders are less likely to be in a fixed location with respect to the airbag at the point of impact, called the "out of position" effect (Chawla and Mukherjee, 2007). The motorcycles with mounted airbags only consider frontal collisions for airbag deployment decisions and do not provide safety during "roll out" and slippage crash types. Due to drawbacks in tethered-triggered airbag systems and mounted airbag systems, the authors in this paper focused on an airbag safety jacket with an air inflation mechanism triggered by a discriminative crash algorithm through the fusion of crash sensors.

According to the literature analysis, frequently reported collision contact points were at the right front and left front of the motorbike. Based on 906 motorcycle crashes, MAIDS reported frequency of crashes with the collision contact points: 28.9% at the center front (front wheel), 16.5% at the left front (front wheel), 16.9% at the right front (front wheel), 12.6% at the left center (rider seat), 13.1% at the right center (rider seat), 2.8% at the left rare (rare wheel), 1.4% at the right rare (rare wheel) and 2% at the center rare, etc. (MAIDS, 2004). As per the analysis based on ITRDA data in 2003, HONDA analyzed the crash data based on the type of collision of motorbikes that cause fatality and severe injuries: 68% for the frontal collisions; 8% for the non-collision, which include fall and roll out. Besides, the causes of rider injury and fatality in motorcycle accidents were categorized as 71% impact with road obstacles and 25% impact with automobiles. Unlike automobile crashes, the crash dynamics of motorbikes are complicated. Motorbikes may encounter a wide variety of crash conditions, and their position may vary significantly depending on the angle of impact. Therefore, air jacket deployment decisions should consider all possible collision types as the driver lacks a strong supporting surface during a collision. Based on crash analysis and complicated motorbike crash dynamics, this paper focuses on the frontal crashes at the initial stage for air jacket inflation. Besides, collision detection due to "roll out and "slippage" was also considered since such accidents are frequently occurred due to imbalance while leaning to small and large curves.

The development of an effective crash sensing system is based on crash sensing characteristics such as predictive, discriminative and real-time (Chan, 2002). The predictive crash characteristics require a finite period to inflate, which is determined by sensor fusion algorithms such as Kalman filter algorithms. In real-time crash sensing, signals are immediately processed upon receiving in a limited window. For the particular application, we developed a crash algorithm based on discriminative crash characteristics in which the algorithm can reliably differentiate airbag deployment and non-deployment situations.

In a nutshell, this paper describes the development of an automatic air-inflated safety jacket based on a novel crash discriminative algorithm. A tubeless double-layer safety jacket and an inbuilt electronic control unit (ECU) with an inflatable mechanism were developed to protect the rider from the impact forces when the rider met with an accident. All modes of motorbike accidents have been considered in designing protective clothing. When a signal generates from any of the fused sensors integrated, based on airbag inflation decision, the induced electric impulse triggers the chemical reaction to generate nitrogen gas similar to the airbag deployment mechanism in automobiles. The airbag jacket is expected to complete inflation in a fraction of a second to protect the rider before falling on the ground or knocking against any obstacle.

2. Materials and methods

This section provides a detailed account of the experimental procedure that was followed in the research, linking the literature to the outcomes where applicable. The experimental procedure is discussed in seven areas, namely, Airbag material development, Protective clothing, Sensor placement and integration, Development of crash algorithm, Experiment setup, Gas generation for jacket inflation and Safety assessment of the jacket.

2.1 Airbag material development

The tubeless air jacket was made out of silicon-coated Nylon 6,6 fabric as per the specifications in Table 1. The construction specifications of the airbag material were compared with the construction specification values of the Mercedes-Benz airbag standards. The airbag material was woven on a rapier weaving machine.

Material Parameter	Specifications of the produced Air jacket material	Specifications of Mercedes-Benz
Weave	1 × 1 plain weave	1 × 1 plain weave
Fabric set (per inch)	68*61	57*53
Count	Warp-420DTwisted Weft-420D Twisted	420D
Weight (GSM)	238	220–260
Thickness (mm)	0.4	0.32 – 0.42

Table 1. Air jacket fabric construction specifications

2.2 Protective clothing

2.2.1 Design and operating principle. The protective clothing is comprised of bladders (an inflatable hollow flexible chambers), an air inflation mechanism, a triggering or actuation mechanism, a power supply and a sensing mechanism or an array of sensors fused. The initial phase jacket design comprises two layers: The inner layer is a body fit jacket and the outer layer acts as a safety jacket. The outer layer has inverted pleats in the front and backside to accommodate more air during inflation. The pleats are opened when the air is inflated. In the deflated condition, the airbag jacket resembles as a regular body fit jacket. The tubeless air jacket sleeves were designed with tiny pleats in the elbow area to provide enough flexibility to move the arm even when the jacket is fully inflated [Plate 1(a)]. The ECU unit comprises an Arduino Uno (10 V), a Bluetooth module ZS-040 (two), an angle sensor, two accelerometer MMA7455, a load cell CZL-601 (20Kg) and a Hx711 module to connect load cell and Arduino board, and this ECU unit was used to detect the collision or accident. The lateral acceleration, vertical acceleration and the motorbike's tilt angle were measured in analog form and converted into digital data with an A/D converter of 16-bit resolution.

