Design and Evaluation of a Novel Wearable Airbag for Mitigation of Falls from Height Injuries in the Construction Sector

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Abstract— **Recent statistics on work-related non-fatal and fatal injuries show that falls from height (FFH) are the leading causes, having a negative impact on socio-economic levels. Among industrial sectors, the construction industry has the highest rate of fatal injuries. Although safety harnesses, personal protective equipment (PPE), and collective protection systems are mandated by national laws, these tools have been insufficient to effectively address the problem. Smart wearable technologies and advanced materials can help predict and react to FFH events. This work proposes the design of a new fall-impact-mitigation wearable airbag to protect the front and back of the user, integrated into a technical vest. The system is activated by a falling-risk-estimation algorithm that can distinguish between voluntary movements and accidental falls. The device meets level-2 protection requirements according to EN1621-4, offering protection to users falling from 1.5 to 4 m. The proposed apparatus naturally extends this to types of falls from the same level.**

I. INTRODUCTION

According to the European Agency for Safety and Health at Work (EU OSHA), work-related injuries and diseases cause economic loss that amounts to 476 billion euros, equal to 3.3% of the European gross domestic product [1]. A recent study on the economic burden of work injuries in five EU countries highlighted that the highest number of non-fatal work injuries occurred in 2015 in Italy $(1, 257, 987)$ with the number of fatal injuries equal to 543 [2]. Considering the total cases of work-related fatal injuries in Italy from 2002 to 2015, the leading events are workers' falls from height (FFH) that represent 33.5%, and heavy loads falling on workers from height that account for 16.7% [3]. In addition, this study found that the economic sector with the highest rate of fatal injuries is the construction industry. This is due to the highly unstructured environment, the physically demanding activities performed, and the presence of short-term workers with limited experience. Frequent events such as slipping, tripping, and falling lead to fatal outcomes.

This research is promoted and conducted in collaboration with the Italian Workers' Compensation Authority (INAIL) under the project "Sistemi Cibernetici Collaborativi - Cadute dall'Alto 2 - Tecnologie indossabili per ridurre gli effetti dell'impatto nelle cadute dall'alto".

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Therefore, developing prevention and mitigation strategies to prevent FFH accidents remains a very active research field with many open challenges. Safety harnesses, personal protective equipment (PPE), and collective protection systems are the ultimate tools for protecting workers from fall hazards. Yet, these devices alone are insufficient in solving the problem [4]. Advancements in wearable technologies and advanced materials can help predict and respond to FFH events, reducing severe or fatal injuries. In this perspective, integrating wearable airbags into common PPE that workers can easily wear can help protect vital body areas during FFH accidents. Wearable airbags can be categorized into collision-detection and fall-detection systems [5]. The collision-detection airbags trigger mechanically after a collision, inflating in the event of an accident. The fall-mitigation airbags protect the user's body by inflating upon detecting a free fall. Therefore, these systems require algorithms to classify human activities, triggering only in case of a fall. In [5], the authors conducted free-fall tests on a 32 and a 16 L airbag system integrated into a jacket. To protect an 85 kg worker from a fall of less than 4 m, the airbag volume is 32 L, and the minimum trigger time for its expansion is approximately 200 ms. However, there is no clear information about the body area protected by this system. In [6], three types of wearable airbags and a sensor system are proposed to protect against FFH, wheelchair overturn, and falls on the same level. The proposed systems were efficient only within a limited range and were designed to protect only the user's head and back.

This work proposes a novel design for a wearable airbag to provide construction workers with a smart PPE that activates only during FFH events and mitigates the aftermath. The system is compatible with the certified PPE currently in use and is integrated into a technical vest that meets the AA abrasion-resistance class according to EN 17092. The system's performance requirements regarding minimum inflation time have been evaluated for two free-fall conditions: from 1.5 and 4 m. The proposed wearable airbag provides protection for the back (cervical spine, spine, and coccyx) and the front (chest and shoulders) of users. Finally, the certification tests defined by the standard EN1621-4 are performed on the front and back airbags, and the results are reported.

This work is organized as follows: Section II discusses the requirements, the fall protection system, the fall detection al-

(a)

(b)

Fig. 1: A mannequin wearing the certified UNI EN 361:2003 harness and the deflated wearable airbag. (a) Front view. (b) Back view.

gorithm, and the experimental protocol. Section III describes the experimental results. Finally, the conclusive remarks are reported in Section IV.

