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Review

Lightweight Textile and Fiber-Reinforced Composites for Soft Body Armor (SBA): Advances in Panel Design, Materials, and Testing Standards

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Abstract

Soft body armor (SBA) remains an essential component of first responder protection. However, most SBA design concepts do not adequately address the unique performance, morphological, and psychological needs of women as first responders. In this review, female-specific designs of ballistic-resistant panels, material systems, and SBA performance testing are critically examined. The paper also explores innovations in shaping and design techniques, including darting, dartless shape construction, modular assembly, and body scanning with CAD integration to create contoured and structurally stable panels with improved coverage, reduced bulk, and greater mobility. In addition, the review addresses broadly used and emerging dry textile fabrics and fiber-reinforced polymers, considering various innovations, such as 3D warp interlock weave, shear thickening fluid (STF) coating, nanomaterials, and smart composites that improve energy dissipation and impact tolerance without sacrificing flexibility. In addition, the paper also examines various emerging ballistic performance testing standards and their revisions to incorporate gender-specific standards and measures their ability to decrease trauma effects and maintain flexibility and practical protection. Finally, it identifies existing challenges and areas of future research, such as optimizing multi-layer systems, addressing fatigue behavior, and improving multi-angle and low-velocity impact performance while providing avenues for future sustainable, adaptive, and performance-optimized body armor.

Keywords: soft body armor; first responders; female-specific panel design; fiber-reinforced composites; lightweight composite panels; ballistic protection; protective textiles; ballistic impact testing standards

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1. Introduction

First responders (FRs) are the frontline providers of aid to the public during disaster situations, emergencies, and critical events [1]. These professionals include paramedics, emergency medical services (EMS) providers, police officers, law enforcement officers (LEOs), firefighters, disaster recovery workers, and support staff such as dispatchers and coordinators. The nature of their responsibilities requires a significant amount of work and frequent exposure to scenarios that endanger their lives or pose risks of severe harm to those around them [2]. In 2019, the Federal Bureau of Investigation (FBI) reported that, out of the 475,848 employed officers, 56,034 law enforcement officers (LEOs) were assaulted, emphasizing the prevalence of violence faced by those in law enforcement [3].

Similarly, an average of 2000 emergency medical services (EMS) providers face injuries from assault each year, which is 22 times more than the national average of assault injuries for other occupations [4]. Of the fire-ground injuries confronted by the firefighters, 13.8% accounted for wounds, cuts, bleeding, and bruising [5]. Beyond these individual threats, complex emergency scenarios, such as active shooter situations and fire-as-a-weapon incidents, require coordinated responses from firefighting, EMS, and law enforcement teams to mitigate risks effectively. Without such integration, not only are civilian lives at greater risk, but first responders themselves are more likely to suffer injuries or fatalities [6]. These challenges highlight the immense risks inherent in first responder professions and the critical need for collaborative strategies and protective measures to safeguard those on the frontlines. As the first line of response and defense, every first responder relies on protective wearables such as body armor, a ballistic chest shield, and helmets, which are crucial in minimizing injury and increasing survivability in dangerous encounters [7]. The inclusion of body armor for ballistic and stab protection has become more pressing for first responders, regardless of the stakes of emergency calls or the area of response, to enhance their protection in unpredictable and violent environments. While large metropolitan cities often face heightened risks, violent threats exist in every community, making personal protection a universal necessity.

In recognition, the Federal Emergency Management Agency (FEMA) has recommended that every department of front liners must equip their personnel with body armor to ensure their safety in the field [8]. Historically, first responder roles have commonly been male-dominated [2]. Over the past few decades, the participation of women in first responder professions, including police, firefighting, and emergency medical services (EMS), has significantly increased, with their representation in these fields ranging from 4% to 32% [9]. According to Statista (2024), as of 2023, approximately 59.9% of full-time law enforcement officers in the United States were female, indicating a gradual increase in gender diversity within the field [10]. In 2020, 9% of all firefighters were female, and this number was 11% for volunteer firefighters, as confirmed by the National Fire Protection Association (NFPA) reports, with an increase rate of 3% since 2015 [11]. Emergency medical services (EMS) have a higher female representation, with women comprising nearly 35% of paramedics and emergency medical technicians (EMTs) [12]. These trends demonstrate the ongoing progress in integrating women into traditionally male-dominated first responder professions.

Lightweight body armor is a vital component of personal protective equipment, providing essential protection for first responders [13]. Body armor systems are designed to safeguard critical thoracoabdominal organs and offer passive defense against ballistic, fragmentation, and stab threats [14]. A typical body armor is designed and developed based on male anthropometric characteristics [15]. Despite the increasing number of female participants as first responder personnel, the distinction in design for male and female soft body armor is not adequately addressed [16]. On average, men are larger than women in stature by 8% and in body mass by 26%, with women generally having smaller torso-related anthropometric measurements, including chest width, chest depth, waist circumference, and back dimensions [17]. Due to these differences in body dimensions, women in these historically male-dominated professions often report wearing body armor that does not fit properly [18]. The female personnel have long been provided with either unisex body armor or smaller versions of designs originally made for men. Such practice forces them to compromise with fitness, comfort, and ballistic protection by using men's soft body armor due to the unique contours of the female body [16]. A major flaw in soft body armor design is its failure to fit with the female bust, leading to breast compression, which hampers their physical and psychological comfort and job performance significantly [19]. Improperly

fitted body armor has a detrimental impact on joint mobility, limiting the range of motion at several joints, including the shoulders, trunk, and thoracic spine [20]. Due to discomfort, sometimes, they take the risk of wearing them for a limited time [21]. It is evident that the absence of gender-specific design is a fundamental issue, and it is essential to consider this when developing body armor for women, as anatomical, physiological, and ergonomic differences between male and female bodies directly impact fit and performance [22]. Body armor specifically designed for women is essential to accommodate physiological differences such as variations in body shape, size, and proportions [23]. Likewise, bust protection, shoulder adjustment, and waist contouring are some of the essential features that need to be considered while making a women-dedicated design to optimize performance and ensure the necessary protection without compromising mobility and safety [24].

This review aims to critically analyze the current state of soft body armor, including the frontal panel design for female first responders, the advancements of ballistic materials, including dry textiles and fiber-reinforced composites, and the evolution of performance testing standards. In addition to this, this study also explores the shortcomings of soft body armor design, considering the anthropometric differences and issues related to comfort and usability. Additionally, the review examines recent advancements in protective equipment, including improvements in manufacturing techniques, material innovations, and customization options. By synthesizing current knowledge and identifying areas for improvement, this review aims to provide valuable insights for researchers, manufacturers, and policymakers working to advance the development of more effective and comfortable soft body armor for all first responders. This research specifically emphasizes the importance of considering specific requirements in body armor design and materials, ultimately contributing to enhanced safety and operational effectiveness for women in emergency services.

2. Review Methodology

This review paper aims to evaluate the evolution of textile-based lightweight body armor, with a focus on state-of-the-art and innovative design features, materials, and performance characteristics for first responders, particularly considering female-specific needs. The main objective was to synthesize findings from the technical literature, standards, and experimental studies addressing both all-gender and gender-specific armor development. The review aimed to identify challenges in fit, comfort, and ballistic protection for women and highlight recent advancements in design and testing protocols. A systematic literature search was conducted following a structured methodology of database searches (Scopus, Web of Science, PubMed, and Google Scholar) from January 1990 to March 2025. The search keywords involve a combination of relevant terms used to ensure comprehensive coverage. These keywords included “first responders,” “soft body armor,” “personal protective equipment,” “panel design,” “female armor panel design,” “fit and comfort,” “adaptive bust,” “anthropometry,” “ballistic impact resistance,” “stab resistance,” “performance,” “mobility,” “lightweight armor,” “fibre-reinforced composite,” “lightweight composite,” “nanomaterials,” “liquid armor,” “multifunctional armor,” and “testing standard.” The search strategy also included Boolean operators (AND and OR) to combine keywords effectively. Search results were then initially screened based on titles and abstracts for relevance. We considered both inclusion and exclusion criteria. For example, the inclusion criteria covered peer-reviewed journal articles, technical reports, standards, or white papers in English that were published between 2000 and 2025, specifically focusing on soft body armor (not hard armor or solely military applications). In addition, studies addressing anthropometric considerations, design innovations, and material development relevant to body armor for first responders, including those specifically addressing female

fit and comfort, were considered. Articles reporting on testing methods or regulatory standards, including the National Institute of Justice (NIJ), Home Office Scientific Development Branch (HOSDB), Association of Test Laboratories for Attack-Resistant Materials and Constructions-VPAM, and International Organization for Standardization (ISO), considering gender-specific design or performance were also considered. Furthermore, research involving material innovation, such as advanced textiles, 3D structures, fiber-reinforced composites, or nanomaterials, was also included. On the other hand, studies exclusively focused on hard armor or strictly military applications without relevance to first responders, articles lacking gender-specific insights or data, and some editorials, opinion pieces, or publications without original research or data were excluded from this research. Following selection, data extraction was conducted systematically. For instance, relevant studies were reviewed in full, and key information was categorized into themes of design considerations for female-specific and adaptive armor, advances in materials for soft body armor (e.g., shear thickening fluids, lightweight composites, and nanomaterials), anthropometric data, and its influence on armor design, comfort, fit, and mobility assessments in the context of performance and testing standards and protocols for soft body armor.