The airbag system has an inflatable tubeless air jacket chamber, a battery for the power supply, a chemical canister encapsulated in polytetrafluoroethylene-coated heat-resistant material, multiple sensors to determine the collision, a trigger mechanism to give an electric spark and a chemical mixture to generate the gas. The air jacket is designed to protect the rider's upper body from neck to waist and arms, as shown in Plate 1(c). Before inflation, the air jacket resembles as a standard motorbike jacket. This air jacket, on average (medium size), is approximately 5 L in volume and 1 kg in weight. When the crash sensors detect a collision or rider fall off or thrown off the motorbike, the sensor feedback generates an output signal in the form of an electric pulse through the crash discrimination algorithm. This electric pulse ignites the small amount of igniter compound in the gas-generator mixture inside the chemical cartridge. The gas-generator mixture contains sodium azide (NaN_3), potassium nitrate (KNO_3) and silicon dioxide (SiO_2). The heat from the ignition decomposes sodium azide and initiates a series of chemical reactions. These synchronized chemical reactions will then start ejecting N_2 gas to fill the bladders of the airbag jacket. The chemical cartridge weighs approximately 160 g, and the weight of chemicals is approximately 100 g. The system operates with two AAA batteries. All the signal transmission and reaction occur within a few hundreds of milliseconds.

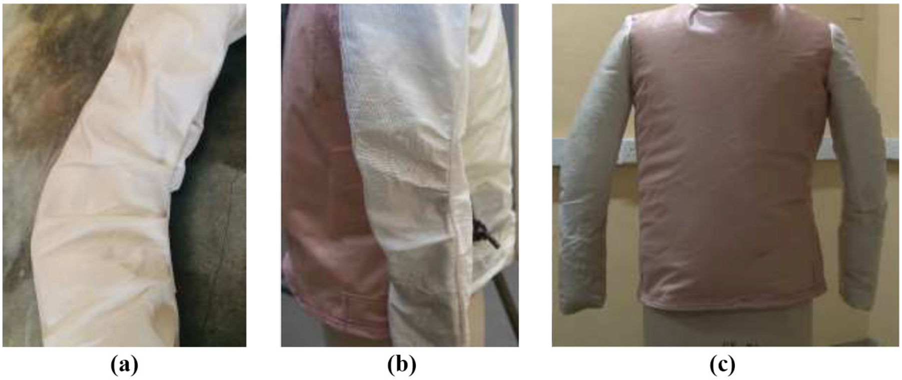
(a) (b) (c)

Plate 1.
Air jacket

Note: (a) and (b) Sleeve construction with gathering; (c) air-inflated visual look

2.2.2 Stitching parameters.

2.2.2.1 Sewing thread for needle and under the thread. The security and integrity of the seams of the jacket are crucial because the protective material exposes to a higher level of stress during inflation. During a clash, the material is exposed to a higher degree of heat and subjected to a higher tensile force. Therefore, the essential requirements of the sewing thread can be listed as maximum strength and tenacity, better elasticity, high temperature resistance, minimum filamentation, higher abrasion resistance, better thickness, superior sewability, etc. Considering the sewing thread's specific requirements for protective system, we used a Nylon 160 Tex bonded sewing thread-a twisted multifilament Nylon thread with a bond application. The bonded threads prevent thread untwisting during multidirectional sewing through dense and multilayered seams. Since we used 301 lock stitch and 401 double lock chain stitch for seams, the same 160 Tex bonded sewing threads were used for the needle, looper and bobbin threads as the stitch is only as strong as its weakest link. Table 2 displays the tested sewing thread specifications used for needle and under thread.

2.2.2.2 Needle size and needle point. A needle of size 28 with a light bolt point was used to assemble all parts across the jacket. A light bolt point needle was selected to avoid excessive damage to the protective material.

2.2.2.3 Stitch type. Four types of stitches as shown in Figure 1 were used for attaching fabric panels of the jacket: 301 double lock stitch, 401 double lock chain stitch, 504 overlock stitch and 516 overlock stitch. The 401 double lock chain stitch is used to impose a seam with high

Construction	Count (Tex)	Tenacity (cN/tex)	% of elongation at break	Strength (lbs)
Twisted multifilament with the bond application	160 Tex	87.5	18.54	23.7

Table 2.
Tested sewing thread specifications

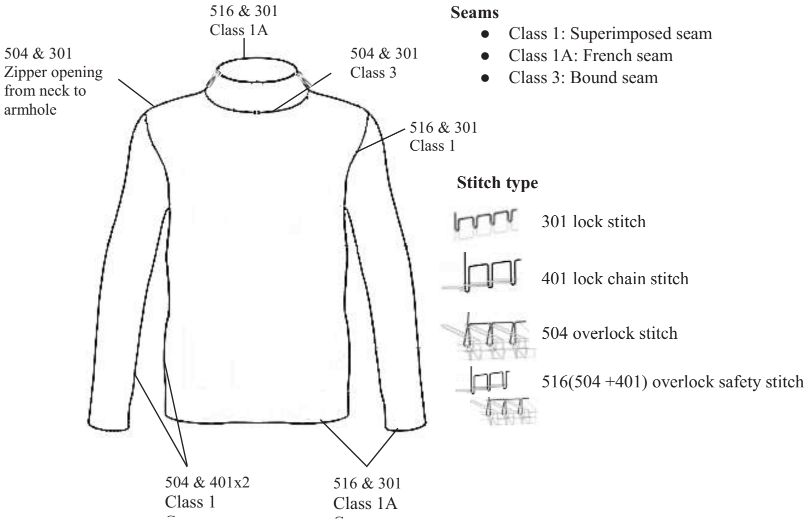

Figure 1.
Seam classes and the stitch types used for seam operations of the outer layer

stretchability as well as high strength. 401 – type chain stitch was used in zones where high stress is applied during the inflation. Stitch type 301 was used when attaching a zipper. However, compared with the lockstitch, the chain stitch was tended to wear and was therefore used in areas where less abrasion was applied. 504 and 516 overedge stitches were used for serging the upper and lower fabric panel to secure the edge and prevent raveling during the seaming operation.

2.2.2.4 Stitch density. To determine optimum stitch density for seams based on seam strength, seam bursting strength and air permeability, samples with stitch densities varying from 6–12 stitches per inch (SPI) were analyzed.

