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A Study on the Proposed Structure, Materials, and Manufacturing Method for Smart Airbag Shells Protecting the Head of Elderly Vietnamese Users

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Abstract

Amid the global trend of population aging and the increasing risk of falls among older adults, the development of active protective assistive devices is of critical importance. Falls not only cause severe physical injuries but also exert significant psychological and financial burdens on the elderly and their families. Smart airbags, which are widely used as safety devices in the automotive industry, should be further investigated for potential applications in healthcare, particularly in protecting the head and other vulnerable regions of the elderly body during falls. This paper presents a comprehensive synthesis and analysis of published research related to the structural design, materials, and fabrication technologies of smart airbags. Based on this analysis, it proposes research directions that are tailored to the anthropometric characteristics of the Vietnamese elderly population and aligned with domestic manufacturing capabilities. The findings provide an essential foundation for the design and development of smart airbag systems for human body protection in general, and head protection in particular, aiming to reduce fall-related injuries among older adults.

Keywords: Human head region, smart airbag system, structural design of smart airbag systems.

1. Introduction

Population aging is one of the most significant challenges of the 21st century, exerting profound impacts on global healthcare systems, social structures, and economic development. According to the United Nations, the number of people aged 65 and older worldwide is projected to reach 1.5 billion by 2050, nearly doubling compared to 2020 [1]. In this context, falls among older adults have emerged as a major public health concern, constituting a leading cause of severe injuries such as fractures, spinal damage, and especially traumatic brain injuries, one of the most common contributors to mortality and long-term functional decline in the elderly.

In Vietnam, this issue is even more pressing as the country is entering a phase of rapid population aging while healthy life expectancy remains relatively low. Older adults in Vietnam face a "double burden" characterized by the coexistence of non-communicable diseases, prolonged chronic conditions, and psychosocial challenges. Notably, the proportion of older adults living alone has been steadily increasing, thereby elevating the risk of serious accidents in daily life. Among these, falls are the most common and result in the most severe consequences, such as head and neck injuries, fractures, and a significant deterioration in quality of life. In addition to physiological factors associated with aging, such as osteoporosis, loss of muscle mass, and declines in neurological function and reflexes, the daily living habits of older adults in Vietnam exhibit distinct characteristics compared to those in developed countries. Specifically, older individuals often move within confined living spaces, reside in houses with uneven floor levels or stairs, slippery surfaces, and a lack of specialized assistive devices, while their access to and ability to use modern technologies remain limited. These factors collectively contribute to a substantially increased risk of falls and exacerbate the severity of injuries when such accidents occur.

In recent years, several domestic studies have begun to address the issue of falls among older adults through motion data analysis and the development of fall detection algorithms based on wearable sensors. The study conducted by Nguyen Tuan Linh [2], focused on the construction of a fall-related motion dataset and the investigation of threshold-based fall detection methods. However, these studies have primarily concentrated on fall recognition and event warning, without addressing body protection solutions aimed at mitigating injury severity when a fall actually occurs. Furthermore, existing domestic research and products related to airbag garments have mainly been designed for motorcycle riders and are therefore not suitable for the anthropometric characteristics, movement behaviors, and daily usage needs of older adults. In contrast, with the rapid advancement of sensor technologies and wearable devices, numerous active protection solutions for older adults have been investigated and implemented worldwide.

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Among these, personal wearable smart airbag systems have attracted considerable attention. These systems operate by early detection of pre-fall states through sensor data and automatically activate protective mechanisms at vulnerable body regions such as the head, neck, and spine. Owing to their rapid response capability and adaptive protective mechanisms, smart airbag systems are increasingly regarded as a promising technological solution for preventing fall-related injuries in older adults [3].

Based on the above analyses, this paper focuses on reviewing and synthesizing published studies related to the structural design of smart airbag systems. On this basis, a structural configuration, material selection, and manufacturing approach for a smart airbag shell are proposed, tailored to the anthropometric characteristics, daily living habits, and socio-economic conditions of older adults in Vietnam, while also ensuring feasibility for domestic manufacturing. The expected outcomes of this study aim to contribute to the reduction of fall-related injuries, enhance the quality of life of older adults, and support the broader adoption of smart protective devices in community healthcare applications.

2. General Overview of Smart Head Protection Airbag Systems

Smart airbags represent one of the most significant technological advancements in the field of personal safety and active protective equipment. Initially developed for the automotive industry to safeguard drivers and passengers during collisions, smart airbag technology has gradually expanded its applications to other sectors such as motorcycles, bicycles, aviation, medicine, and healthcare. Notably, it has shown great potential in supporting older adults, a population group particularly vulnerable to fall-related injuries [4]. Equipped with advanced sensors, signal processing systems, and rapid activation mechanisms, smart airbags are capable of accurately detecting hazardous situations and deploying protective measures within a few hundred milliseconds. This rapid response significantly contributes to reducing the severity of injuries [5].

Essentially, an airbag is an active safety system designed to detect and respond instantaneously to protect vulnerable parts of the human body. The system typically comprises a high-performance fabric bag, motion sensors (such as accelerometers and gyroscopes), a microcontroller-based processing unit, and a gas inflator. Since its inception, airbag technology has undergone multiple stages of development and continues to be improved in terms of mechanical design, operational functionality, and material composition. The fabrics used are generally characterized by low air permeability, high impact resistance, and flame retardancy, ensuring durability and safety during high-speed deployment [6]. In the context of a globally aging population, extending the application of smart airbags to protect older adults from fall-related injuries represents an urgent and highly promising direction. In practice, older individuals face an increased risk of falling due to age-related declines in balance, vision, muscle strength, and reflexes. Head injuries resulting from falls are particularly severe and may lead to brain hemorrhage, traumatic brain injury, or even death. Therefore, the development of specialized airbag systems designed to protect the head region of elderly individuals constitutes a significant advancement in both engineering and public healthcare.

Smart airbags for older adults during falls are wearable devices specifically designed to protect critical body regions, particularly the head, from mechanical impacts in unexpected fall situations. According to the definition provided by Healthcare and Pharmaceuticals [7], these systems are classified as personal protective equipment integrated into products such as vests, soft helmets, or body-worn belts, capable of automatically detecting abnormal motion and deploying airbags within a fraction of a second. As a result, the head and other commonly impacted areas, such as the hips, back, spine, and wrists, are effectively cushioned, thereby significantly reducing the risk of severe injury.