3. Frontal Soft Body Armor (SBA) Panel Design for Females

3.1. Design and Production

Soft body armor is among the two categories of body armor, the other one being hard body armor. Their constituents and protection levels distinguish them from each other. Soft body armor is made of multiple layers of strong woven fabric and weighs less than 4.5 kg. Soft body armor, also commonly referred to as a "vest," is designed to protect vital organs. As shown in Figure 1, it is typically constructed with two ballistic panels, one at the front and one at the back, that are held on the torso of the wearer [3]. A typical soft body armor provides protection against low-to-medium threats, like bullets from handguns and shotguns and small pieces from explosions. It follows the protection Levels IIA, II, and IIIA set by the National Institute of Justice and can stop common handgun bullets such as 9 mm full metal jacket, 0.357 Magnum, and 0.44 Magnum rounds [1,2]. On the other hand, hard body armor is made of metal or ceramic plates and is designed to stop bullets from more powerful weapons (NIJ Level IIIA). The NIJ Level IIIA is a protection standard set by the National Institute of Justice (NIJ) that defines the ability of body armor to stop specific threats, including handgun rounds such as 0.357 SIG and 0.44 Magnum. This level offers the highest level of protection against handgun threats under the NIJ 0101.06 standard but is not designed to stop rifle rounds or armor-piercing ammunition. In high-risk situations, soft body armor is often combined with hard armor to offer better protection against heavily armed threats [25].

In the early stages, anthropometric differences were not considered in producing gender-specific body armor, resulting in females wearing smaller male-based body armor [16]. Subsequently, unisex tailoring technology was introduced as a practical initial approach [23]. All body armor improvements and technological advancements were focused on male wearers. Apparently, it has become a general assumption for most women to continue to use smaller unisex body armor [26]. However, this method minimizes the difference in torso structure between males and females, as it utilizes the same style and manufacturing [23]. Such practice fails to incorporate the female torso into a male-based system, which causes poor fit, discomfort, and restricted movement [27]. Research has pointed out that the variations in upper body torso between the sexes also contribute to discrepancies in thermal comfort, fit, and mobility [28]. The bust area has always been a critical issue in female body armor due to insufficient coverage and support. Such issues also result in pressure points and chafing; also, the protection of the bust area might be

compromised [29,30]. Additionally, the heavyweight and bulkiness of male-based body armor contribute to fatigue and reduced endurance [31,32]. The restricted range of motion further limits mobility and dexterity, particularly in high-stress environments where agility is crucial [20,33–35]. Beyond physical discomfort, ill-fitting armor also affects psychological well-being, leading to decreased confidence, lower job satisfaction, and a sense of being undervalued [36,37]. The growing importance and need for incorporating gender-specific details in body armor prompted the development of contoured female armor panels. These panels include bust-accommodating shapes and adjustable straps to improve fit [22]. Building on this approach, researchers also explored the use of filler materials, such as foams and pads. Such a procedure helps conform to the unique contours of the female torso and enhance comfort [38]. However, the challenge remained the same for the design and material selection since female body armor production requires additional consideration to address their curvaceous body shape [36,39]. To overcome the challenges, various techniques such as cut-and-sew, overlapping, folding, and molding were proposed and dedicated to females [40].



Figure 1. (**a**) Soft body armor serves as essential protective gear for LEOs, providing defense against various threats encountered during their daily duties. (**b**) This type of armor comprises two panels that overlap to safeguard the wearer's vital organs from the front, back, and sides. (**c**) Each panel consists of ballistic materials enclosed within a protective casing and held together by a carrier [3]. Reprinted from ref. [3] with permission from Elsevier.

3.1.1. Traditional Cutting and Stitching Method

The cutting and stitching method has been a traditional approach in designing female-specific body armor. This method incorporates the usage of different kinds of darts to simulate and accommodate the bust area. A demo of detailed measurements is illustrated in Figure 2 [23]. According to the dart points, a 2D pattern is prepared for a frame for cutting composite or ballistic fabrics for individual panels. These panels are then stitched together using various sewing techniques, with reinforcement applied to key areas for durability. Fasteners and adjustment features like zippers, hook-and-loop closures, and buckles are added to allow easy wear and a customizable fit. Finally, finishing touches include trimming excess fabric and adding padding or foam inserts to improve comfort and create a contoured fit [22]. This method creates contours that improve fit and comfort for female wearers. Many manufacturers have adopted this approach, with some even developing designs that include pleats, dual cups, or contoured front panels to enhance adaptability to different body shapes [41,42]. However, despite its fitness advantages, this technique presents significant drawbacks, particularly in terms of ballistic performance. The seams created during stitching become structural weak points, reducing the armor's ability to withstand high-impact projectiles due to discontinuous yarns in those areas [22]. This has led to concerns about the overall protection provided by such designs. Such concerns prompted researchers to explore ways to optimize the placement of protection zones and improve material distribution.

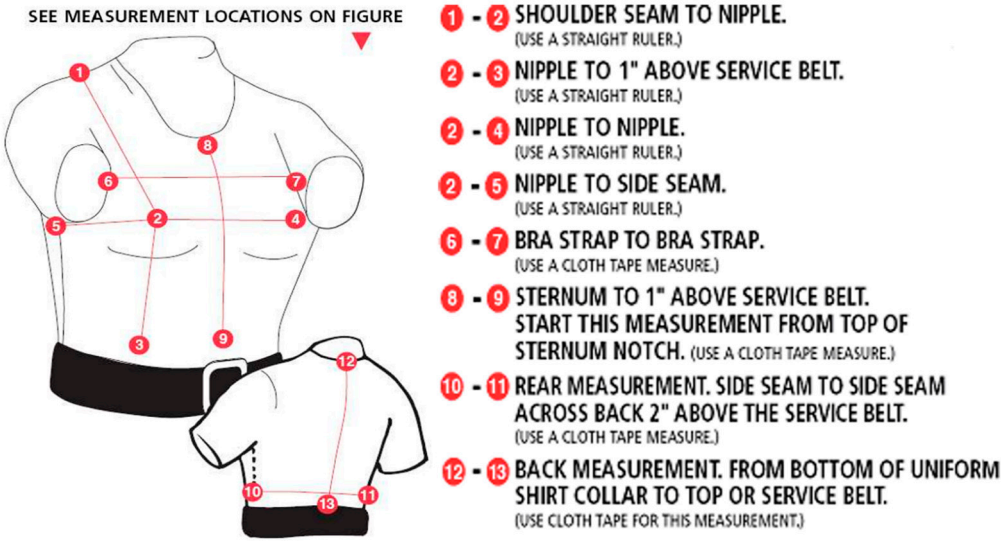


Figure 2. Female size measurements [23].

3.1.2. Folding Method

The folding and overlapping method is a rarely implemented design method to develop female body armor [43]. The folding method is mainly a shaping technique to transform two-dimensional reinforcement materials into three-dimensional forms. As shown in Figure 3, this process involves folding and stitching fabric along specific seams to contour the bust and torso, providing a better anatomical fit. However, the folding technique has structural limitations, including discontinuities in material, weak stitching points around the folded materials, and reduced ballistic resistance [22]. Wearers may also experience discomfort due to sharp ridges formed by multiple layers of folded fabric, particularly under the armpits, leading to restricted mobility and irritation [23]. To mitigate the issue, some studies highlight that folding methods incorporating V-shaped darts in successive layers can enhance fit while attempting to maintain an even thickness. However, this technique still leads to increased fabric bulk, itching, and restricted mobility [16,44]. Overlapping, on the other hand, involves layering multiple sheets of ballistic-resistant fabric, typically made from aramid polymer yarns, to create contoured protection [22]. This method allows a better fit around the female bust by using overlapping seams to join side sections to a central panel, ensuring a more form-fitting and comfortable design [23]. While overlapping seams provide stronger reinforcement by superimposing ballistic materials on the front panel, they remain vulnerable to small ballistic projectiles that can sever thread loops at the seams [45].

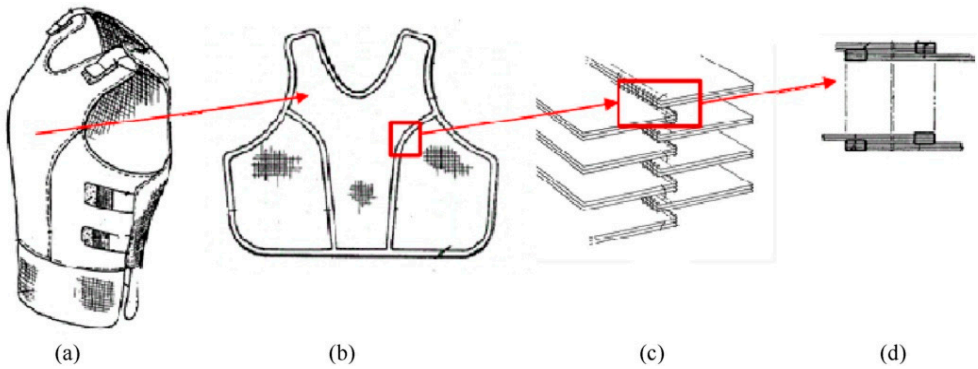


Figure 3. Women's body armor with overlapping seams. (**a**) Perspective view. (**b**) Plan view. (**c**) Exploded perspective view of different ply joined with overlapping. (**d**) A vertical section through the overlapping seams [16].