2.2.3 Seam types. The air-blocking performance of the jacket is determined by the types of seams used. The number of seams must be a minimum, and it must permit the air to inflate the jacket preventing outgassing. During the inflation, a higher-pressure force will be applied on the outer layer than the force applied on the inner layer. Therefore, seams used for panel joining in the outer layer should minimize outgassing to retain the air pressure for a sufficient period. Seam types were selected based on both sewability and outgassing factors. Seam classes in Figure 1 are numbered according to BS 3870 standard. Since a thick yarn was used as the sewing thread, outgassing may occur at the seams. An epoxy-based sealing material was applied between the seam margin to prevent outgassing from the outer peripheral suture of the seam region.

2.3 Sensor placement and integration

Occupant impact velocity (OIV) is a competing severity metric to evaluate the severity of the crash and predictor for occupant injury. The OIV requires a full crash plus to calculate the theoretical impact velocity. The kinematics of the vehicle and occupant are different after a crash. There has been no study to date evaluating whether the occupant's dynamic model provides an additional benefit in terms of injury prediction in real-world collisions since crash dynamics are first absorbed by the vehicle (Gabauer and Gabler, 2006). In this study, a crash algorithm was developed in which crash dynamics were evaluated from the sensors integrated on the bike.

The existing crash detection systems in the literature focused on crash sensor integration at the front wheel: suspension fork legs (Kobayashi and Makabe, 2013) and front cowl framework (Kuroe *et al.*, 2004). The front wheel-suspension system is the part of the motorcycle that experiences the initial impact forces in a typical motorcycle frontal collision. In this study, two accelerometers were integrated near the front axle, one each on the right and the left suspension fork legs (ACC_RIGHT, ACC_LEFT). The average signal of the left and right-hand side accelerometers was used to detect front crashes. Kobayashi and Makabe (2013) showed that the averaging process reduces the effect caused by the forceful steering of the front wheel suspension system at the early stage of the crash. All the sensors were calibrated considering the motor bike's reference frame:

$$\mathrm{a_x}(t) = \frac{\mathrm{ACC}_{\mathrm{Right}_{x+}}\mathrm{ACC}_{\mathrm{LEFT}_{x}}}{2}, \tag{1}$$

$$\mathrm{a_y}(t) = \frac{\mathrm{ACC}_{\mathrm{Right}_{y+}}\mathrm{ACC}_{\mathrm{LEFT}_{y}}}{2} \tag{2}$$

$$\mathrm{a_z}(t) = \frac{\mathrm{ACC\_Right}_{z+}\mathrm{ACC\_LEFT}_{z}}{2} \tag{3}$$

a_x (t) = Forward acceleration/longitudinal acceleration is positive forward and negative backward, along the X-axis.

a_y (t) = Lateral acceleration is positive to the right and negative to the left, along the Y-axis

a_z (t) = Vertical acceleration is positive upward and negative downward, along the Z-axis

Even though tilt angle can be measured using the accelerometers, a separate angle sensor was used due to the signal difference in ACC_RIGHT and ACC_LEFT, during the forceful steering at the early stage of some crashes. The ANG_1 is fixed on the frame above the footrest.

θ_{tilt} (t) = Lean angle, which is positive to the right and negative to the left, around Z-axis,

A load cell was fixed on the occupant's seat to check the occupant's availability.

If L_cell = 1, the occupant is availableif L_cell = 0, the occupant is not available

2.4 Development of the crash algorithm

This section focuses on the crash algorithm which triggers the air inflation mechanism of the jacket using signals received by the sensors upon collision. A crash algorithm based on discriminative crash characteristics was proposed so that algorithm can reliably differentiate airbag deployment and non-deployment situations.

2.4.1 Identifying crash patterns. The proposed crash discrimination algorithm was designed to recognize two generic crash patterns of a motorbike. The algorithm should be able to discriminate between these two cases, which were discerned based on crash algorithm metrics.

Crash pattern 1 characteristics

- Collisions with a stationary or moving barrier, which include head-on crashes, frontal crashes, pole crashes, offset crashes, etc.
- Collisions with bumpers and potholes.

Crash pattern 2 characteristics

- The rider will fall due to slippage exceeding the maximum lean angle while taking a bend.
- The rider will fall inwards or outwards the bend depending on the motorbike dynamics.
- The rider will fall due to imbalance on a straight road, either "roll out" or "slippage".

2.4.2 Signal processing. The signals measured by the sensors were sent to the micro-controller through a low-pass filter (LPF). Eliminating noise in the sensor measurements is crucial to increase the accuracy of the signal, particularly a high signal-to-noise ratio (S/N). The exponential moving average was used as the low-pass filtering method, as it results in a shorter lag than the moving average method. The filtering process removes undesirable noises, which would otherwise create air jacket inflation during a low severity crash. The LPF input variables were set as N = 5 samples, and $\alpha = 0.333$.

$$y(n) = \alpha x(n) + (1 - \alpha) y(n-1) \tag{4}$$

where y (n) is the current output, y (n − 1) is the previous output, and x (n) is the current input; and α is 2/(N + 1)

2.4.3 Crash algorithm wake up. Crash algorithms are not in continuous operations. The algorithm is triggered when minimum interpretable signals of a crash are entered. The start and the end of the algorithm for the crash algorithm wake-up were based on the following inequalities.