3. Study on the Proposed Structure, Materials, and Manufacturing Methods for Smart Airbag Shells

3.1. Requirements for Smart Airbags for the Elderly

To ensure both protective effectiveness and user safety, smart airbag systems designed for older adults must satisfy stringent technical requirements identified in recent studies on wearable fall protection systems [8]. First and foremost, mechanical durability is a critical determinant. The materials used for airbag fabrication must exhibit high tensile strength, the ability to withstand substantial impact forces, appropriate thermal stability, and sufficient flexibility to ensure user comfort and prevent skin irritation during prolonged daily use [8]. In addition, lightweight structures with good foldability are emphasized as key design criteria to minimize bulkiness and user fatigue, which is particularly important for older adults, a population group commonly experiencing reduced muscle strength and mobility [9]. Equally important are the dynamic characteristics of the airbag system. Numerous studies have demonstrated that ultra-fast inflation speed is a crucial condition for achieving effective impact protection, requiring the airbag to be deployed within several tens of milliseconds immediately after the wearable sensor system detects a fall event or pre-fall motion patterns [10]. Furthermore, the ability to maintain an appropriate internal air pressure for a certain duration after deployment plays a decisive role in attenuating impact forces acting on vulnerable body regions such as the head, neck, and hips, thereby significantly reducing the risk of severe injuries [10, 11]. A study on the design of head and neck protective airbags [12] proposed an airbag with dimensions of

470 × 330 mm and a volume of approximately 10 L, while airbags for hip and thigh protection were designed with dimensions of 250 × 450 mm and a volume of about 10 L. Each airbag was equipped with an independent inflator and gas canister; the two airbags together weighed 1.1 kg and were integrated into a jacket. Inflation tests reported in [13] showed that 380 ms after activation of the airbag deployment module, more than 80% of the airbag volume was filled with gas, forming a cushioning layer, with the deployed airbag dimensions reaching 300 × 260 × 80 mm. Another study on the development of a smart airbag system [14] demonstrated the capability to detect pre-fall signals approximately 300 ms before impact and deploy an airbag to protect the head and neck of older adults, achieving post-deployment dimensions of 470 × 330 mm and a volume of approximately 10 L.

Based on a synthesis of existing research findings, this paper focuses on the design orientation of a smart airbag shell structure, which houses both the airbag deployment mechanism and the gas-containing chamber after inflation. The airbag shell is fabricated from high mechanical strength textile materials with impact resistance and puncture resistance, and is manufactured using combined sewing, bonding, and welding, bonding techniques to ensure waterproof performance and gas tightness. The proposed design emphasizes compactness, light weight, and ease of wear. The head and neck-covering airbag is specifically designed to conform to the anthropometric characteristics of the head and neck of Vietnamese older adults of both sexes, with an estimated post-deployment size of 470 × 330 × 80 mm and a volume of approximately 8 L. This design approach is expected to enhance the feasibility of domestic manufacturing while promoting the wider adoption of smart airbag systems in community healthcare and elderly care applications [8, 9].

3.2. Analysis of Selected Smart Airbag Design Structures Studied

During the research and development of smart protective devices for older adults, various airbag structures have been designed and tested with the aim of protecting the head during fall incidents. Each design represents a different technical approach, ranging from the arrangement of air chambers and deployment mechanisms to the placement of sensors and inflation components. Analyzing existing structures not only helps assess the advantages and limitations of each approach but also provides an essential basis for selecting or proposing a more suitable configuration for real-world use, particularly for older adults in Vietnam. In this section, several representative designs are reviewed to clarify their effectiveness, applicability, and potential for improvement in future research. According to patent *US10390580 B2 (2019)* [15], the smart airbag system, designed for head protection during falls, consists of four main components: a neck-worn collar, an internal airbag, an external fabric cover, and a gas inflation system.

The neck-worn collar (1) is the component that comes into direct contact with the user. It functions like a necklace designed to be worn around the neck, over regular clothing, as a preventive measure in the event of an accident, while also housing the entire airbag system when it is not activated. The collar includes a connecting mechanism between its two ends (2), such as a zipper, Velcro, or buckle, to allow users to easily put on and remove the device. The structure of the neck-worn collar is illustrated in Fig. 1 [15].

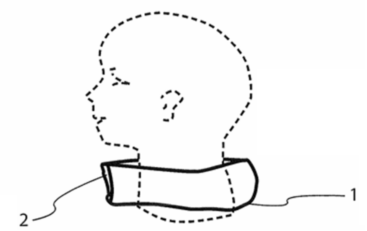

Fig. 1. Smart airbag before deployment

In the non-activated state (Fig. 1), the airbag system resembles an accessory-like collar (1) worn around the user's neck.

The airbag section (3) consists of an inner airbag (4) that contains the inflation gas, which is enclosed by an outer airbag shell (5). The structure of the outer shell determines the final shape of the airbag section when the inner airbag is inflated [15]. In the deployed state (Fig. 2), the airbag system (3) comprises two main components when viewed from the outside inward: the inner airbag (4) and the outer airbag shell (7).

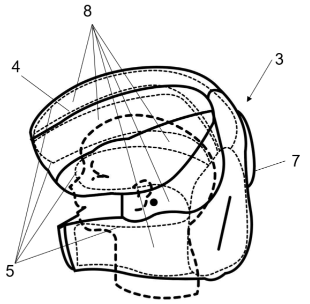

Fig. 2. Airbag in the deployed state

The inner airbag (4) consists of multiple first elongated chambers (5), each forming a protective section when inflated. These first elongated chambers can provide protection to the frontal, parietal, temporal, and cervical regions upon deployment. In addition, the inner airbag includes a second chamber (6), which is connected to the first chamber and can form a protective section for the occipital region of the skull when inflated. This finger-and-palm–like design allows for flexible airflow and uniform expansion. The inner airbag is typically made from a waterproof material, such as a thermoplastic polyurethane (TPU) membrane. Fig. 3 illustrates the inner airbag in its non-inflated state [15].

The outer airbag shell (7) consists of multiple elongated lateral sections (8), each containing one of the first elongated chambers of the inner airbag, ensuring that these chambers remain fixed within their designated positions during inflation and cannot shift out of alignment. The outer shell includes an outer layer and an inner lining, which together form the lateral sections and can be bonded using stitching, adhesive, or straps. The outer shell is connected to the inner airbag at position (9) to prevent gas leakage. Although it does not require high waterproofing capability, the shell must be strong, heat-resistant, and capable of withstanding impact and abrasion to protect the inner airbag [15].