II. Materials and Methods

A. Requirements

We defined the functional requirements for the development of the wearable airbag considering a FFH scenario. Considering a fall from a height $h = 4$ m, a male worker representative of the 50^{th} percentile with a mass $m = 78.5$ kg will have a final velocity v_f given by

$$v_f = \sqrt{2gh} \approx 8.8\,\mathrm{m/s}, \tag{1}$$

where $g = 9.81\,m/s^2$ is the acceleration due to gravity. In such a condition, the total kinetic energy transmitted from the impact is

$$E = \frac{1}{2}mv_f^2 \approx 3.1\,\mathrm{kJ}, \tag{2}$$

and the impact occurs at time $t_f \approx 0.9\,\mathrm{s}$ without considering the friction and drag due to the air. Considering a fall from a height $h = 1.5$ m, the minimum activation time for the airbag results $t_m \approx 0.5\,\mathrm{s}$. Therefore, the prototype must inflate and reach the minimum required pressure in less than $t_m \approx 0.5\,\mathrm{s}$. It must stay inflated for more than $t_f \approx 0.9\,\mathrm{s}$ and must withstand a minimum kinetic energy of $E \approx 3.1\,\mathrm{kJ}$.

B. Design

The airbag system is designed to mitigate the risk of injury, protecting the user's spinal column, shoulders, and chest. Referring to Figure 2, two inflatable bags, one in the front and one in the back, have been integrated between the outer and inner layers of a technical vest with high visibility elements. The user can adjust the size using the hip straps and four front buckles, allowing the vest to fasten and ensuring compatibility with a certified harness type UNI EN 361:2003. The vest is made of a technical fabric with AA abrasion resistance, compliant with the EN 17092 standard. Referring to Figure 2, the back and the front airbags have a volume of about 15 l and 11 l, respectively.

Once inflated, both reach a maximum thickness of about 120 mm. During activation, the system unfolds to protect the entire back of the user, including the cervical spine and the coccyx area. A similar unfolding mechanism protects the shoulders. The front airbag protects the chest, the abdomen, and the hips. Overall, the wearable airbag weighs about 1.6 kg. Once a falling, tripping, or slipping motion occurs, the smart wearable belt detects the unexpected behavior and triggers the airbag system by applying a 3.3V voltage, providing a continuous current of 1.2 A for at least 3 ms. Figure 3 shows one of the two gas generators that are filled with 45 grams of carbon dioxide and inflate the system.
In the unfortunate event of a fall, the airbag system can be reused by replacing the gas generators, provided the external vest is checked for integrity. The procedure for

(a) (b)

Fig. 2: A mannequin wearing the certified UNI EN 361:2003 harness and the inflated wearable airbag. (a) Front view. (b) Back view.

Fig. 3: Electrically triggered gas generator filled with carbon dioxide.

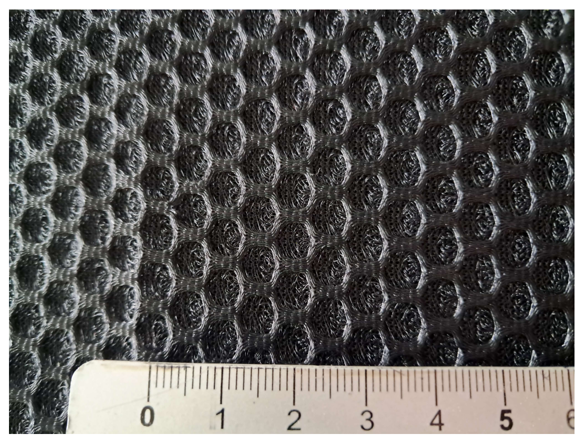

Fig. 4: Honeycomb pattern of the interior layer of the vest.

replacing the gas generators takes less than five minutes, is straightforward, and can be performed even by non-trained technicians. Referring to Figure 4, the internal layer of the vest features a honeycomb pattern that improves the system's breathability and enhances its usability.

C. Falling Detection Algorithm

To activate the wearable airbag, a smart belt has been developed that integrates the necessary electronics to acquire and process data from the 9-axis IMU sensor, run a real-time fall-detection algorithm on the edge, and trigger the gas generator in the event of an imminent impact. The Raspberry Pi Pico 2 is the processing unit of the smart belt, powered by a 5V battery. A dedicated battery is combined with a relay to provide the current required for airbag activation. Three LEDs indicate the user's current status: green for no fall, yellow for fall in progress, red for airbag activation.

The fall detection algorithm is based on a simplified version of a deep Recurrent Neural Network that takes IMU data (accelerations, angular velocities, and orientation) as input [7], [8]. It can distinguish activities of daily living from free-falls, thereby preventing undesired activations of the wearable airbag. As reported in the work of [8], the ML

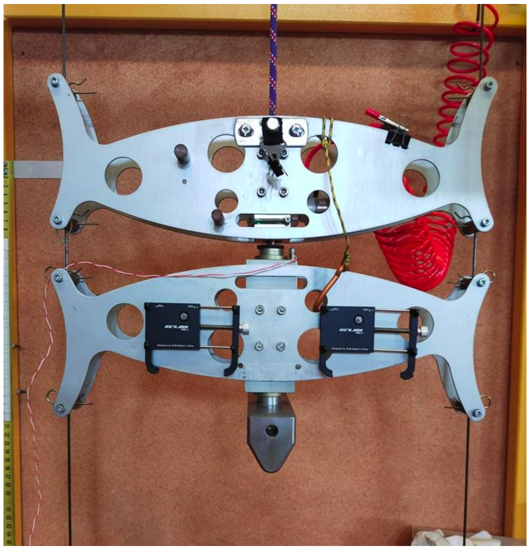

Fig. 5: The striker used for impact tests according to the EN1621-4 standard.