The wake-up signal relies on below two metrics

The longitudinal acceleration: a_x (t)

The longitudinal speed of the bike on a curve v_x (t)

Lean angle: θ(t)

Inequality 1: At the frontal collision, the deceleration of the motorbike is considerably greater than any possible value during braking. This condition is considered to prevent false entities due to aggressive braking or decelerating maneuvers. The threshold deceleration is determined according to the normalized data of deceleration due to the braking force of multiple motorbikes (Ecker *et al.*, 2001; Limpert, 2008). This is initiated when two consecutive deceleration pulses less than −0.7 g occurred within a short period (10 milliseconds).

$$|a_x(t)| > |a|_{brake}, \quad |a|_{brake} = 0.7g \Rightarrow a_x(t) < -0.7g \tag{5}$$

Inequality 2. The slope of the bike while riding should not exceed the possible maximum lean angle. This is initiated when consecutive lean angle pulses greater than 15° occurred within a short period (10 milliseconds). Watanabe and Yoshida found that maximum lean angles used by a novice rider were typically in the range of 15°–25°, and those of experienced riders were in the range of 34°–40°. Accordingly, to wake up the algorithm while learning, a minimum value for θ_{tilt}_bend is set as ±15°.

In lowers speeds, while leaning on the bend, air jacket deployment is not an absolute requirement as the rider can take control without tipping over by keeping their foot on the ground. In that case, it is required to define a minimum value for v_x (t) while riding on a bend as the initial estimation, set v_x_bend =10mph

The cash algorithm wake-up inequality can be written as v_x (t) $\geq$ 10mph and $\theta_{tilt} \geq 15^0$.

An experimented θ_{tilt}_bend and v_x_bend are required to develop a more sophisticated algorithm based on physical testing. However, the above inequality is substantially informative for initial testing.

2.4.4 Setting cash algorithm metrics. The signals delivered as the output from the sensors can be classified into three groups as the inputs for the crash algorithm: crash force-dependent metrics, crash energy-dependent metrics and combination metrics of crash energy and force. For instance, the deceleration, the deceleration change and jerk can be regarded as crash force-dependent metrics since deceleration is proportional to the force applied. Moreover, during a crash, the kinetic energy of the vehicle is transformed towards the plastic deformation of the vehicle structure. Therefore, the velocity change, the summation of the velocity change squared and deceleration change squared can be regarded as crash energy-dependent metrics. Table 3 represents the different crash metrics used in previous studies.

Jeong and Kim (2001) stated that even filtered deceleration signal changes significantly, hence changes the derivative of deceleration, the jerk, even more drastically. Thus, metrics such as jerk, power, energy and power rate are sensitive to noises, and an algorithm using these metrics could eventually lead to undesirable air jacket deployment. The proposed algorithm relied on the below metrics to detect the crash patterns mentioned above as they deemed most appropriate to express the crash characteristics and were comparatively less noisy.

2.4.4.1 Metrics that specifically express the characteristics of Crash pattern 1.

Crash force-dependent metrics	Energy-dependent metrics	Combination of Force and Energy metrics/ Single cash metrics
deceleration: $\mathbf{a}(\mathbf{t}) = \frac{\Delta v(\mathbf{t})}{\Delta \mathbf{t}}$	Velocity change: $\Delta v(t) = v(t_{i+1}) - v(t_i) = \int a(t)dt \approx \sum a(t) \cdot \Delta t$	$j(t)$, $\Delta v(t)$, $\sum a(t)^2$, $\sum \sqrt{\frac{da(t)}{dt}^2 + 1}$(Cho *et al.*, 2011)
deceleration change: $\Delta a(t) = a(t_{i+1}) - a(t_i)$	Velocity after the crash: $v(t) = \Delta v(t) + v_0$	$a(t)$, $p(t)$,$\frac{dp(t)}{dt}$, $a(t)^2$, $\Delta v(t)$ (Jeong and Kim, 2000)
Jerk (acceleration waveforms): $\mathbf{j}(\mathbf{t}) = \frac{\mathbf{da}(\mathbf{t})}{\mathbf{dt}} \approx \frac{\Delta \mathbf{a}(\mathbf{t})}{\Delta \mathbf{t}}$	Acceleration squared: $a(t)^2$	$\sum\lvert\Delta a(t)\rvert$, $\Delta v(t)$ (Jeong and Kim, 2001)
Summation of the absolute decelerations: $\sum\lvert\Delta a(t)\rvert$	Summation of the deceleration squared: $\sum a(t)^2$	$j(t)$, $a(t)$, x (t), $\Delta v(t)$ (Kelley and Cashler, 1995)
	Energy: $E(t) = \frac{mv(t)^2}{2}$	$a(t)$, x (t) (Kobayashi and Makabe, 2013)
	Displacement: x (t)	$a(t)$, quasi-static roll angle, $v(t)$ (Jeong and Kim, 2000)
	Power: $p(t) = \frac{dE(t)}{dt} = mv(t).a(t)$	$\Delta v(t)$ (Taylor *et al.*, 2008)
	Summation of deceleration signal length: $\sum \sqrt{\frac{dp(t)}{dt}^2 + 1}$	
	Power rate: $\frac{dp(t)}{dt} \approx v(t).j(t) + a(t)^2$	

Table 3. Crash metrics in previous research

- Velocity change: $\Delta v(t)$, $\Delta v(t) = \int a(t)dt$
- Summation of the absolute decelerations: $\sum\lvert\Delta a(t)\rvert$

2.4.4.2 Metrics that specifically express the characteristics of Crash pattern 2.

- Maximum Lean angle limit of the motorbike ($\boldsymbol{\theta_{max}(t)}$)
- Tilt angle $\boldsymbol{\theta(t)}$- this metric expresses crash characteristics of “slippage” and “roll” while leaning on a curve.