The inflation device (10) is positioned at the back of the neck, with an activation sensor configured to detect abnormal user movements indicative of an accident. This sensor can transmit a trigger signal to the inflation device to fill the airbag [15]. The inflation of the first elongated chambers (5) of the inner airbag essentially corresponds to the expansion of the matching elongated lateral sections (8) of the outer shell. The cross-sectional area of each first chamber may vary along its length and is generally smaller than that of the corresponding outer shell section. This size difference creates a rapid expansion mechanism: as the inner chambers inflate, they stretch the outer shell sections, quickly transforming the structure from a folded/collapsed state to a fully deployed state. The smaller size of the inner chambers reduces the required gas volume, thereby shortening deployment time and lowering energy consumption during activation [15]. According to patent US8402568B2 (2013) [16], a system and method are proposed to protect the user's head in the event of a fall or collision. The system consists of a wearable device (1), an airbag (2), an inflation device (3), and an activation unit.

In Fig. 4, the airbag consists of a first section (7) that protects the neck and the back of the head, and a second section (8) that forms a hood covering the skull when deployed. Both sections are folded and stored inside the wearable device (1) when not inflated. The wearable device, which can be a collar or scarf, wraps around the user's neck and includes an opening (12) at the front or back of the neck. This opening can be fully or partially opened and closed using various mechanisms, such as zippers, buttons, Velcro, magnets, hooks, clips, pins, adhesives, tapes, ties, or similar. The first section (7) is inflated first to provide a stable foundation for inflating the second section (8). The collar can be made from soft, durable, and flexible materials, such as acetate silk, denim, felt, cotton, beaver nylon, or similar materials [16]. The interior of the collar houses the airbag system, which comprises the main components: the airbag, the inflation device, and one or more compartments to arrange and secure the internal components.

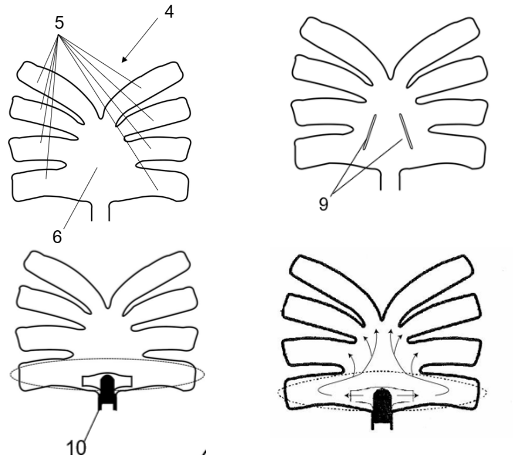

Fig. 3. Inner airbag in the non-inflated state

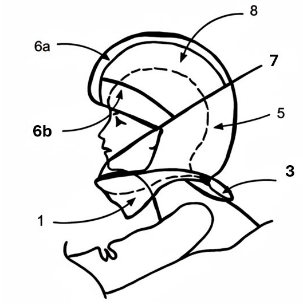

Fig. 4. Side view of the product in an inflated position

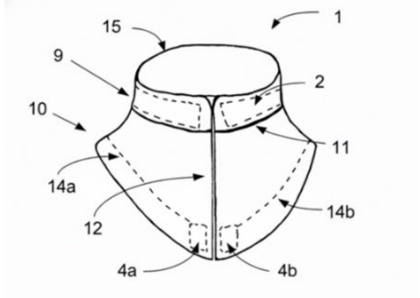

Fig. 5. Front-view of an embodiment according to the invention

Fig. 5 shows the front view of the product with the airbag in the non-activated state. The position of the folded airbag, the stitching lines, and the arrangement of the compartments inside the collar can be clearly observed. The airbag (2) is typically made of fabric material, folded, and then packed into the upper part (9) of the collar, usually within a separate compartment inside the collar. In the non-activated state, the airbag is designed to start at the front-left side, near the closable opening (12), run around the neck, and end at the front-right side, also near this opening. To secure its position, the airbag is stitched or attached along the dividing seam (11) between the upper (9) and lower (10) parts of the collar, and it is also sewn along the front edge up to the vicinity of opening 12.

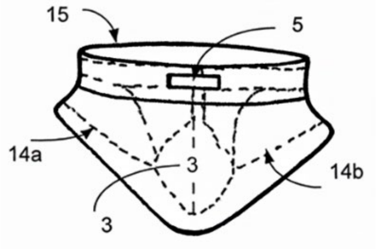

Fig. 6. Back view of the airbag helmet configuration

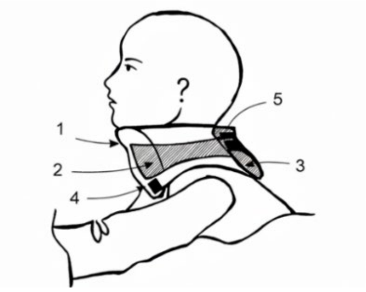

Fig. 7. Side view of the airbag helmet worn by a user in the non-inflated state

Fig. 6 and Fig. 7 illustrate the overall structure of the product in the non-inflated state. Fig. 6 shows the back of the airbag, where the inflation device is located, and the internal airbag is secured by stitching. Fig. 7 presents a side view of the product when worn by the user, demonstrating how the collar fits snugly around the neck while maintaining flexibility, providing a stable base for the airbag to deploy correctly when activated.

The inflation unit (3) is positioned at the middle of the back side of the lower part (10) of the collar and is directly connected to the airbag (2). This device functions as a pre-charged pneumatic pump without using explosives, reducing heat generation and noise while enhancing user safety and comfort. Compared to conventional inflation systems, unit (3) is more compact, requiring only approximately 10 liters of gas, depending on the user's head size. The casing or gas cylinder is about 65 mm in length, with a tube wall thickness of approximately 1.2 mm, thicker than standard cylindrical gas cylinders, to ensure higher durability and safety during operation [16]. The inflation unit (3) is connected to the airbag (2) through a gas distributor (5), which directs the gas from the pump into the airbag chambers. The pump can be secured using screws, adhesive, stitching, or other attachment methods. The gas distributor (5), positioned inside the airbag (2), can be designed in T-, Y-, I-, arrow-shaped, or multi-chamber cylindrical forms to ensure even gas distribution. During inflation, the high gas pressure generates a downward thrust, counteracted by the reaction force from the durable fabric of the airbag, maintaining stability and safety during deployment. The pump is powered by a 3 V battery, placed in sockets (4a) or (4b) integrated into the collar. The battery can be rechargeable (electric or mechanical) or single-use. The system also integrates status indicators (LED, sound, vibration) to monitor power and detect malfunctions [16]. The activation unit, comprising sensors and a control microcircuit, is located at sockets (4a, 4b) and connected to the inflation unit via wires (14a, 14b). Its function is to detect abnormal movements, such as falls or strong impacts, precisely trigger the airbag, and prevent false activation under normal conditions [16]. The inflation unit (3) is placed at the back of the collar, while sockets 4a and 4b are located at the front, on either side of the opening (12), to balance weight. The upper part (9) of the collar surrounds the fabric airbag (2), the front of the lower part (10) houses the sockets 4a and 4b, and the back of the lower part (10) encloses the inflation unit (3). In the event of an incident, such as a fall, the system activates, inflating airbag (2) to encircle the neck and head, functioning as a protective hood.