3.1.3. Molding Method

Although the abovementioned methods are commonly used to allow better adaptation to the body's curve, the body armor remains vulnerable to projectile impact and faces comfort issues. Commonly, these issues are raised due to weakness at the seams. Therefore, further research focused on developing seamless frontal body armor [26]. The molding method, being more advanced, eliminates the need for seams and stitching. Instead, it provides the body armor with a contoured form that better fits the female torso. This method enhances comfort, ballistic protection, and overall wearability by mimicking the natural bust shape through a seamless frontal panel [46]. With this method, a three-dimensional structure is created from a two-dimensional woven ballistic fabric, such as p-aramid (CT709). This fabric contains low resin contents that facilitate shaping by imposing heat and pressure, resulting in a curved, flexible, and form-fitting panel. This technique was a joint venture by Triumph International and Teijin Aramid. It is also known as Twaron® Laminated Fabric Technology (LFT). The method comprises flexible and laminated fabric layers that are sandwiched with a polyethylene (PE) film, as shown in Figure 4a [47]. Efficiently constructing body armor panels using this method requires accurate body measurements and 3D modeling to replicate female body morphology for an optimal fit. However, this process is challenging due to the structural and geometric complexity. Even slight variations in bust size or torso curvature can significantly impact the final product and pose difficulties in numerical modeling. To improve efficiency, recent studies have explored 3D warp interlock fabrics and advanced CAD-based parametric modeling to refine the molding process to accommodate a broad and diverse range of female torso measurements, as shown in Figure 4b [47].

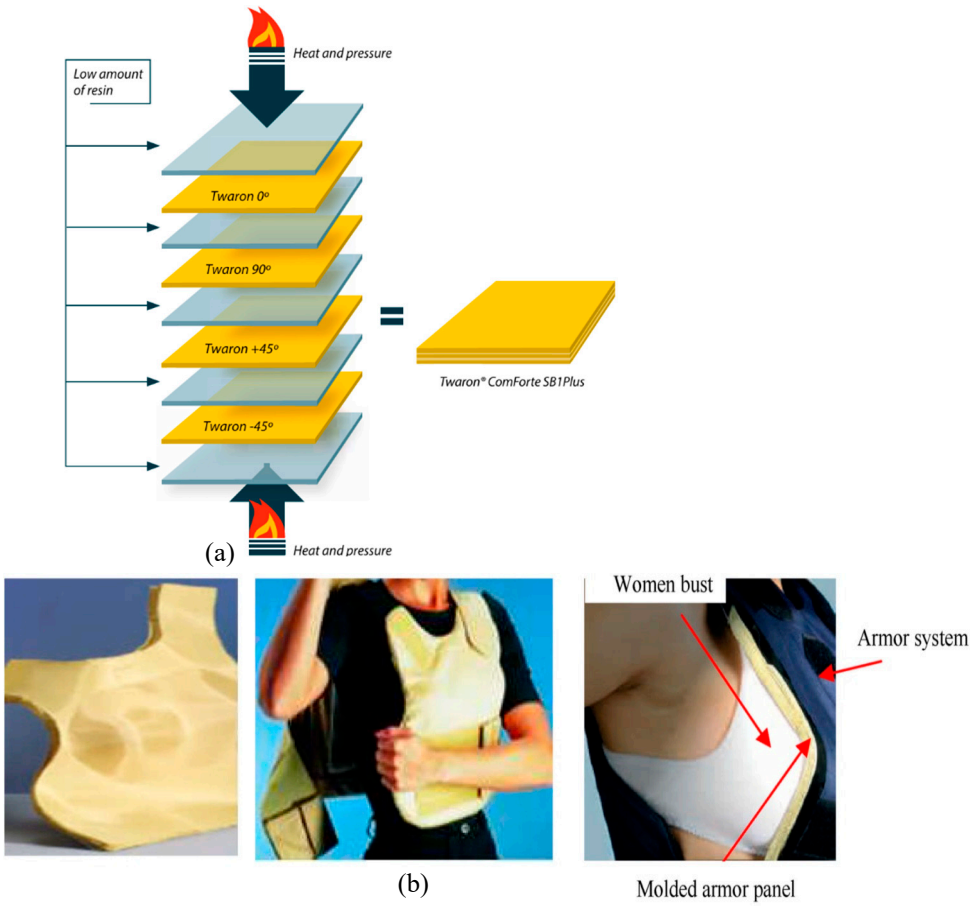


Figure 4. Female body armor: (**a**) molding process and (**b**) developed female body armor through the molding process [47].

3.1.4. Technological Development in Panel Design

Recent advancements in female body armor design have introduced cutting-edge technologies such as 3D scanning, virtual body modeling, and CAD integration, enabling the precise collection of female-specific anthropometric data. In addition, the combination of processes, such as the integration of virtual modeling with CAD-based molding processes, improved the development of patterns with precise dimensions. Moreover, it eliminated traditional stitching and darting methods that compromised the structural integrity of armor panels [45]. At the initial stage of studies, the conventional pattern design is created using 3D scanning. As shown in Figure 5, 3D scanning is used to create a virtual mannequin to confirm the actual body measurements, replacing the traditional method of measuring using tape. Then, the 3D model is flattened into a 2D basic vest pattern using special CAD software. The flattening process is conducted following reference points, including neckline, shoulder seams, bust darts, side arms, waist, and bottom hem, resulting in a basic pattern in a French waistcoat design. A dart rotation method is used to project the bust area accurately in the final pattern. Then, the final product is prepared using a traditional cut-and-sew method [16].

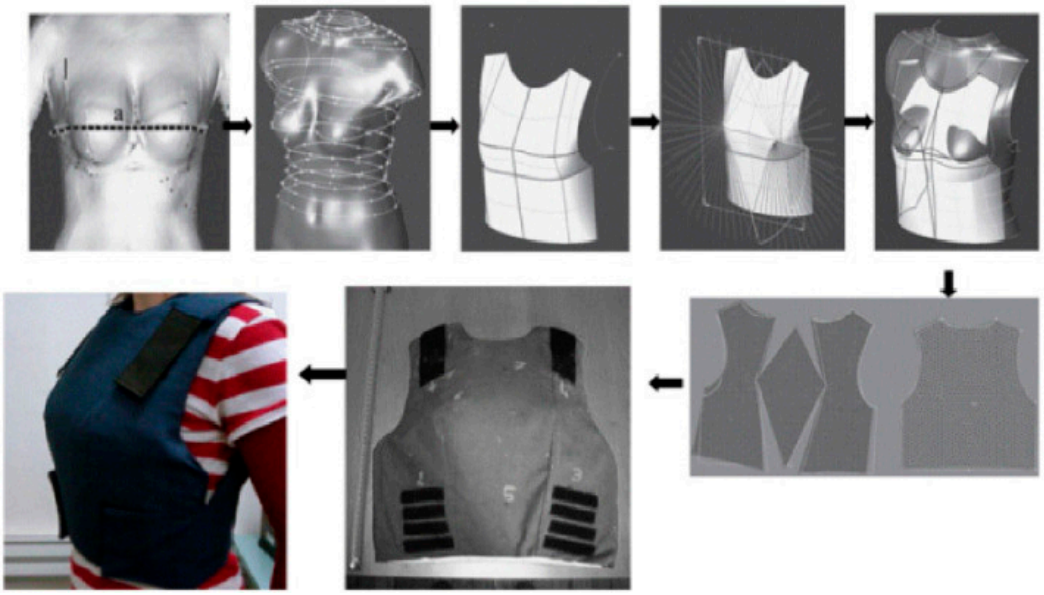


Figure 5. Production process of women's ballistic vest with a 3D virtual model [16].

Furthermore, a study examined a novel application of the above technology through an innovative 2D–3D–2D pattern re-engineering method to develop the first layer of female soft body armor [45,46]. The study utilized 3D Design Concept (Lectra commercial software) to develop a 3D virtual mannequin with a parametric bust design. This enables the adjustment of bust sizes while preserving a consistent overall body dimension (Figure 6a). The method mainly eliminates dart inclusion to achieve the required breast volume. Both horizontal and vertical grids are then applied to map the body's contours to generate a 3D vest model, helping to understand how the fabric will stretch and fit (Figure 6b). The 3D vest model is flattened to create a 2D pattern design for seamless first-layer panels, as shown in Figure 6c. In continuation of the above study, a seamless woman's ballistic vest is designed with multi-layered patterns. The full patterns are made with automatic pattern generation on an adaptive 3D virtual mannequin [48]. The multi-layered pattern construction starts with creating a first layer, followed by adding successive fabric layers on the 3D virtual mannequin, as illustrated in Figure 6d. The thickness of each layer is digitally coded into the 3D design software, which automatically adjusts the placement

of each successive layer to maintain uniform protection and comfort (Figure 6d). After finalizing the 3D structure, the model is flattened into a 2D pattern, following classical pattern-making principles while maintaining precision and accuracy, as shown in Figure 6f. This automated process ensures a seamless design without stitching or darts, which could compromise safety. Hence, it enhances fit, comfort, and ballistic protection, making the vest more effective for female security personnel.