$\theta(t) = \tan^{-1}\frac{a(t)_{lateral}}{g}$, neglecting the superelevation angle of the road. $a(t)_{lateral}$ is lateral acceleration,

$$a(t)_{lateral} = a_y \Rightarrow \theta(t) = \tan^{-1}\frac{a_y}{g} \quad (6)$$

$$\theta_{upper}(t) = \tan^{-1}\frac{a_y}{g} + \rho, \quad (7)$$

$$\theta_{lower}(t) = \tan^{-1}\frac{a_y}{g} - \rho, \quad (8)$$

$$\rho = \pm 10^0, \text{ if } \theta(t)_{\text{tilt}} < 0 \Rightarrow \rho = -10^0, \text{ if } \theta(t)_{\text{tilt}} \geq 0 \Rightarrow \rho = +10^0$$

This paper introduces a scalar constant (ρ), which expresses the maximum and minimum lean angle values during a stable position. The estimation for scalar constant depends on the type of the motorbike, and additional physical testing is required to define a range for ρ. For the considered application, an initial estimation value is set for ρ corresponding to an additional 10°. The new formula is sufficiently informative and easy to compute the lean angle while leaning on a curve.

Considering all the signal processing, consideration of crash characteristics, limiting values of sensory signals and the crash metrics, the entire crash algorithm developed in a nutshell is depicted in Figure 2. For the initial experimental set-up, the threshold value for $\sum|\Delta a(t)|$ was set at 8.0 g, the threshold value for $|\Delta v(t)|$ was set to 10 mph and the threshold value for $|\theta(t)max|$ was set to 55°. However, an experimented threshold values are required to develop a more sophisticated algorithm based on physical testing. If the threshold values of the crash metrics are exceeded during the collision, the airbag jacket will be set to the "FIRE" stage and will ignite the gas-generator mixture in the chemical canister by an electric spark.

2.5 Gas generation for jacket inflation

An electrical pulse given to the chemical mixture initiates reactions and generates N_2 gas to fill the bladders of the airbag jacket. The chemical mixture contains sodium azide (NaN_3), potassium nitrate (KNO_3) and silicon dioxide (SiO_2). When a motorcycle undergoes a collision, a series of three chemical reactions, based on equations (9)–(11), are occurred to produce N_2 gas to inflate the airbag jacket and convert highly toxic sodium azide into nontoxic harmless byproduct. Adequate amounts of N_2 gas are produced by the reactions given in equations (9) and (10). In the subsequent reaction of equation (11), SiO_2 converts all the by-products (K_2O and Na_2O) into alkaline silicates, which is a safer, harmless and neutral compound (Nayak *et al.*, 2013).

$$2NaN_3 = 2Na + 3N_2 \tag{9}$$

$$10Na + 2KNO_3 = K_2O + 5Na_2O + N_2 \tag{10}$$

$$K_2O + Na_2O + 2SiO_2 = K_2O_3Si + Na_2O_3Si \tag{11}$$

The electric impulse generated through the crash discrimination algorithm ignites the igniter compound, facilitating a high-temperature condition around 300°C which is required to decompose NaN_3 to produce sodium (Na) and N_2 gas. The generated nitrogen gas fills the bladders of the jackets and thereby inflates the jacket during a collision. The purpose of KnO_3 and SiO_2 is to remove highly reactive and explosive Na from the reacting chemical composition. KnO_3 reacts with Na and produces potassium oxide (K_2O), sodium oxide (Na_2O) and N_2 gas. The additional N_2 gas generated from this reaction also fills the bladders. In the final stage, both K_2O and Na_2O react with SiO_2 to produce harmless sodium silicate and potassium silicate.

2.6 Experiment setup

The ECU was connected to the air jacket to foresee whether the air jacket inflates without any burst and measured inflation timing and volume. Except for the maximum lean angle crash metric condition, it is required a special laboratory setting to replicate real-world crashes to generate sensor data that exceeds the threshold values for velocity change, the