Inflation occurs in two stages. In stage 1, the collar section (7) inflates first, surrounding and stabilizing the neck and throat to prevent injuries caused by impact or sudden jerking motions in the head and neck region. In stage 2, the top section (8) inflates, forming a protective hood covering the crown, temples, and forehead to reduce impact on vulnerable skull areas during an accident. The collar section (7) can transfer gas to the top section (8) via a pressure-regulating valve or semi-permeable membrane, allowing gradual gas flow as pressure increases. The top section is reinforced with seams 6a and 6b, extending from the collar to the forehead and arranged symmetrically along the central axis. Spacer components (cords or flexible rods, approximately 7 cm long) are inserted between the inner and outer seams to maintain shape when inflated and allow folding when deflated. This structure ensures that the inflated top forms a closely fitted protective hood, providing comprehensive head protection for the user [16].

When the airbag is inflated, the top section (8) expands along a curved profile to cover the head, as illustrated in Fig. 8 (stages VIII–XI). This deployment process consists of 11 steps. In the initial stages (I–VI), the airbag inflates vertically, forming a cylindrical shape to protect the neck. During stages I–II, the airbag begins to expand and breaks the surrounding seam (15); by stages III–VI, the cylindrical structure is fully formed, providing early protection to the user's neck to reduce the risk of severe injury. Once the collar section (7) is fully inflated (stages V–VII), the internal pressure increases, opening the valve connecting the collar and the top section (7–8), allowing the top section to begin inflating. Due to the internal seam system and reinforcing mesh, the top section inflates along a natural curve, covering the crown, temples, and forehead (stage XI). At this stage, the airbag achieves its optimal protective shape [16].

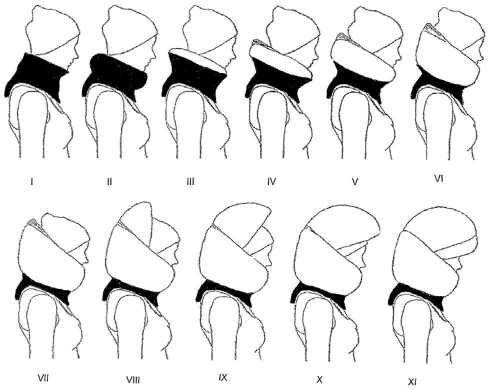

Fig. 8. Sequence of side views illustrating the inflation process of the airbag helmet at different time instants

To ensure the airbag maintains its shape during impact, the structure is designed with either no exhaust holes or only very small ones, unlike automotive airbags. The main material is silicone-coated nylon fabric, with a rigid and durable outer layer to withstand impact and a soft, stretchable inner layer to enhance flexibility. Reinforcing silicone fibers increases thickness, durability, and foldability, ensuring effective deployment when activated. In the process of investigating head protection solutions for the elderly during falls, two smart airbag structures described in U.S. Patents US10390580B2 (2019) and US8402568B2 (2013) were analyzed and compared. The design outlined in US10390580B2 features a hand-shaped configuration that surrounds the head, utilizing a smaller inflation volume. This enables faster deployment of the airbag, thereby enhancing protection effectiveness in sudden fall scenarios. However, a key drawback of this design lies in its manufacturing complexity; the presence of numerous folded seams and intricate stitching makes it difficult to produce, particularly in domestic manufacturing settings. Additionally, these features may increase the risk of air leakage during use. In contrast, the design described in U.S. Patent US8402568B2 is simpler, consisting of two main chambers, which allows for easier manufacturing, compact folding, and reusability. This structure is well-suited for daily use by elderly individuals, particularly in regions with limited technological and manufacturing capabilities. However, a notable limitation of this design is its requirement for a large inflation volume, which results in a longer activation time. This delay may reduce the effectiveness of protection in fast-occurring fall scenarios.

3.3. Proposed Overall Structural Design of a Smart Airbag Helmet for Fall Protection in the Elderly

At present, no officially published anthropometric head sizing system specifically for older adults is available in Vietnam. Therefore, within the scope of this paper, detailed geometric dimensions of the airbag shell are not presented. The primary objective of this study is to propose an overall structural concept for a smart airbag shell, with a focus on structural configuration, material selection, and manufacturing methods (sewing–bonding) to ensure gas tightness, mechanical durability, and practical usability. It should be emphasized, however, that the geometric dimensions of the airbag shell and the structural solutions proposed in this study are not hypothetical. Instead, they will be designed in detail based on anthropometric head data of Vietnamese older adults that have been obtained through a separate, independent study conducted by the authors. Specifically, direct anthropometric measurements of the head were collected from male and female older adults aged 60 to 80 years, with a sample size of 266 participants selected from three representative regions: Hanoi, Ninh Binh, and Ho Chi Minh City. The collected data were analyzed using principal component analysis (PCA) to identify the dominant control dimensions, in combination with K. Pearson tests to assess the normality of anthropometric variable distributions, with the support of Statistical Package for the Social Sciences (SPSS) 30.0 software. Based on these analytical results, an anthropometric head sizing system for Vietnamese older adults aged 60–80 years, comprising 15 optimal size categories for both males and females, was established. These results have been reported in our previous studies [17]. Based on the obtained dataset, a sizing system was established to provide a scientific foundation for the detailed design of smart airbag shells tailored to the anthropometric characteristics of Vietnamese older adults. As the present paper focuses on proposing the overall structural concept of the smart airbag shell and its manufacturing technology, detailed results regarding the head sizing system of Vietnamese older adults and the specific dimensions of the smart airbag shell will be fully presented in the authors' subsequent publications. Building upon the aforementioned anthropometric data, together with an analysis of the limitations of existing patented solutions, the development of a new smart airbag structure is necessary. Such a structure should ensure rapid activation, reduce the required gas volume, facilitate manufacturing, and simultaneously accommodate the anthropometric characteristics and daily usage habits of Vietnamese older adults.