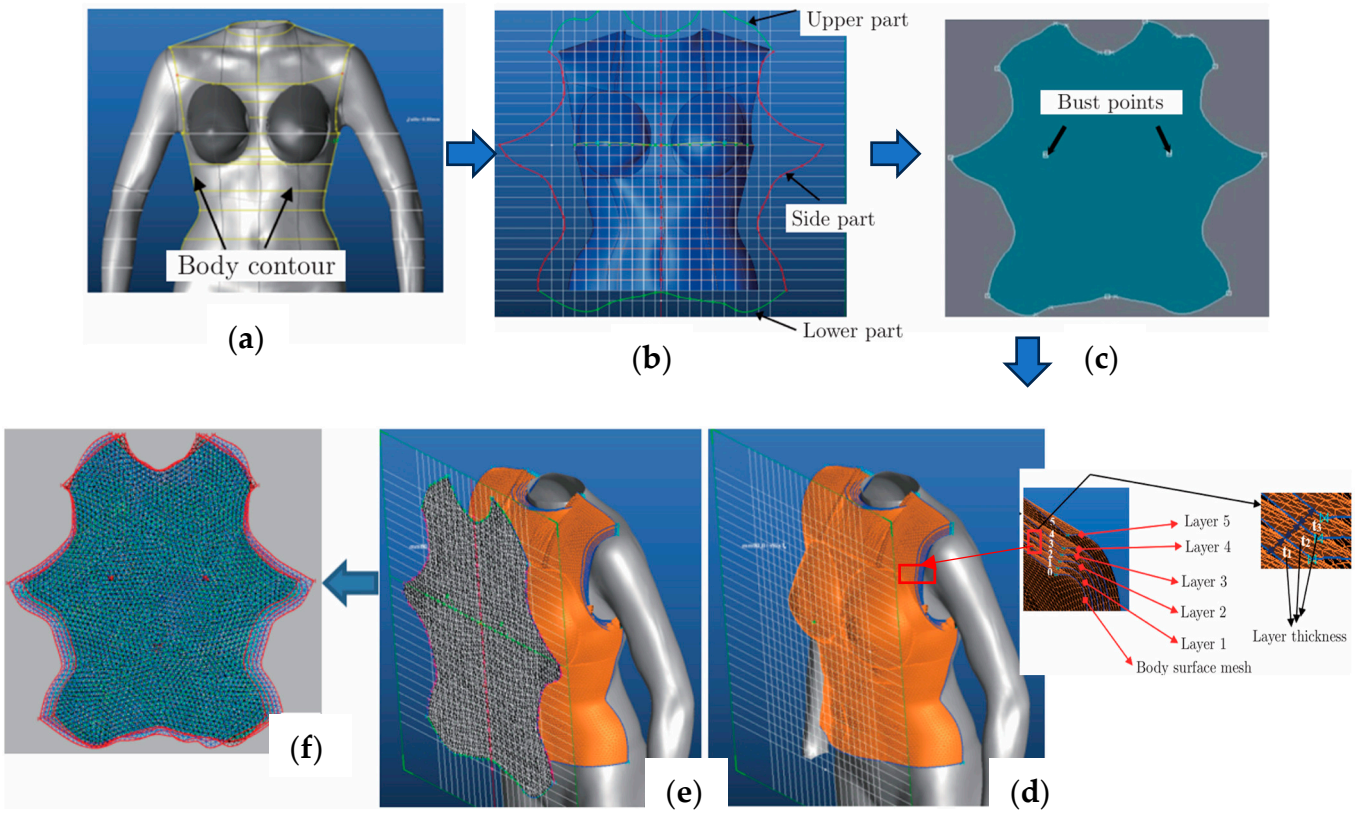


Figure 6. (**a**) Three-dimensional virtual mannequin (90B bust size) with the different reference points. (**b**) Developing a 3D grid mesh in the 3D virtual mannequin. (**c**) Development of the first layer of the frontwoman's ballistic vest panel block pattern through the 2D/3D/2D flattening process. (**d**) Two-dimensional pattern design for seamless female first-layer panel [45] and development of multi-layer frontal seamless female soft body armor panel mesh on the virtual adaptive female body surface, along with projection grids. (**e**) Pattern of block projection for multi-layer through flattening. (**f**) Flattened multi-layer soft body armor panel pattern. Reprinted from ref. [48] with permission from Elsevier.

Another study investigated the angle-interlock weaving process to enable seamless dome formation [49]. This method involves strategically interlacing fibers at precise angles to create a continuous, three-dimensional fabric structure without requiring cuts or folds, enhancing both structural integrity and flexibility. The study incorporated high-performance fibers like Kevlar® or Dyneema®, chosen for their strength and flexibility. Warp and weft yarns are arranged on a loom in a multi-layered structure, where the warp yarns pass through multiple weft layers, ensuring a secure binding, as shown in Figure 7a [25]. This multi-layered weft yarn is known as a through-the-thickness arrangement, as shown in Figure 7b [47]. This allows for the high displacement of yarns to accommodate complex curves while maintaining high tensile strength and flexibility.

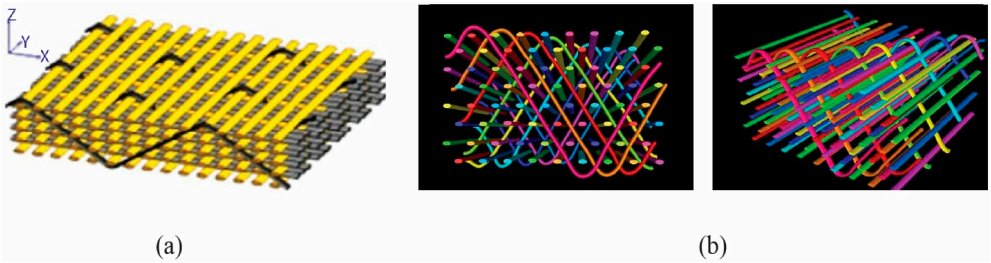


Figure 7. (**a**) Angle-interlock fabric. Reprinted from ref. [25] with permission from Wiley. (**b**) (Left) Cross-section view and (right) 3D modeling view of the through-the-thickness angle-interlock fabric [49].

Researchers also explored the behavior of angle-interlock fabric with the help of geometric modeling regarding the mobility of a multi-layer structure [49]. Comparing angle-interlock fabric with different types of woven fabrics, researchers found it to perform better while imposing different shapes. Angle-interlock fabric can bend more and maintain an even thickness. In addition, the study used TexGen software to show that warp crimp values and unidirectional warp yarn insertions significantly influence moldability and final shape. Overall, through the analysis of visual slices and geometric modeling, the angle-interlock fabric is found to be conducive to complex shapes. Several studies have also involved 3D warp interlock fabric to develop a seamless female body armor [50–56]. For example, in one of the studies, both 3D modeling and 3D warp interlock were brought together by researchers to create an advanced molding method [48]. In the study, the 3D warp interlock fabric was constructed using high-performance aramid yarn with low shear rigidity. This allows easy shaping in the molding process while maintaining strength and durability. The fabric was manufactured using an automatic dobby weaving machine, where Wisetex® and DBweave® designing software generated the 3D design structure and the drawing plan of the fabrics, as shown in Figure 8.

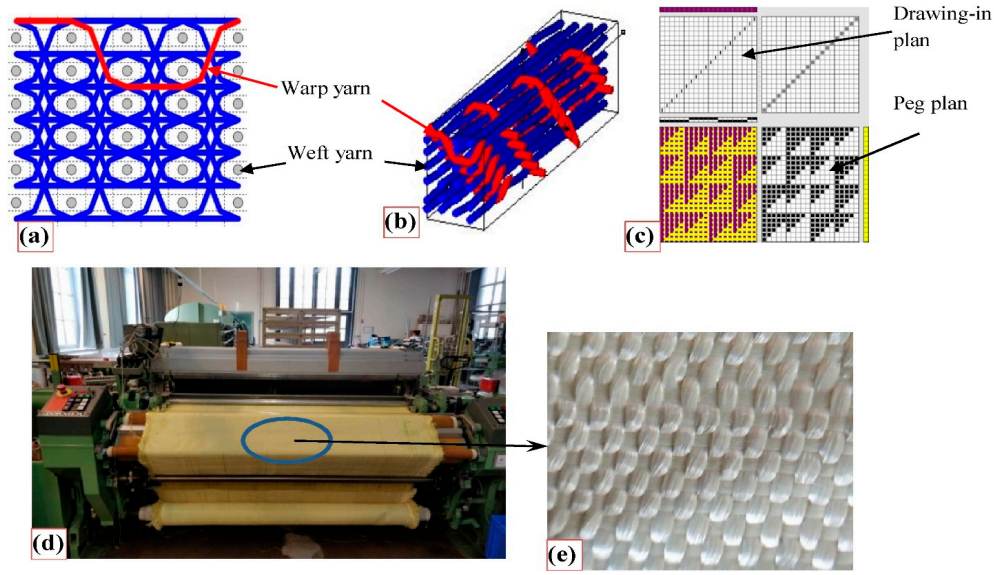


Figure 8. Three-dimensional warp interlock production process: (**a**) Design schematic representation in a cross-section view; (**b**) 3D graphical representation; (**c**) weave design and peg plan (a unit repeat); (**d**) production on dobby loom; and (**e**) produced fabrics. Reprinted from ref. [48] with permission from Elsevier.