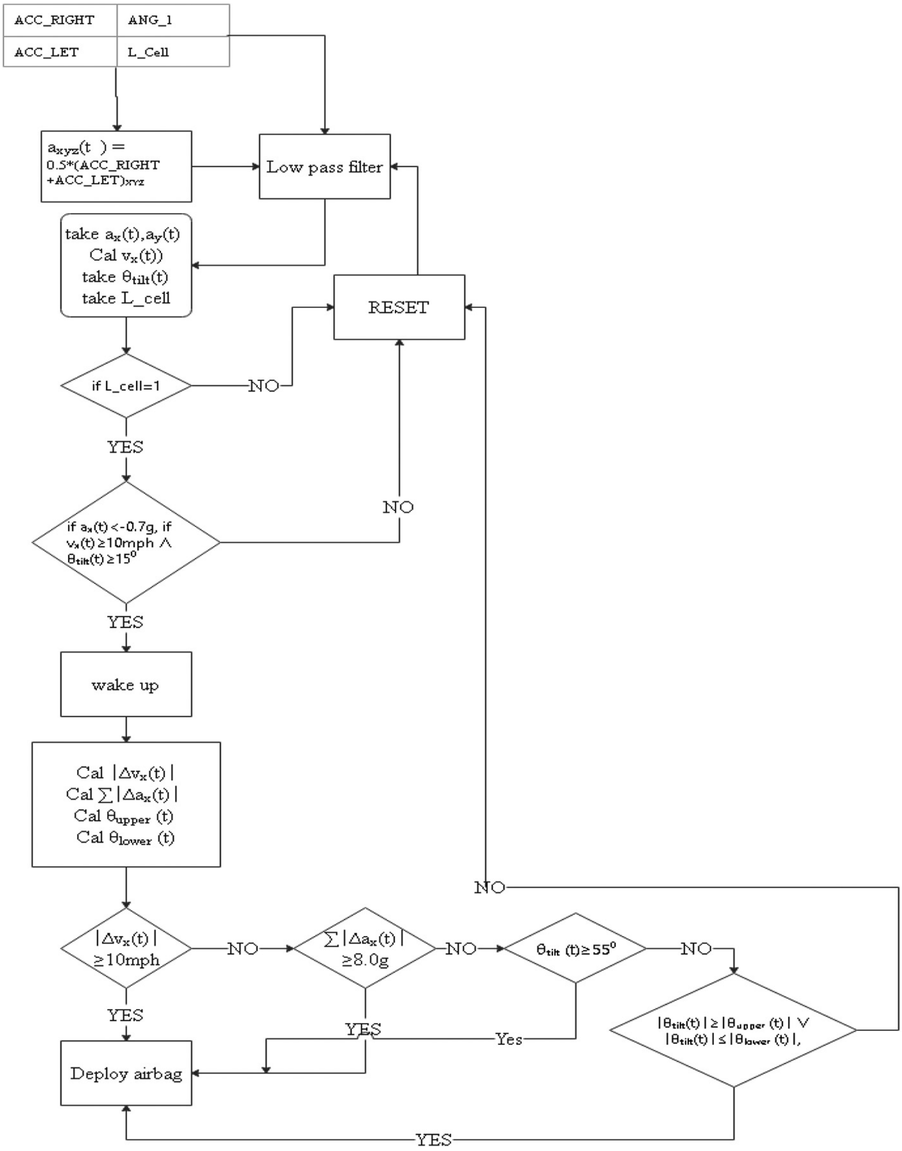

Figure 2.
Crash algorithm

summation of the absolute decelerations and tilt angle for "slippage" and "roll out" metrics. Therefore, the functionality of the crash algorithm was determined through simulation by setting values for crash metrics in Arduino program that are greater than the threshold values. The preliminary effectiveness assessment of the jacket inflation was tested by setting values for sensor data in the program and thereby assessing the functionality of the airbag jacket, inflation time and volume of the jacket when it is fully inflated. Accordingly, the effectiveness of jacket inflation when exceeding the threshold values of velocity change, the summation of the absolute decelerations and tilt angle for “slippage” and “roll out” metrics were assessed through simulated sensor output data. The effectiveness of jacket inflation for maximum lean angle condition was checked by changing the tilt angle position of the angle sensor (Plate 2). The air jacket’s inflation time was measured from the video clips of a high-resolution and high-sensitivity camera. However, to assess the effectiveness of the jacket during real-world collisions, laboratory-based full-scale crash tests ought to be performed using a crash test dummy as per ISO13232 standard.

2.7 Safety assessment of the jacket

2.7.1 Raw material verification. In verifying raw material for protective safety jackets, both protective fabric properties and motorbike clothing safety standards were considered. Protective fabric properties were tested according to the ASTM standard, and clothing safety assessment was verified according to EN 13595–1: 2002 standard. The tests related to material specifications, protective fabric properties and motorbike clothing safety standards were experimentally tested in the testing laboratory of the Department of Textile and Clothing Technology, University of Moratuwa.

EN 13595–1: 2002 is the European standard for protective clothing for professional motorcycle riders – jackets, trousers and one-piece or divided suits. The standard consists of four parts. Part 1 includes the requirements and the examination procedures of clothing, while Parts 2 to 4 describe laboratory testing procedures for three of the specialized tests: Part 2 for impact abrasion test, Part 3 for seam burst strength and Part 4 for impact cut test. The EN 13595 standard clothing template for protective clothing specifies four different

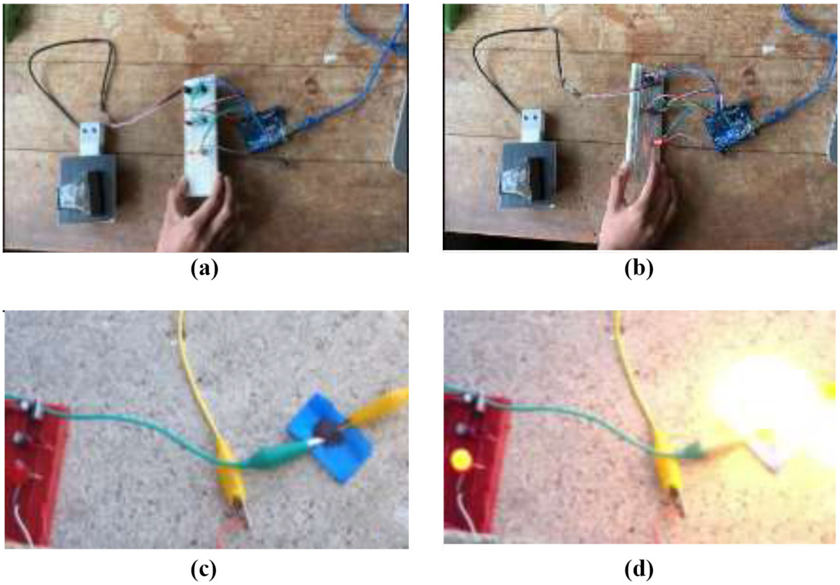

Plate 2. Generating electric spark when ECU activated for tilt angle

Notes: (a) Tilt angle is less than the maximum lean angle; (b) tilt angle exceeds the maximum lean angle; (c); (d) electric spark initiates the chemical reaction to generate N2 gas zones, labeled as Zone 1, Zone 2, Zone 3 and Zone 4, each with different levels of required performance. Zone 1 requires a greater resistance to damage, while areas with little damage are labeled in Zone 4 and require little resistance to wear. The jacket design of this study did not use different fabrics in each of the four zones of the standard template and was deemed unnecessary for differentiation in protection levels across the jacket. Therefore, samples were not taken from different regions of the respective zone, and tests were performed based on Zone 1 requirements of Level 1 and Level 2 protective clothing.