Based on this rationale, the present study proposes an improved smart airbag structural solution, designed as a single air chamber encircling the head–neck region, integrating a sensor module and an inflation system that are suitably positioned at the front and back of the neck, respectively, to optimize protective performance, shorten deployment time, and simplify the manufacturing process. The proposed smart airbag for head protection is designed to protect the head and neck of elderly users in the event of a fall, while still ensuring convenience and aesthetics so that it can be worn regularly in daily activities. Its shape is inspired by the traditional Russian fur hat, which features a snug-fitting structure that covers the ears and nape effectively, offering a familiar and easily acceptable appearance for older adults. To better illustrate the overall structural concept, Fig. 9 and Fig. 10 present the front and back views of the smart airbag for head protection proposed by the research team for elderly users. These figures clarify the coverage structure, the degree of snug fit, and the arrangement of the extended section at the nape before proceeding to the detailed description of the internal technical components.

Fig. 9. Illustration of the proposed airbag showing the front and back views

Fig. 10. Artistic illustration of the proposed airbag model for elderly users, showing the front and back views

The outer shell of the smart airbag helmet is designed as a neck-covering helmet that fully encloses the head, extends down to the nape and neck, and fits snugly around both ears. This structure forms a continuous protective frame, securing the air chamber and the technical module inside while maintaining a stable shape when worn. The extended section at the neck and nape is naturally curved to cover and protect the posterior neck area, where the gas cylinder, solenoid valve, and air conduits are integrated, while also enhancing impact absorption in the event of a backward fall. In addition to its protective role, the outer shell also contributes to the helmet's aesthetic shaping and balanced weight distribution, ensuring a snug, stable, and comfortable fit while minimizing shifting during movement. To improve breathability and comfort during prolonged use in Vietnam's hot and humid tropical climate, the shell is equipped with a passive ventilation system positioned around the neck and nape areas. This system includes two symmetrical air intake slots located on the front sides of the neck and two small exhaust vents placed on the rear sides near the nape. The intake slots are angled upward to utilize natural airflow from the front, directing cool air into the inner neck lining, while the exhaust vents are angled outward and downward, allowing hot and humid air to escape without compromising the airtight integrity of the air chamber. As a result, the neck and nape remain well-ventilated, reducing heat buildup during extended wear in hot and humid conditions. Due to its hood-and-neck integrated structure with a built-in ventilation system, the product achieves an optimal balance between safety, ergonomics, and aesthetics, allowing older adults to use it for extended periods comfortably while maintaining the stable operational performance of the airbag system upon activation.

The airbag serves as the core component responsible for protecting the head and neck from impact during a fall. Unlike conventional multi-chamber designs, the airbag in this model is constructed as a single, seamless chamber that envelops the entire head, from the forehead, crown, and both sides of the ears to the occipital region and upper neck. This single-chamber structure enables uniform distribution of compressed air, preventing localized tension or pressure imbalance between regions while enhancing geometric stability during inflation. Inside the airbag, a system of structural reinforcement ribs, formed through stitched–bonded or welded–bonded seams, functions as a flexible internal frame that guides the airbag to expand into a predefined shape that fits closely around the head and neck, preventing asymmetric expansion or folding. Upon activation, the airbag inflates to create a cushioning layer surrounding the head and neck, absorbing impact energy and reducing the risk of traumatic brain injury and cervical spine injury. The airbag is connected to a mini one-way valve that maintains stable internal pressure after deployment, preventing sudden deflation during protection. The technical module functions as the control center that operates the entire smart airbag system. It is responsible for signal acquisition, data processing, activation, and distribution of compressed air to the airbag upon the occurrence of a fall. The technical structure is designed as a compact, integrated unit that can be positioned around the anterior or posterior neck region to ensure balanced weight distribution, minimize user discomfort, and optimize protection effectiveness for the head.

The main components of the technical module include: (1) a sensor system responsible for collecting the user's motion data; (2) a microcontroller that processes and analyzes signals to detect fall events; (3) a power supply system that provides energy for the entire device; and (4) the inflation and deployment system, consisting of the gas cartridge, activation mechanism, and air conduits, which generates and delivers compressed gas to the airbag. The specific technical elements of the smart airbag system currently being developed and experimentally tested by the research team include: a battery that supplies power to the entire system; a power switch used to connect or disconnect the battery from the circuitry; a USB charging module that manages charging and protects the battery; a microcontroller unit (MCU) that processes sensor signals and controls the system; capacitors for noise filtering and voltage stabilization for both the MCU and sensors; an inertial sensor module that measures acceleration and angular velocity for fall detection; a boost converter that raises and stabilizes the supply voltage; a miniature solenoid valve for rapid gas release upon activation; a puncture mechanism that connects to the CO_2 cartridge and pierces the cartridge seal via a needle; a connector for the air conduit; a gas cartridge serving as the compressed gas source; and air tubing that transfers gas from the puncture mechanism to the airbag. These components perform distinct functions but operate in a tightly integrated manner to ensure the system remains stable, safe, and capable of rapid response once activated. To ensure the effective operation of the technical module, the installation and arrangement of its components must meet the following technical requirements:

- The sensors should be positioned in a fixed location, isolated from head and neck movements, to ensure the accuracy of the collected data.
- The battery and charging circuit should be positioned in a location that allows convenient access for charging and replacement.
- The CO_2 cartridge and the inflation system should be positioned to ensure uniform gas distribution to the airbag, without obstructing or posing any risk to the user during deployment, while also allowing easy removal and replacement after activation.
- Other auxiliary components (capacitors, boost converter, electrical wiring, and air tubing) should be arranged symmetrically, with optimized routing to minimize energy loss and maintain balanced mass distribution across different regions.

The analysis of related patents indicates that US Patent 8,402,568 B2 [16] positions the gas inflation unit at the center of the rear collar, directly connected to the airbag. Sensors, the battery, and control components are located on the front sides of the collar (positions 4a and 4b) to manage the inflation process and prevent unintended activation. Meanwhile, US Patent 10,390,580 B2 [15] also places the inflation device at the rear of the collar (position 10), symmetrical to the front sensor module, which helps balance the weight and optimize the deployment direction of the airbag around the head. However, a common limitation of these designs is the long route of the power supply, which increases energy loss and response delay. Based on the above analysis, the research team proposes the following arrangement for the technical module of the head-protecting airbag: the sensors, microcontroller, battery, and power switch are evenly distributed on both sides of the anterior neck recess (corresponding to positions 4a and 4b in US Patent 8,402,568 B2), while the inflation unit and CO_2 cartridge are positioned at the rear of the neck (corresponding to position 3). The charging and boost circuits are compactly stacked on top of the microcontroller module to save space and ensure the shortest possible signal paths. This arrangement balances the mass between the front and rear, providing stability during wear, while clearly separating the two functional clusters: sensor–control and inflation–gas supply. However, this arrangement also introduces additional design requirements, such as the need for a front opening to allow battery charging and a rear opening for replacing the gas cartridge after activation, as well as the need to design optimal electrical routing to minimize energy loss due to the symmetric placement of components on both sides of the neck. Despite these limitations, this solution is feasible, effectively meeting technical performance, center-of-mass balance, and user safety requirements, while inheriting the advantages of existing international designs.