The panel pattern was constructed using the same 2D–3D–2D pattern re-engineering method. Using the measurement of a virtual mannequin, the bust shape was digitally

modeled and then converted to a solid mold with the help of specialized 3D design software such as SolidWorks Standard version, which was either 3D-printed or carved from wood/material composites to ensure durability for high-pressure forming processes, as shown in Figure 9a. A custom punching bench was designed to facilitate the molding process, consisting of a blank holder to hold the bust mold and an open die system to shape the dome-like structure, as shown in Figure 9b. Once the multi-layer fabric panels were carefully placed onto the mold, each layer was gradually shaped to achieve a natural curvature. This ensured precise layer thickness calculations for optimal ballistic resistance and flexibility. A manual or hydraulic pressing system applied controlled pressure, gradually forcing the fabric into the 3D dome shape while preventing wrinkles or uneven stretching. The molded shape was held in place for a specific time, allowing the fabric to set properly and maintain structural integrity and impact resistance, as shown in Figure 9c. Additionally, a small amount of fixation liquid was applied to the panel after the dome formation to achieve a more stable shape.

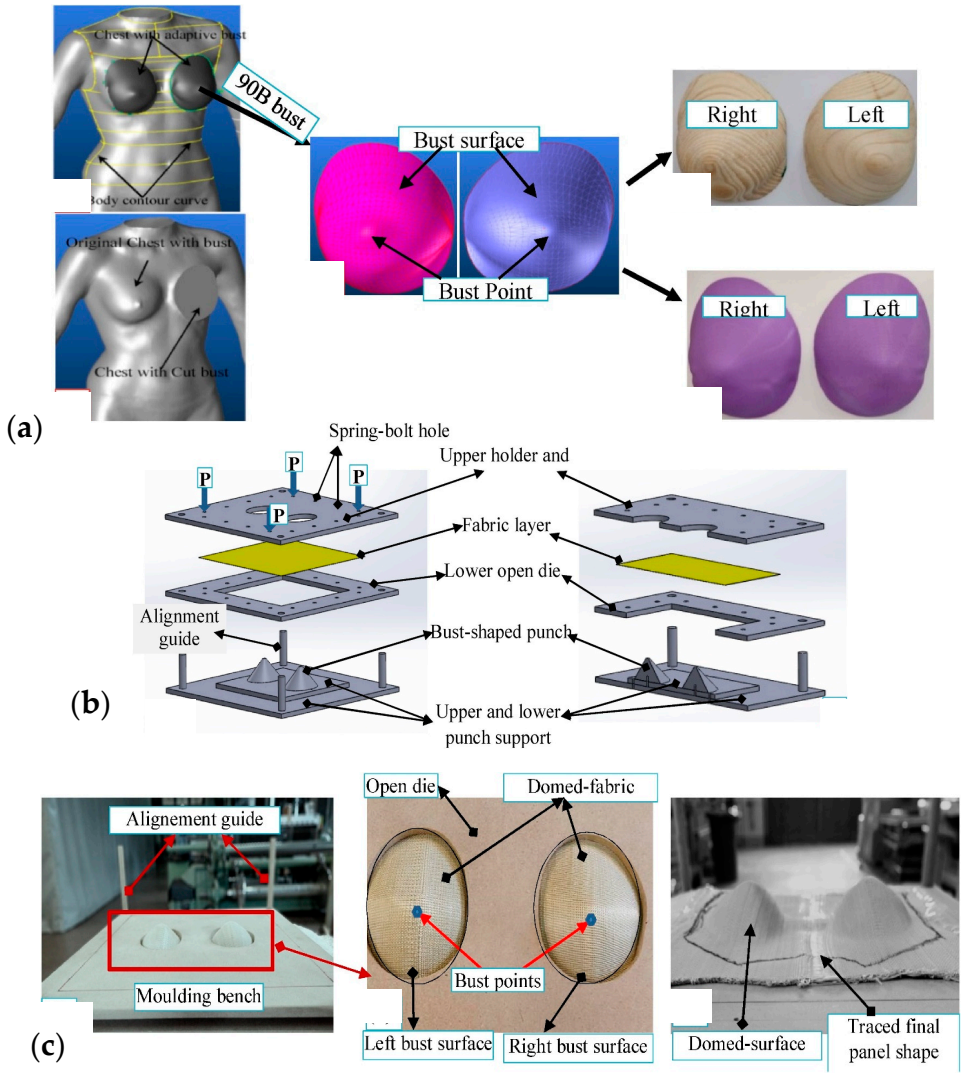


Figure 9. A 90B bust size bust cup molding: (**a**) 3D virtual mannequin with original bust and adaptive bust (90B), virtual 90B bust size busts, and solid molded busts using a specialized shape molding machine and surface-molded right and left bust with 3D printing. (**b**) Adapted manual forming bench setup in both a schematic view and a sectional view from the side. (**c**) Dome formation processes of female frontal soft body armor with molding bench setup at the zoom area for the domed surface for the right and left bust and its final domed-shape frontal panel. Reprinted from ref. [48] with permission from Elsevier.

In another study, 3D modeling of the bust area was performed using mathematical modeling [40] with Rhinoceros software (McNeil, Seattle, WA, USA). A geometric block projection of the bust area was generated, followed by forming another block projection without the bust area and dart points, which are adjustable for different sizes. Combining these two blocks, a basic pattern was developed to form a seamless panel. The model was tested using 3D warp interlock fabric, which was shaped through a molding process to validate the design. The mathematical modeling approach improved pattern accuracy and armor fit, reducing the need for seams and darts. The 3D warp angle-interlock fabric successfully conformed to the body's curves while maintaining structural integrity and ballistic performance. Extending this process, another study constructed the whole panel using multiple layers of angle-interlock woven fabric, as shown in Figure 10 [26].

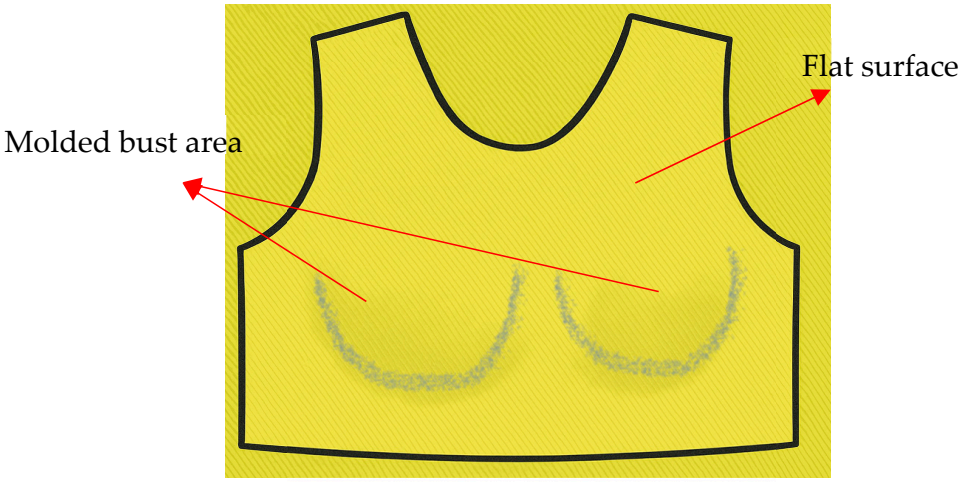


Figure 10. Two-layer front panel of female body armor [26].

Another study integrated 3D scanning technology with a knitting machine to develop female body armor [57]. Female body measurements are drawn from a 3D body scanner made by Textile/Clothing Technology $[TC]^2$ to provide accurate sizing data. Since knitted armor is seamless, the 3D body shape needs to be converted into a flat 2D pattern that can be programmed into the knitting machine. The 2D base pattern is developed using Seiki SDS-ONE APEX3 software, which allows precise 3D-to-2D pattern conversion. The 2D seamless design consists of front and back panels joined at the shoulders, allowing it to be pulled over the head. Based on the 2D pattern, a knit package is created and converted into machine language using computer software, specifying the machine type (N. SES183-SWG) and generating the complete knitting process, as shown in Figure 11a. In this process, two types of design are produced, as shown in Figure 11. A Kevlar–wool blend and 100% Kevlar yarns were chosen for their ballistic protection, moisture management, and comfort.