2.7.2 Seam performance verification. Seam performance was experimentally evaluated based on air permeability, seam Edgecomb resistance and seam bursting strength tests following ASTM and EN 13595–1: 2002 standard. The seams of the jacket belong to Class 1 (Superimposed), Class 1 A (French) and Class 3 (Bound) seams (Figure 1). During the inflation, the pressure inside the jackets develops within a fraction of a second and hence exerts a high pressure-force on areas stitched with Class 1 Seams. Further, those areas are the most permeable areas where outgassing can occur during inflation. Therefore, seam performance was evaluated from areas with Class 1 seams.

3. Results and discussion

3.1 Raw material performance

Table 4 illustrates that tearing strength, breaking strength, abrasion resistance and elongation in weft direction results are higher than the requirements of the Mercedes-Benz standard. However, elongation in warp direction marginally fails at 31.56% (<33%). The air permeability of the fabric is 8.58 dm^2/min, which is well below the air permeability requirement of the Mercedes-Benz standard. According to all tested values, the developed Nylon 6,6 fabric seems suitable to use as the raw material for the air jacket because values of physical properties testing satisfied the Mercedes-Benz airbag standard requirement. Seam burst strength, impact cut resistance and impact abrasion resistance results of the jacket resemble a Level 2 protective clothing according to EN 13595–1: 2002 standard even though seams burst strength and impact cut test marginally fail for Level 2 standard. A Level 2 protective clothing provides moderate protection for motorbike riders, which is higher than the protection provided by Level 1. Besides the evaluated properties, some more built-in properties are attainable when using Nylon 6,6 fabric as the raw material, such as heat capacity, folding behavior, energy absorption, coating adhesion, functionality at extreme hot and cold conditions, reduced skin abrasion (softness) and heat stability.

3.2 Assessment of seams performance based on SPI

Table 5 displays the seam performance results of the jacket with SPIs from 6 to 12. According to the results observed, SPI 12 was found as the suitable SPI to stitch the jacket due to maximum edge comb resistance, maximum seam bursting strength and minimum air permeability. Though the fabric has a very low air permeability of 8.58 dm^2/min, the overall air permeability of the protective clothing is determined by the permeability through seams. The air permeability with Class 1 seams is approximately 10.87 dm2/min at 500 Pa with 12 SPI. The tested value is closer to the air permeability requirement of the Mercedes-Benz standard. Moreover, due to the sealing material between the seam, the degree of outgassing was drastically reduced to the expected value of the ASTM standard.

3.3 Emulation of the crash sensor

In Plate 2, it can be observed that the control system is activated for exceeding the threshold value of the maximum lean angle metric. The crash algorithm described in Figure 2 was

Table 4.
Raw material testing results

Standard testing for Airbag	Testing Machine	Tested values for air jacket	Mercedes-Benz Standard
Air Permeability-fabric (Static) ASTM D 737–96	Auto air permeability tester	8.58 dm^2/min	< 10 dm^2/min at 500 Pa
Bursting Strength (diaphragm method) ASTM D 3786–01	Fabric- diaphragm bursting strength tester	1500Kpa	-
Tearing Strength (N) ASTM D 2261			
warp	Instron Universal Tester	218.57N	>115N
weft		237.23N	>115N
Breaking Strength (kN)			
ASTM D 5034	Instron Universal Tester		
warp		2.576 kN	>2.5 kN
weft		2.612 kN	>2.5 kN
Elongation (%)			
ASTM D 5034	Instron Universal Tester		
Warp		31.51 kN	>33kN
Weft		26.42 kN	>23kN
Abrasion Resistance ASTM D 4157	Wyzenbeek Abrasion Tester	40000	>50

Standard testing for Motorbike jacket safety	Testing Machine	Tested values for air jacket	Standard threshold value	
			Level 1	Level2
Seam Burst Strength (kPa) at 12 SPIEN 13595–1: 2002	Fabric- diaphragm bursting strength tester	768kPa	>700kPa	>800kPa
Impact Cut Test-knife penetration (mm), knife speed of 2.8 m/s EN 13595–1: 2002	Blade cut resistance tester	15.8 mm	<25mm	<15mm
Impact Abrasion Test (seconds) EN 13595–1: 2002	Impact abrasion tester	6.48	>4.0 sec	>7.0 sec

coded into the program inhibited in Arduino bode to emulate the functionality of tilt angle and displayed with lighting up LEDs. Thereby, the functionality of the maximum lean angle condition is demonstrated and provides solid evidence that the code functions as desired in exceeding the maximum lean angle of 55°: LED lights up as shown in Plate 2(b) when the tilt angle exceeds the threshold value. According to the final setup, two-wire ends are used to trigger the electrical spark of the air inflation mechanism. This electric spark ignites the igniter compound in the chemical mixture and starts detonating for generating heat to produce N_2 gas [Plate 2(d)].

Similarly, when sensor data of deceleration and tilt angle output are simulated to exceed the threshold values of the crash metrics – velocity change, the summation of the absolute decelerations and tilt angle for “slippage” and “roll out” – an electric impulse is sent to the canister which contains sodium azide. This electric signal ignites an insignificant quantity of an igniter compound and generates heat to decompose sodium azide and thereby generate nitrogen gas to fill the air jacket. The fully inflated air jacket through sensor data simulation is shown in Plate 3. Subsequently, through the preliminary effectiveness assessment, it was observed that the time the sensor detects the collision to the time the air jacket is fully inflated is around 100 milliseconds, and during this time, approximately 15 liters of N_2 gas is released from the canister to fill bladders of the jacket. Further, the time taken by the

Table 5.
Seam performance with SPI

SPI	Seam Strength-Edgecomb Resistance (N) ASTM D6479	Seam Bursting Strength (kPa) EN 13595–1: 2002)	Air Permeability (dm^2/min) At 500Pa ASTM D 737–96
12	620.51	768	10.87
11	568.80	692	12.85
10	517.10	633	14.32
9	465.39	582	12.89
8	413.68	559	16.46
7	361.97	526	17.52
6	310.26	467	18.32
Standard requirement	–	700kPa for Level 1 and 800 kPa for Level 2	<10 dm^2/min

Plate 3.
Fully inflated jacket

protective for full-inflation is less than the approximate estimated falling time of the rider–120 milliseconds.