3.3.1. Overall operating principle

During use, the smart airbag helmet operates through the coordinated interaction of the motion sensor system, central microcontroller, and compressed air inflation system. All sensors, integrated within the technical module located at the neck–nape region and on both sides of the head, continuously capture and analyze the wearer's head acceleration, tilt angle, and angular velocity in real time. During normal movement, the collected data fluctuates within a stable range, and the system remains in standby mode. However, when sudden changes in acceleration or angular velocity exceed safety thresholds, indicative of a loss of balance or free fall, the signal processing algorithms within the microcontroller quickly identify the fall event.

Once the activation conditions are confirmed, the microcontroller immediately sends a control pulse to the solenoid valve, opening the gas path from the CO_2 cartridge to the air conduit system. Within just a few milliseconds, compressed gas is released at high pressure and distributed evenly to the airbag surrounding the head and neck. The airbag rapidly inflates into its predetermined shape, forming a cushioning layer that envelops the entire head, both ears, and the occipital region, absorbing and dispersing impact energy while minimizing the risk of traumatic brain injury and cervical spine damage. After the airbag is fully inflated, the one-way valve maintains stable internal pressure, ensuring protective capability throughout the fall. When the impact subsides, the system can automatically return to standby mode, or the user can remove it to replace the gas cartridge and recharge the battery. Due to its closed-loop operation and instantaneous response, the smart airbag helmet not only provides superior protection compared to traditional protective equipment but also enhances safety, usability, and practical applicability for elderly users in daily activities.

3.3.2. Advantages of the smart airbag for head protection structure for the elderly

The proposed smart airbag for head protection structure offers several notable advantages in terms of protective capability, rapid response, and daily usability.

First, the integration of a branched air conduit system enables rapid and uniform distribution of compressed air from the inflation module to the main airbag, ensuring nearly simultaneous inflation around the head, nape, and upper neck. As a result, the airbag maintains stable internal pressure, minimizing asymmetric expansion or local deformation, while significantly reducing deployment time, a critical factor in enhancing protective performance during sudden falls.

Second, the technical module is arranged to achieve a balance between performance and ergonomics: sensors, microcontroller, battery, and power switch are evenly distributed on both sides of the anterior neck recess, allowing accurate motion detection and convenient access for charging and maintenance. Meanwhile, the inflation unit and CO_2 cartridge are positioned at the rear of the neck, near the head's center of gravity, enhancing stability during wear and optimizing the airflow path to the airbag. This distribution also reduces localized pressure on the nape and forehead, providing a sense of balance, lightness, and safety for the user.

Third, regarding comfort and climate adaptability, the helmet shell is made of lightweight, breathable, moisture-resistant, and antibacterial materials, combined with a passive ventilation system consisting of two air intake vents on the anterior neck and two small exhaust vents located behind the ears near the nape. This structure allows natural airflow around the neck and nape, reducing heat accumulation and perspiration, particularly under Vietnam's hot and humid tropical climate.

In terms of protective effectiveness, when activated, the airbag envelops the entire head, neck, and nape, forming a continuous cushioning layer capable of absorbing and dispersing impact energy, thereby significantly reducing the risk of traumatic brain injury and cervical spine damage. Internal air pressure is maintained by a mini one-way valve, ensuring sustained protective performance throughout the fall. Additionally, the airbag is designed as a single, seamless chamber, simplifying the manufacturing process, reducing seams or joints prone to air leakage, aligning with domestic production capabilities, and lowering fabrication costs. Finally, in terms of practical applicability, the product features a compact form factor, resembling a soft helmet or winter fashion hat, making it easy to integrate with everyday clothing and enhancing acceptability and aesthetic appeal among elderly users. However, due to its neck–nape-encompassing structure and weight concentration in this region, the product is not suitable for high-intensity physical activities such as running, long-distance cycling, or sports. It is better suited for elderly individuals engaged in light movement, daily indoor or outdoor activities in areas with gentle airflow, where fall protection is needed while maintaining long-term comfort and safety.

3.4. Proposed Material Selection for Manufacturing Smart Airbag Shells

Most charts, graphs, and tables are one column wide (3.5 inches/88 millimetres/21 picas) or page wide (7.16 inches/181 millimetres/43 picas). The maximum depth a graphic can be is 8.5 inches (216 millimetres/54 picas). When choosing the depth of a graphic, please allow space for a caption. Figures can be sized between column and page widths if the author chooses, however it is recommended that figures are not sized less than the column width unless necessary. The materials used for airbag fabrication must possess special properties, including gas impermeability, flame resistance, impact resistance, high tensile strength, and elasticity, allowing them to withstand high pressure during inflation. Representative materials include rubberized cellulose fabrics or synthetic polymers such as polyester, nylon 6, and nylon 6,6 [18]. The ideal fabric weight for airbags ranges from 150 to 200 g/m^2, with a thickness of approximately 0.35 mm, and an additional coating layer of 70–80 g/m^2 is typically applied to enhance gas retention and tear resistance [18].

Given the strict safety requirements for airbags, material selection plays a critical role in product performance. In the 1970s, the first-generation automotive airbags employed neoprene-coated nylon fibers, typically in deniers ranging from 420 to 840, due to their mechanical strength, thermal resistance, and air impermeability [19]. This design persisted through the late 1980s and early 1990s. However, from the mid-1990s, under pressure to reduce costs and improve environmental sustainability, manufacturers focused on uncoated fabrics that were lighter, more flexible, and easier to process. A significant advancement occurred in 2017 when Elsayed Ahmed Elnashar [20] developed airbag fabrics using nylon 66 fibers (235–940 tex) combined with nanotechnology. This fabric exhibited high tensile strength, good elasticity, and effective tear resistance. Uniform gas retention across the entire fabric surface was identified as crucial to ensure rapid and uniform inflation. Elsayed Ahmed Elnashar [20] also noted that multifilament nylon 6,6, with high tensile strength, thermal resistance, and fine fibers ranging from 210, 420 to 840 denier, is the most widely used material for smart airbags today. In certain cases, nylon 6 is also used due to its softer texture, reducing friction against the skin during direct contact. Although polyester has been considered as an alternative, it fails to meet thermal resistance requirements, as its melting point is approximately 40% lower than that of nylon 66, allowing hot gas to permeate the fabric and compromise user safety.