Researchers have attempted to replicate the bust shape via a new technique to create ergonomically designed soft body armor for female first responders [58]. The method is performed using high-performance protective triaxial fabric made of polyester, Vectran, and Kevlar. The fabric is then cut into appropriate panel sizes and positioned on a mold replicating the female bust shape. The fabric is positioned between clamps, as shown in Figure 12, and is gradually stretched in cycles while applying heat up to 500 °C to help mold it into the shape of a 3D bra cup. The stretching force is carefully controlled to prevent fabric damage, ensuring the material retains strength and flexibility. Once the desired shape is formed, the fabric is compressed and kept under constant heat for 30 min, followed by cooling under tension to ensure it retains its curvature. The final step involves testing

flexibility, durability, ballistic resistance, reinforcement, and attachment modifications for enhanced comfort and integration into full-body armor systems.

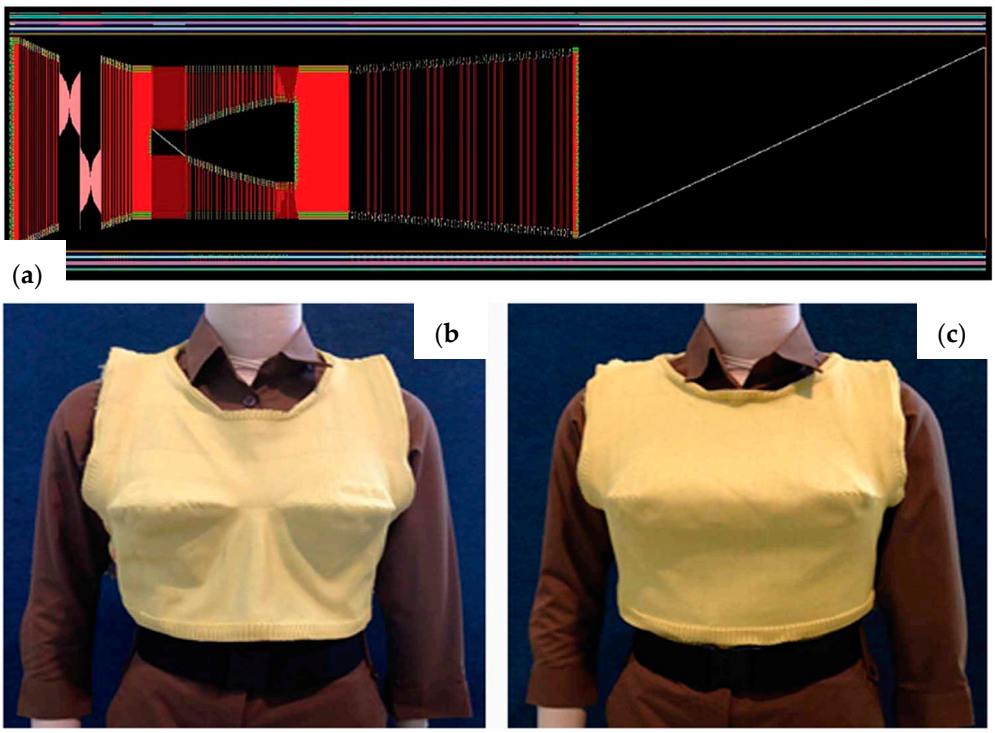


Figure 11. (**a**) Overall knitting process and knitted 3D seamless female body armor vests on a mannequin dressed in a female officer's duty uniform. (**b**) Bra-vest design and (**c**) loose-vest design [57].

Apart from the studies focusing on technological and fabric structural advancement, a novel approach has been conducted to introduce a cluster-based sizing chart [3]. The study categorized individuals into nine male and eight female sizes by analyzing anthropometric data from a diverse sample of male and female officers, ensuring a more tailored approach to armor fitting. Unlike traditional sizing methods that rely only on height and weight, this system incorporates chest circumference, waist circumference, and torso length, addressing key fit-related challenges. Based on the article, a summarized chart is provided in Table 1, allowing one to quickly determine the appropriate armor size, thus reducing misfit issues that compromise comfort, mobility, and protection.

The future of protective equipment for women lies in continuous anthropometric research to refine sizing systems, material applications, and ergonomic considerations. Current studies focus on machine learning algorithms that analyze large datasets of female body measurements to create more inclusive and adaptive sizing categories [59]. Integrating AI-assisted design tools in pattern making and virtual prototyping is expected to revolutionize the customization of protective gear, ensuring that every female user receives properly fitted armor [40]. Additionally, ongoing research into smart textiles and biomechanical feedback systems will allow for dynamic sizing adjustments, where armor can automatically adapt to body movements and improve impact absorption in critical zones [21]. Future developments will likely incorporate sustainable and biodegradable ballistic materials, ensuring both protection and environmental responsibility [43]. These advancements mark a transformative shift in female protective equipment, prioritizing ergonomics, safety, and efficiency, with continued anthropometric studies guiding the way toward better-fitting and high-performance protective gear for women.

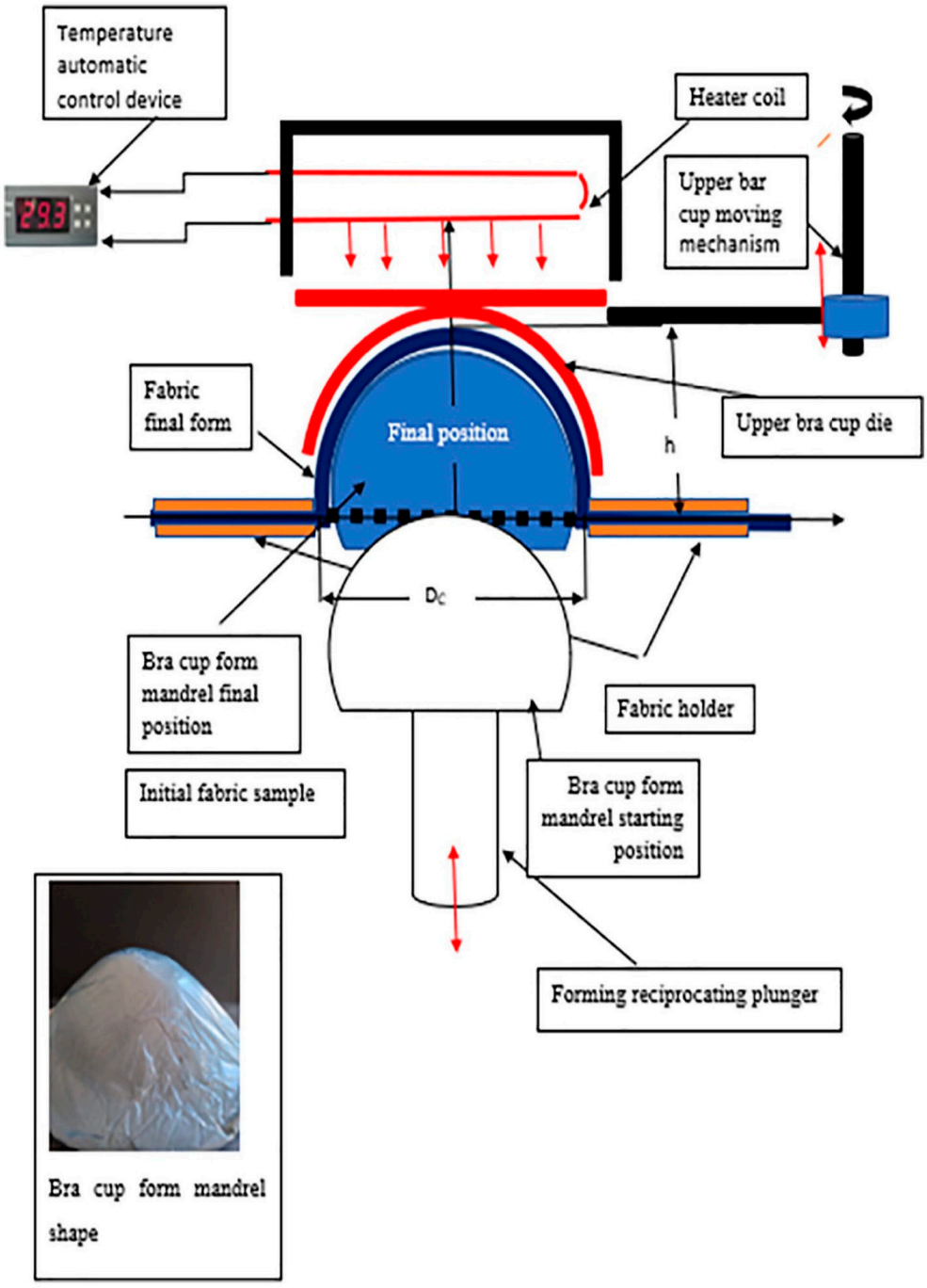


Figure 12. Sketch of the setup unit [58].