4. Conclusion

In this study, the authors have attempted to design an protective safety jacket for motorbike riders, meeting both functional and safety parameters. During a collision, the inflation of the jacket is activated through a crash discriminative algorithm. Based on the sensor data, the algorithm can reliably differentiate air jacket deployment and non-deployment situations. Unlike existing tethered-triggered protective systems and mounted protective systems, the air jacket deployment mechanism is incorporated with the jacket to provide safety for the rider without a delay in response time during a collision.

In terms of comfort and aesthetic features, which provide more convenience to the wearer, the authors faced a challenge to fabricate the best technical fabric and make the air jacket with the most appropriate seam types and sewability. As motorcycle clothing cannot be very expensive and therefore one of this study's key objectives is to minimize the manufacturing cost by sacrificing the aesthetic and some functional finishes such as UV resistance and flame resistance.

The fused sensors were emulated with the ECU under laboratory conditions, and the trigger signal generated by the crash discrimination algorithm is used to generate approximately 15 liters of N_2 gas to fill the air jacket within 100 milliseconds, which is less than the approximate estimated falling time of the rider–120 milliseconds. The air canister is encapsulated in a heat-resistant packet as it is unable to control the heat produced by the chemical reaction while producing N_2 gas.

Though the ECU and the crash algorithm were tested under laboratory conditions through emulation, it is required to perform laboratory-based full-scale crash tests using a crash test dummy, following ISO13232 standard, to evaluate the performance and effectiveness of the air jacket in the event of a real-world collision. The air inflation mechanism needs further developments to minimize heat generation and hence provide occupant safety and reliability.

References

Aikyo, Y., Kobayashi, Y., Akashi, T. and Ishiwatari, M. (2015), "Feasibility study of airbag concept applicable to motorcycles without sufficient reaction structure", *Traffic Injury Prevention*, Vol. 16 No. sup1, pp. S148-S152.

Chan, C.Y. (2002), "A treatise on crash sensing for automotive air bag systems", *IEEE/ASME Transactions on Mechatronics*, Vol. 7 No. 2, pp. 220-234.

Chawla, A. and Mukherjee, S. (2007), "Motorcycle safety device investigation: a case study on airbags", *Sadhana - Sadhana*, Vol. 32 No. 4, pp. 427-443.

Cho, K., Choi, S.B. and Lee, H. (2011), "Design of an airbag deployment algorithm based on precrash information", *IEEE Transactions on Vehicular Technology*, Vol. 60 No. 4, pp. 1438-1452.

Dias, I., Abeysiri, N. and Bandara, SJ. (2018), "Identifying the factors related to motorcycle crash severities in urban roads in Sri Lanka", *Annual Sessions of IESL 2018*, *Colombo, Sri Lanka*, pp. 283-291.

Ecker, H., Vienna, J.W., Robert, G.H., Ag, B., Ag, R.R.S.S. and Omv, M.G. (2001), "Braking deceleration of motorcycle riders", *International Motorcycle Safety Conference*, *Orlando FL*, pp. 1-13.

Gabauer, D.J. and Gabler, H.C. (2006), "Comparison of Delta-V and occupant impact velocity crash severity metrics using event data recorders", *Annual Proceedings – Association for the Advancement of Automotive Medicine*, Vol. 50, pp. 57-71.

"Honda Gold Wing Motorcycle Airbag System Explained - auto-evolution" (2021), available at: https://www.autoevolution.com/news/honda-gold-wing-motorcycle-airbag-system-explained-12559.html (accessed 5 September 2020).

Jeong, H.Y. and Kim, Y.H. (2000), "New crash discrimination algorithms and locations of accelerometers", *Seoul 2000 FISITA World Automotive Congress*, *Seoul, Korea*, pp. 1-8.

Jeong, H.Y. and Kim, Y.H. (2001), "New algorithm and accelerometer locations for frontal crash discrimination", *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 215 No. 11, pp. 1171-1178.

Kelley, J.P. and Cashler, R.J. (1995), "SIR deployment method based on occupant displacement and crash severity", United States Patent.

Kobayashi, Y. and Makabe, T. (2013), *Crash Detection Method for Motorcycle Airbag System with Sensors on the Front Fork*, Motorcycle R&D Center/Honda R&D Co., Ltd., Japan.

Kuroe, T., Namiki, H. and Iijima, S. (2004), *Exploratory Study of an Airbag Concept for a Large Touring Motorcycle: Further Research Second Report*, Japan.

Limpert, R. (2008), "Motorcycle braking dynamics", available at: www.pcbrakeinc.com/epub/aiqwinter2008mcbrakes.pdf

MAIDS (2004), *MAIDS in-Depth Investigation of Accidents Involving Powered Two-Wheelers. Final Report 1.2*, Brussels, Belgium.

Nayak, R., Padhye, R., Sinnappoo, K., Arnold, L. and Behera, B.K. (2013), "Airbags", *Textile Progress*, Vol. 45 No. 4, pp. 209-301.

Rome, L.D. and Stanford, G. (2006), "Motorcycle protective clothing: fashion or function", *The Human Element: International Motorcycle Safety Conference, Long Beach, CA, US*, pp. 1-13.

Taylor, P., Hannan, M.A., Hussain, A., Mohamed, A. and Samad, S.A. (2008), "International journal of crashworthiness development of an embedded vehicle safety system for frontal crash detection", *International Journal of Crashworthiness*, Vol. 13 No. 5, pp. 579-587.

Corresponding author
Thantirige Sanath Siroshana Jayawardana can be contacted at: jaya@uom.lk