In this study, the authors consider polyamide 66 (nylon 6,6) with fiber deniers from 420 to 840 as the most suitable material for smart airbags due to its elasticity, fatigue resistance, high tensile strength, abrasion resistance, and low friction coefficient. These properties make it well-suited for high-impact conditions, balancing mechanical strength, thermal resistance, gas impermeability, and stability under harsh operating conditions [20]. However, nylon 66 still presents certain limitations, particularly its relatively high production cost and limited moisture absorption, which may restrict large-scale industrial application in developing countries [21]. Aramid fibers, known for extremely high mechanical strength and superior thermal resistance, represent another option. However, their high cost and processing difficulty limit large-scale industrial production [12]. Recently, reinforced polyester fibers have attracted attention as a potential alternative. With a melting temperature of approximately 258 °C, comparable to that of nylon 6,6 (260 °C), reinforced polyester demonstrates stable thermo-mechanical behavior while offering significant advantages in terms of cost-effectiveness and manufacturability. Consequently, reinforced polyester can be considered a viable substitute for polyamide 66 in automotive airbags and wearable smart protection systems [22]. Based on these analyses, future research will focus on identifying the optimal material for airbag fabrication, balancing strength, gas retention, weight, and production cost, while applying modern processing techniques to enhance the performance, durability, and safety of smart airbags for elderly users in Vietnam.

However, when considering domestic manufacturing conditions and practical applicability, material availability and manufacturability become critical factors. The current situation in Vietnam indicates that coated technical textiles meeting requirements for gas tightness and load-bearing capacity are relatively accessible. Typical examples include TPU-coated nylon fabrics and PU-coated polyester fabrics. These two material categories are widely used in applications requiring waterproof performance, air retention, and high mechanical strength, and are therefore regarded as suitable candidates for investigating their application in airbag shells for protective helmets and smart airbag systems.

To evaluate manufacturing feasibility under domestic production conditions, the authors conducted collaborative experimental testing at Company No. 76 One-Member Limited Liability Company (under the Ministry of National Defence), which is equipped with laboratories and specialized facilities for assessing key performance indicators of airbag shells, including puncture resistance, burst strength, and the performance of sewing–bonding structures, factors that are critical to gas tightness and overall structural durability of the airbag. Experimental results indicate that for PU-coated polyester fabric (150D), the measured puncture force ranged from 164 to 201 N, which is significantly higher than that of TPU-coated nylon fabric (70D), with values ranging from 113 to 117 N. This difference can be attributed to the inherent characteristics of polyester fibers, which have a larger filament size and higher tensile strength, together with the PU coating that provides superior abrasion resistance, thereby enhancing puncture resistance. In contrast, nylon fibers exhibit a finer and more flexible structure, offering greater flexibility but lower mechanical resistance to penetrating impacts. According to EN 388: 2016 [23], materials with a puncture resistance greater than 150 N are classified as Level 4, the highest level of puncture resistance. Consequently, both fabric types investigated in this study achieve a high-performance rating in terms of puncture resistance under international standards.

In contrast, when considering burst resistance, TPU-coated nylon fabric exhibited a clear advantage, with measured burst pressures exceeding 2200 kPa and in some cases reaching the upper limit of the testing equipment. Meanwhile, PU-coated polyester fabric demonstrated lower burst pressure values, ranging from 1821 to 2100 kPa. This difference is primarily attributed to material structure. The TPU-coated nylon fabric has an average thickness of approximately 0.20 mm and employs high-strength 70D yarns, which enable the TPU coating to maintain a dense, stable, and gas-tight structure under high internal pressure. In comparison, the PU-coated polyester fabric is thinner (~0.15 mm); although it offers superior puncture resistance due to the use of 150D yarns and higher fabric density, the PU coating is more susceptible to degradation under concentrated loads, resulting in reduced burst resistance. Regarding the waterproof and airtight performance of bonded seams, both materials satisfied the requirements based on seam tape evaluations [24], indicating that the seam-sealing process is compatible with the technical requirements of airbag shells. Based on the comparative results, PU-coated polyester 150D is well suited for regions requiring enhanced resistance to direct mechanical actions such as abrasion, friction, and puncture, serving as an “outer protective layer.” In contrast, TPU-coated nylon 70D is the preferred option for areas demanding high burst resistance and stable gas retention during inflation, owing to its toughness and the strong adhesion of TPU to the nylon substrate. Accordingly, a rational design approach is a multilayer structure, in which the outer layer employs PU-coated polyester to enhance mechanical protection, while the inner layer utilizes TPU-coated nylon to ensure gas retention and pressure resistance. This solution enables the advantages of each material to be fully exploited, thereby improving the overall reliability and safety of the airbag shell in smart protective applications.

3.5. Proposed Manufacturing Methods for Smart Airbag Shells

The selection and optimization of manufacturing methods for smart airbags play a crucial role in ensuring product performance, durability, and safety during use. Common fabrication techniques include sewing, which is widely employed to achieve high mechanical strength of seams in airbag fabrics [24]; thermal welding techniques such as hot-air, high-frequency, and ultrasonic welding, which are increasingly applied to coated and laminated textiles to form airtight joints with low gas leakage [25]; and adhesive bonding, which has been shown to enhance seam integrity and durability in fiber-reinforced textile structures, either as an independent joining method or in combination with sewing and welding [26].

The sewing process employs high-precision industrial sewing machines to join the fabric layers of the airbag. These machines must meet stringent requirements, ensuring that the fabric fiber structure remains intact and that thread breakage does not occur during manufacturing. Critical technical parameters such as needle type, stitch length, stitch density (stitches per inch), and sewing speed must be carefully adjusted to achieve optimal seam quality. Deviations in these parameters can lead to serious failures, such as seam rupture during airbag deployment, which directly threatens user safety. The sewing threads used in airbag fabrication are typically made from fibers with high mechanical and thermal properties, most commonly polyamide or aramid fibers. Polyamide is particularly advantageous due to its superior tensile strength and elasticity compared to polyester, along with its higher specific heat capacity and melting point. These characteristics help maintain seam integrity under the elevated temperatures generated during airbag deployment. Aramid threads are also employed to enhance heat resistance and flame retardancy. The selection of an appropriate stitch density, aligned with the fabric type and the direction of principal stress, is a critical design parameter that significantly influences the overall performance of the airbag system.