Table 1. Female body armor sizing system based on anthropometric measurements [3].

Size	Chest Breadth (mm)	Chest Circumference (mm)	Waist Breadth (mm)	Waist Circumference (mm)	Waist Front Length, Sitting	Weight (kg)	BMI	Stature (mm)
XZ	296	910	245	300	805	360	64.0	24.9
S	317	971	263	330	902	371	73.2	25.9
M	336	1058	285	339	944	376	78.0	30.4
R	355	1082	305	355	1017	392	91.7	30.8
L(S)	366	1139	322	284	1065	366	96.7	35.3
L(l)	367	1173	336	402	1121	410	97.9	35.4
XL	402	1232	355	436	1234	403	117.7	37.4
XXL	434	1316	374	465	1297	432	117.3	44.6

4. Materials Used for Developing Soft Body Armor

4.1. Evolution of Materials Used for Body Armor

The history of body armor dates to 2500 B.C., when early protective clothing was crafted from metal or leather lamellae or a combination of both, a practice widely adopted by civilizations like the Assyrians and Greeks [60]. Animal skin, like rhinoceros and ox skin, was also used as a protective component for developing layers of body armor in the Chinese and Mongolian civilizations as early as 500 B.C. Later, chain-mail armor was introduced by the Celts in the 4th century B.C. [61], which was widely adopted by the Romans and other European countries until the 12th century [60]. The construction of the body armor transformed traditional metal armor into a more structured plate-based design and became more prevalent among Medieval knights during the 12th to 16th centuries [61]. With the advancement of body armor for protection from ammunition, the first bulletproof armor was developed in the 1850s by an Australian. It was a boilerplate iron body armor that was effective against firearms.

Meanwhile, the Japanese had already manufactured body armor made of silk in the Medieval period, which is considered the first soft body armor ever recorded. However, such body armor can resist bullets with a velocity of up to 400 m per second, which is unsuitable for protecting from the more evolved ammunition shooting bullets at a speed of more than 600 m per second [62]. Therefore, experiments to develop soft body armor continued. During the First World War, materials like cotton, linen, and tissue were used, along with silk, in the United Kingdom to create neck protection and vests. Americans used a combination of steel plates and strong fabric garments to make bulletproof body armor, where plates were sewn into the strong fabrics [13]. World War 2 and the Korean War were the key events that accelerated the advancement of body armor by introducing flak jackets sewn with steel plates, providing improved ballistic protection [63]. However, its heavy weight and lack of flexibility limited its widespread use. A breakthrough in body armor research came in the 1960s, with the invention of ballistic nylon, which came up with a lightweight solution for soft body armor. The invention of para-amides in the mid-sixties by DuPont under the name of Kevlar® revolutionized the advancement of soft body armor by being five times stronger than steel, yet lightweight and flexible, making it the standard for law enforcement armor [64]. Figure 13 presents the history of body armor according to its generation [65]. With the invention of Kevlar®, the production and development of thinner and more lightweight armor with more resistance became trendy. Its market became more competitive, resulting in the introduction of new substances, such as DSM's Dyneema®, Teijin Twaron's Twaron®, Toyobo's Zylon®, Honeywell's GoldFlex® and Spectra®, and Pinnacle Armor's DragonSkin® [44].

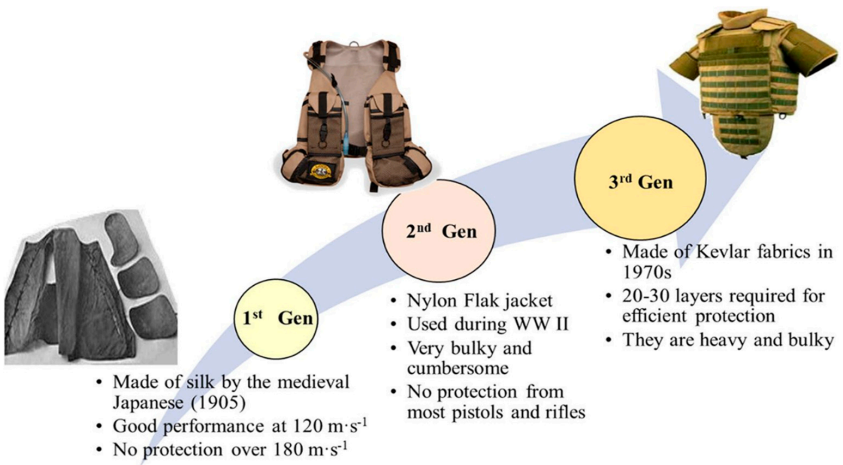


Figure 13. History of body armor. Reprinted from ref. [65]. with permission from Springer Nature.

4.2. Commonly Used Materials for Lightweight Body Armor

A recent study provided a comprehensive discussion about the materials used for soft body armor, focusing on high-performance fibers used in ballistic protection [66]. Para-aramid fibers, such as Kevlar, Twaron, and Technora, are widely used due to their high tensile strength, thermal stability, and resistance to abrasion and chemicals. Kevlar, developed by DuPont, is five times stronger than steel, making it highly effective against bullets and stab threats. At the same time, Twaron and Technora offer similar high-strength properties with enhanced durability [67]. Another key material is ultra-high-molecular-weight polyethylene (UHMWPE), known for its lightweight nature and high impact resistance, with brands like Dyneema and Spectra excelling in ballistic applications. Poly (p-phenylene benzobisoxazole) (PBO) fibers, such as Zylon, offer exceptional resistance and thermal stability, often blended with Kevlar for added strength [68]. Historically used in military armor, nylon fibers provide flexibility and moderate impact resistance but are less effective than aramids [69]. Glass fibers, commonly used in defense applications, offer high tensile strength and cost-effectiveness but suffer from low fatigue resistance [70]. Lastly, carbon fibers are valued for their high strength, stiffness, and lightweight nature, making them suitable for structural reinforcement in protective gear [71,72]. Each material has unique advantages and trade-offs, influencing its application in modern ballistic armor systems. These different fibers could be woven together in a 2D, UD, or 3D structure and used as impact-resistant materials in the dry form [73–75], or they can be impregnated with thermoplastic and thermoset resin [76–78]. In one study [76], experiments and simulations were conducted to assess the impact damage tolerance of thermoplastic (Elium) and thermoset (epoxy) 3D fiber-reinforced composites (3D-FRCs), using compression after impact (CAI) tests. The thermoplastic 3D-FRC shows good damage tolerance, with very little decrease in CAI strength and stiffness at different impact energies, unlike the thermoset 3D-FRC, where these properties decrease significantly in performance. Table 2 provides a comparative account of fibers and composites generally used in the making of lightweight body armor in terms of their manufacturing methods, advantages in terms of performance, some possible disadvantages, and approximate prices. The analysis, therefore, draws attention to the choices between material systems and manufacturing methods, with insights into their feasibility in designing soft body armor that is scalable and cost-effective and has great performance.

Table 2. Comparison of materials, manufacturing methods, and cost approximation for lightweight body armor.

Material/Composite	Manufacturing Method	Advantages	Challenges	Approximate Cost Implications	Ref.
Para-Aramid (Kevlar®, Twaron®)	2D/3D weaving, Lamination	High ballistic resistance, lightweight	UV degradation, limited multi-threat resistance, moderate flexibility	Moderate to High	[66,67].
UHMWPE (Dyneema®, Spectra®)	UD Laminate, Hot pressing	Excellent ballistic resistance, lightweight	Thermal instability, difficult recycling	High	[66,67].
Thermoplastic 3D-FRC (Elium®)	Resin infusion, Compression molding	High impact tolerance, less damage sensitivity, recyclability	Higher resin cost, process adaptation required	Moderate to High	[76]
Thermoset 3D-FRC (Epoxy)	Resin infusion, Compression molding	High strength, established processes	Brittle failure, sensitive to impact damage, less recyclable	Moderate	[76]

Table 2. *Cont.*

Material/Composite	Manufacturing Method	Advantages	Challenges	Approximate Cost Implications	Ref.
STF-treated Fabrics (Kevlar + Silica/PEG)	Dip coating, Sandwich Laminate	Improved energy absorption, lightweight	Fluid leakage, breathability issues	Moderate to High	[74]
Graphene/Carbon Nanotube Composites	Infusion, Coating, Hybrid laminate	High strength, multifunctional (conductivity, sensing)	High material cost, limited scalability	High	[79].
3D Warp Interlock Fabrics	3D weaving	Seamless shaping, reduced weak points	Complex weaving, limited scalability	Moderate	[54–56].
Shear Thickening Gels (STG) + Foams	Infusion into foam matrix	Enhanced shock absorption	Process development, material stability	High	[80]

4.3. Recent Dry and Fiber-Reinforced Composite Materials for SBA Development

Lightweightness has always been the most desirable attribute for body armor, prompting researchers to develop innovative ideas using different and smart materials. Since high-performance fibers with a high molecular weight require up to 50 fabric layers for protection, the body armor is bulky and rigid. This reduces comfort and limits its use mainly to torso protection [81]. In the quest to construct lightweight body armor, Gates Jr. proposed a fluid-based armor system in 1968 to reduce the number of layers while remaining flexible and even repairing itself after impact [82]. Further research on this idea led the way for the invention of a new method in 2000 that involved coating body armor with a special fluid called shear thickening fluid (STF) [83]. It is a non-Newtonian fluid that increases its viscosity with an increasing applied shear rate [84]. The fluid is formed by making a colloidal dispersion consisting of solid particles like silica, calcium carbonate, or silicon carbide with a dispersion liquid such as water, polyethylene glycol (PEG), ethylene glycol (EG), or silicone oil [85]. EG and PEG are the most used substances due to their conjoined stability, high boiling point, polarity, and non-flammability [86]. According to hydrocluster theory, the liquid turns solid-like because shear forces cause tiny particle clusters, called "hydroclusters," to form and spread, making the fluid much thicker [87]. As shown in Figure 14, under relaxed conditions in Zone I, the particles in the fluid are randomly spread out at equilibrium. As the shear rate increases, they start forming layered structures that cause shear thinning, decreasing the viscosity, as shown in Zone II. When the shear rate reaches a certain point, these layers break apart, and the particles clump together into hydroclusters that cause shear thickening, as shown in Zone III [82].