Fig. 6: The anvil and the load cell used for impact tests according to the EN1621-4 standard.

approach has an average error of 150 ms (of detecting the impact with the ground during a fall), and the full inflation time of the airbag is 80 ms. To this value, we add a buffer period of 70 ms, resulting in an average worst-case time of 300 ms from detection to impact.

D. Experimental protocol

Three impact tests were performed on this prototype to certify the protection level of the front and back airbags. These tests were performed according to the EN1621-2 (Motorcyclists' protective clothing against mechanical impact - Part 2: Motorcyclists' back protectors - Requirements and test methods) and the EN1621-4 (Motorcyclists' protection against mechanical impact Part 4: Motorcyclists' inflatable protectors - Requirements and test methods) standards. These standards are often employed across different fields of application, as they provide detailed prescriptions for evaluating the minimum area to protect and the admissible force transmitted to the body due to impact. According to EN1621-4, a steel striker falls from a height of 1 m onto an inflated airbag placed on an anvil. Referring to Figure 5, the striker has a V shape with an angle of 60°, a length of 160 mm, and a weight of 5 kg. The anvil, shown in Figure 6, is a steel cylinder with a diameter of 100 mm. The impact surface of the anvil has a

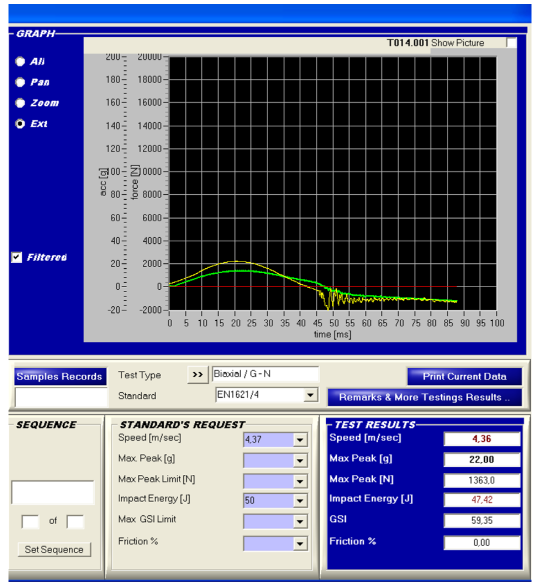

Fig. 7: The impact test results of the front airbag. The max force in green and the peak acceleration in yellow.

curvature of 1500 mm. The anvil is connected to a load cell that measures the force transmitted by the striker through the airbag.

Inflating tests were performed to evaluate if the time required by the airbag to pass from rest to protective state meets the requirements discussed in Section II. During these tests, the time required to inflate the wearable airbag from 0 to 0.18 bar (back) and from 0 to 0.25 bar (front) was evaluated with an error of ± 2 ms. The pressure thresholds $p_p = 0.18$ and $p_p = 0.25$ bar were prescribed by EN1621-4 to achieve level 2 protection against impacts. To perform the tests, the front and rear airbags were equipped with pressure and temperature sensors to measure the time elapsed before reaching the pressure threshold after triggering the gas generators. The temperature sensor is used to verify that the wearable airbag's internal temperature does not change significantly after the gas generator is activated. The data were recoded for 19 s at a frequency of 500 Hz.

III. Results

A. Impact test

As shown in Figure 7, the striker reached an impact velocity of 4.36 m/s, releasing a kinetic energy of 47.4 J on the front airbag. On average, the residual force transmitted by the striker to the anvil through the airbag is 1.368 kN. This force value demonstrated that the front airbag reaches level 2, which corresponds to the maximum level of protection provided by the EN1621-4 standard. Under the same experimental conditions, the average residual force transmitted by the striker through the back airbag is 1.037 kN. Therefore, the back airbag also meets the level 2 protection requirements of the EN1621-4 standard.