In addition to conventional sewing methods, welding techniques have received increasing attention due to their superior ability to produce airtight seams. There are four ways of applying the heat such as radio frequency welding, hot air welding, ultrasonic welding, and hot wedge welding. These methods utilize thermoplastic materials to bond fabric layers, either by using the base fabric itself or an additional adhesive layer. Upon melting, the thermoplastic material penetrates the fabric structure and solidifies upon cooling, forming high-strength, gas impermeable joints. Additionally, CO_2 laser welding is employed in certain specialized designs due to its ability to create precise, clean seams with minimal welding fumes, making it suitable for highly automated industrial manufacturing processes. However, welding methods also present certain limitations. Welded seams typically exhibit lower elasticity compared to sewn seams, which increases the risk of cracking, breakage, or joint failure under high tensile stress. Moreover, once a weld is compromised, it is nearly impossible to repair, whereas stitched seams can be reopened and resewn. As a result, many modern airbag designs employ a combination of both sewing and welding techniques to leverage the advantages of each. For instance, some airbags use welded seams to ensure airtightness, which are then reinforced with sewing to enhance mechanical durability [27]. Additionally, several advanced studies have explored the application of adhesive layers or sealants at joint interfaces to enhance gas impermeability and improve the overall durability of the product. Chiou and Crouch [28] demonstrated that applying a silicone adhesive layer with a thickness ranging from 0.254 mm to 1.27 mm over sewn seams significantly enhances joint adhesion and gas impermeability. The adhesive is cured at temperatures between 100 °C and 250 °C for durations ranging from 1 to 60 minutes, ensuring the formation of a stable bond. During inflation, this adhesive can effectively prevent air leakage for at least 6 seconds, which is the minimum time required to ensure effective head protection in the event of a fall.

However, adhesive layers and surface coatings also present certain limitations. Most coatings are silicone-based, which possess fiber-lubricating properties that may increase the risk of thread slippage and seam separation. In addition, when the airbag is folded and stored in a compact volume, the coating may create adhesive forces between fabric layers, potentially hindering proper deployment during impact events. Furthermore, the relatively high production cost of silicone coatings can significantly influence the overall manufacturing cost of the final product [28].

In a recent study, Barnes *et al.* [29] proposed the use of hot-melt adhesive materials compressed into the seam regions of the airbag, in combination with a light coating of silicone, urethane, or rubber-based compounds. This approach enhances airtightness, increases elasticity, and reduces the risk of leakage at seam interfaces. It is particularly well-suited for head protection airbags, which require rapid response, high durability, and precise deployment within extremely short timeframes.

The authors have conducted preliminary experiments on a combined sewing–bonding manufacturing approach for smart airbag shells, aiming to exploit the mechanical strength and repairability of stitched seams while improving gas tightness at joint regions through the application of auxiliary bonding layers. Initial experimental results indicate that the sewing–bonding approach shows potential to meet technical requirements in terms of airtightness and mechanical durability under experimental manufacturing conditions. However, technological parameters such as adhesive type, bonding layer thickness, reinforced bonding regions, and the influence of bonding layers on the folding and deployment behavior of the airbag have not yet been optimized and require further investigation.

In parallel, the authors are continuing to explore and experimentally evaluate a welding–bonding approach, in which thermoplastic material layers are joined using welding techniques to form airtight seams, followed by reinforcement with bonding layers or thin coatings to enhance seam strength and geometric stability during airbag deployment. These manufacturing approaches will be systematically evaluated and compared with the sewing–bonding method based on criteria including airtightness, joint strength, burst pressure resistance, elasticity of joint regions, foldability and storage capability, and compatibility with domestic manufacturing technologies. Based on comparative results, the most suitable manufacturing approach for smart airbag shells intended for head protection of older adults will be selected and optimized, providing a foundation for subsequent functional testing and evaluation of the protective performance of the fabricated airbag systems.

Each airbag fabrication method has its own inherent advantages and limitations. The selection of the most suitable technique depends on multiple factors, including technical specifications, material characteristics, intended application, and manufacturing cost. In current practice, contemporary design approaches increasingly incorporate multiple fabrication methods such as sewing, thermal welding, and adhesive bonding. This integrated strategy aims to optimize the overall performance and ensure high reliability of smart airbag systems designed to protect the heads of elderly individuals in fall-related incidents.

4. Conclusion

Falls among the elderly represent a critical public health concern, increasingly emphasized in the context of global population aging. Head injuries resulting from falls can lead to severe and often long-term consequences, significantly impacting individuals' quality of life and placing a substantial burden on healthcare systems. In line with the growing integration of smart technologies in healthcare, smart airbags have emerged as a proactive and effective solution for mitigating fall-related injuries, particularly those involving head trauma.

This paper has provided a comprehensive overview of research related to the structure, materials, and manufacturing technologies for smart airbag shells, focusing on optimizing head protection for the elderly. Through the analysis of patents and international literature, several materials have been identified as commonly used, including nylon 66 (polyamide), high-strength polyester fibers, aramid fibers, and flexible nylon 6. Each material presents distinct advantages in terms of mechanical strength, thermal resistance, weight, softness, and production cost. However, limitations also exist, such as high cost (nylon 66, aramid), suboptimal gas retention (polyester), or dimensional stability issues (nylon 66). Beyond material considerations, the patents demonstrate the effectiveness of airbag structures, ranging from collar-type designs to anthropometrically shaped neck bands. These designs offer rapid deployment, good coverage, and suitability for wearable devices in the daily activities of elderly users. Nevertheless, some designs remain limited in breathability, exhibit concentrated weight around the neck, or have aesthetic drawbacks, potentially causing discomfort during prolonged use.

Based on these evaluations, we propose a smart airbag structural design with several improvements: a seamless air chamber surrounding the head and neck, combined with internal shaping ribs to maintain form and ensure uniform pressure distribution. Sensor and microcontroller units are positioned on both sides of the front neck, while the air pump and CO_2 cartridge are placed at the back of the neck, optimizing airflow, reducing deployment time, and balancing weight. The helmet shell closely fits the head, extends down to the neck, and integrates passive ventilation slots, ensuring ergonomics, breathability, and aesthetic appeal, facilitating daily use.

In this study, we presented the proposed airbag structural design; the next step involves fabricating technical components and prototype airbags using modern manufacturing techniques in Vietnam. During the design and fabrication process, the research team will continue refining the airbag structure to achieve the most practical and effective solution. Future research will focus on identifying optimal materials for airbag fabrication to reduce weight, increase strength, and enhance gas retention; applying advanced manufacturing techniques to improve performance and stability; refining sensor algorithms for more accurate fall detection; and conducting practical tests with elderly participants to evaluate protective effectiveness and user comfort. These directions aim to finalize the design, increase reliability, and expand the application potential of smart airbag helmets for community healthcare in general and for the elderly population in Vietnam in particular.

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