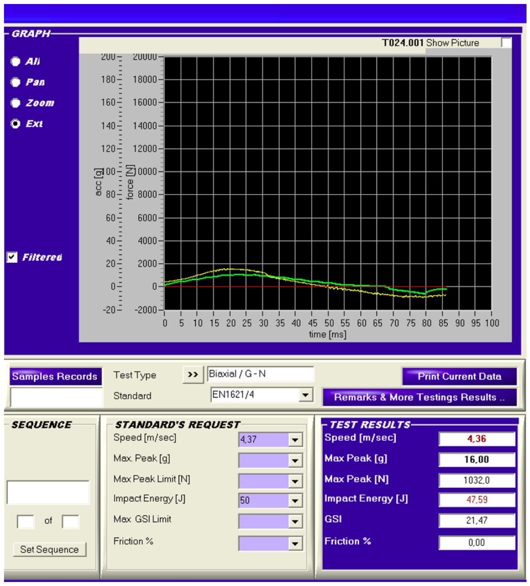

Fig. 8: The impact test results of the back airbag. The max force in green and the peak acceleration in yellow.

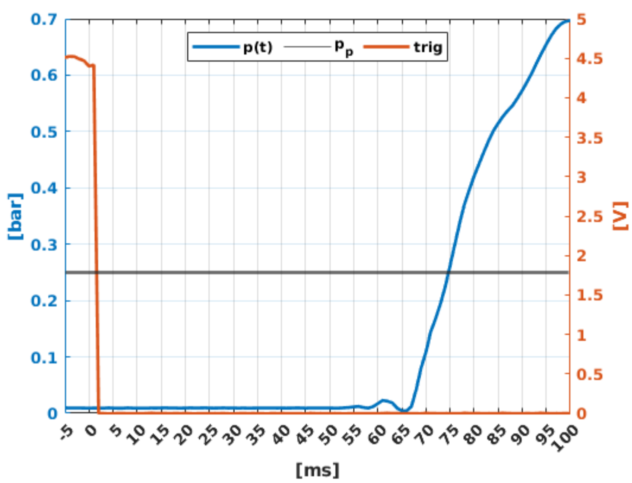

Fig. 9: The inflating test results of the front airbag. After the trigger signal (red), the airbag pressure $p(t)$ (blue) reaches the protective pressure $p_p = 0.25$ bar (black) in 76 ms.

B. *Inflating test*

The experimental results show that the front airbag reaches the minimum protective pressure $p_p = 0.25$ bar after 76 ms, as depicted in Figure 9, and remains above the threshold for more than 19s. After activation of the gas generator, a slight variation in the airbag temperature is detected, but it is almost negligible. Concerning the back airbag, the minimum protective pressure $p_p = 0.18$ bar is reached after 83 ms, as shown in Figure 10. Therefore, the wearable airbag meets the requirements defined in Section II regarding the activation time to protect the user when falling from 1.5 m.

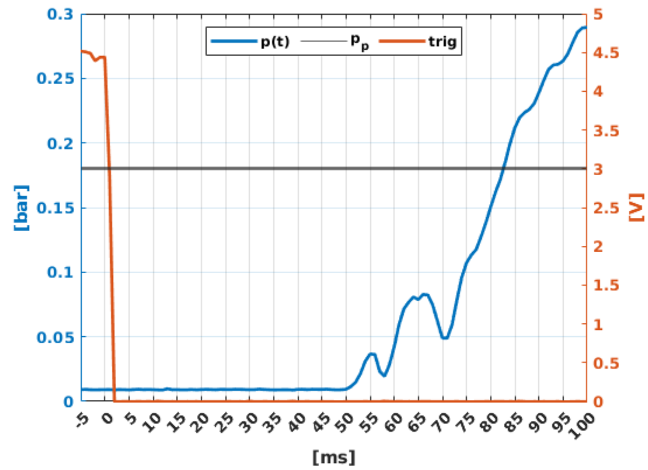

Fig. 10: The inflating test results of the back airbag. After the trigger signal (red), the airbag pressure $p(t)$ (blue) reaches the protective pressure $p_p = 0.18$ bar (black) in 83 ms

IV. CONCLUSIONS

FFH represents the leading cause of non-fatal and fatal injuries at work, with the sector bleeding most, being construction. The short time before impact, the risk of unnecessary activations, and the need to dissipate large amounts of kinetic energy pose significant engineering challenges in the design of smart PPE. This work presents a new smart wearable airbag designed to address these challenges and mitigate the outcomes of FFH in the construction sector. The system complements existing PPE, providing an additional level of protection to the user's frontal and dorsal regions. The fall detection algorithm detects a fall event in less than 300 ms, and the system is fully inflated in about 80 ms, making it compatible with falls from 1.5 m to 4 m. Impact tests show that our wearable airbag meets the Level 2 protection requirements of the EN1621-4 standard. Future work will focus on testing the system on mannequins and subjects to further characterize the overall performance. Usability, wearability, and acceptability tests will evaluate workers' and stakeholders' opinions on this new wearable airbag, leading to further development of the system and potentially paving the way for mass adoption in the construction sector.

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