There are some other popular theories that have tried to explain the shear thickening phenomenon, such as order–disorder theory [88], dilatancy theory [89], and contact theory [90]. Still, the specific function of an STF during impact remains a topic of debate. The specific characteristic of this fluid has been utilized as an energy absorber for body armor. When the STF-impregnated fabric is under ballistic impact, it causes a relative movement of yarns, causing the shear force that triggers the hydroclustering of STF particles, as shown in Figure 15. This reaction reinforces the fabric structure, which distributes the impact energy across a larger area rather than concentrating it solely on the impact zone, thereby enhancing overall energy dissipation and protection [25].

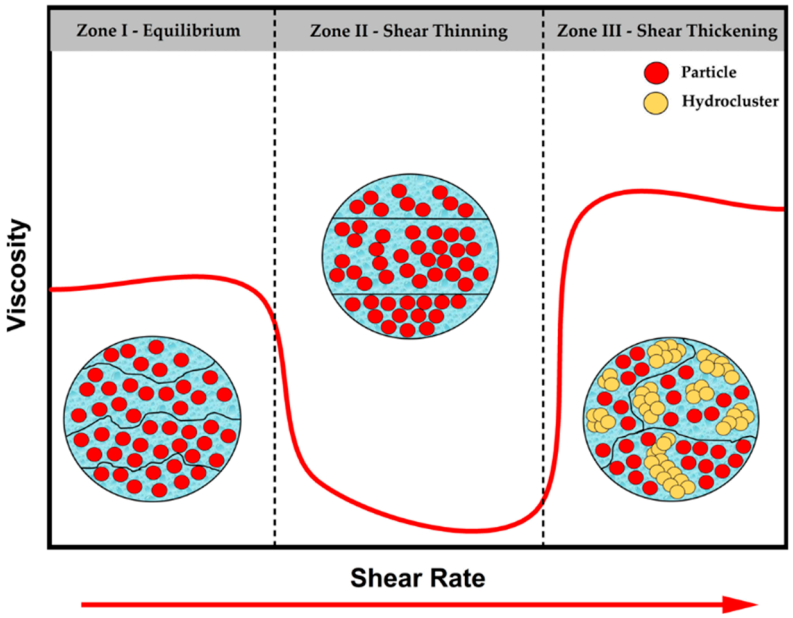


Figure 14. Schematic representation of the rheological behavior of a typical STF [82].

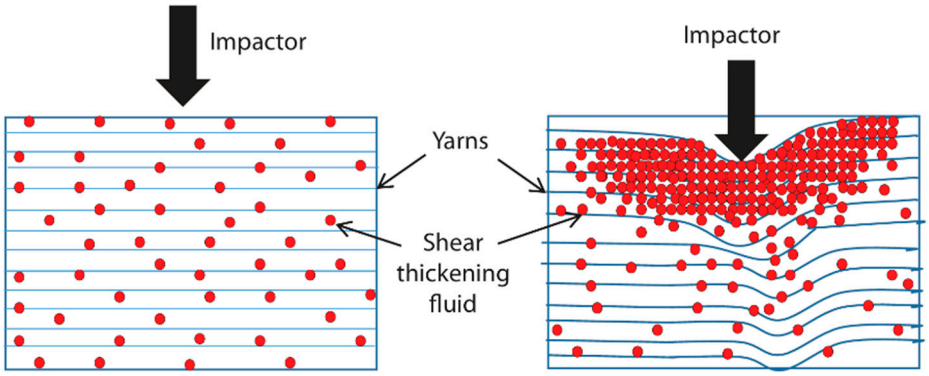


Figure 15. Schematic representation of STF–fabric interaction before and after impact. Reprinted from ref. [25] with permission from Wiley.

The STF-impregnated fabric is constructed by mixing particles into a liquid-dispersing phase using mechanical, magnetic, or ultrasonic devices to create a uniform suspension. Alcohol is used to dilute viscous fluids, which eases the process of spreading and allows them to be evenly absorbed into the fabric. The soaking process is followed by drying to remove the excess fluid, which can be accomplished by padding. It helps increase yarn friction and balance the fabric's resistance, preventing fibers from pulling out or breaking upon impact. The process is illustrated in Figure 16 [82].

The impregnation of high-performance fabric such as Kevlar by STF to create STF/Kevlar soft body armors was introduced by Wagner et al., who reportedly improved Kevlar's ballistic performance [89]. After that, various studies explored the application of STF with different viscosities on Kevlar fabric, consistently demonstrating an improvement in impact energy absorption [91–93]. Additionally, both experimental and numerical studies have been conducted to examine the ballistic performance of STF/Kevlar fabric. The findings indicate increased friction from STF infusion, along with its shear thickening behavior, ultimately improving the fabric's resistance to impact [94,95]. A recent review on STF-impregnated ballistic fabric, using all the articles from 2003 to 2022, found that most research involves Kevlar and Twaron fabric soaked in STF made of silica (SiO_2) nanoparticles mixed in PEG [82]. The concentration of silica nanoparticles varies from 20%

to 50%, which is a suitable range for ensuring sufficient thickening under impact while maintaining good flexibility. The performance of body armor based on the different ranges of silica concentrations is summarized in Table 3. The study showed that silica particles between 100 and 500 nanometers work best in shear thickening fluids (STFs) for soft body armor because they offer a good balance between strength and flexibility. Smaller particles mix well and prevent settling, while larger ones may reduce flexibility and cause uneven coating. Similarly, polyethylene glycol (PEG) with a molecular weight of 200 to 400 is ideal, as it ensures smooth spreading and maintains flexibility. Heavier PEG makes the fluid too thick, which can reduce performance.

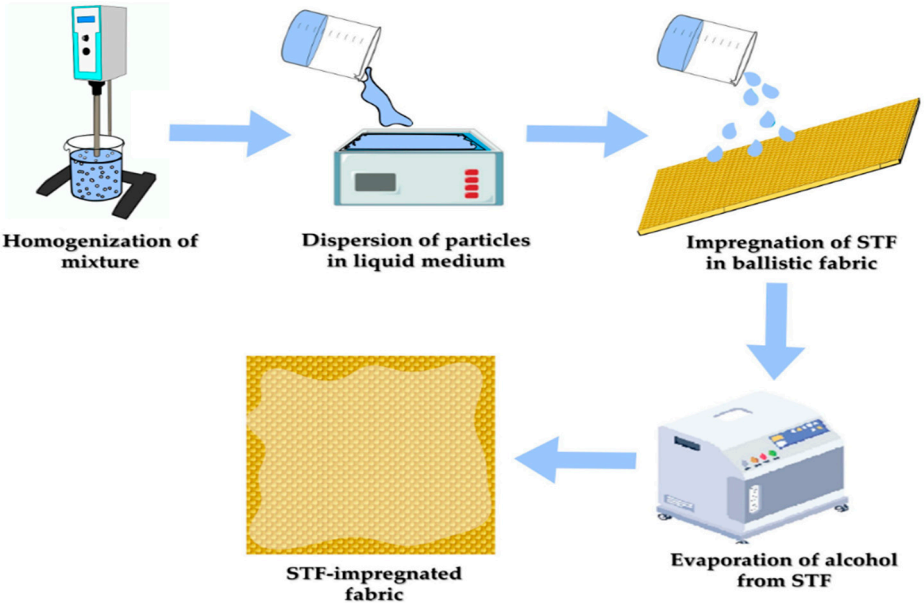


Figure 16. Scheme of the preparation method of shear thickening fluids [82].

Table 3. Effect of silica concentrations on ballistic performance [82].

Silica Concentrations (wt.%)	Impacts on STF Behavior	Effect on Ballistic Protection
<20%	Very fluid, weak thickening effect	Minimal improvement in energy absorption
20–30%	Moderate thickening, good balance	Improved protection while keeping flexibility
40% (Most common)	Strong thickening, ideal viscosity	Best balance of impact resistance and flexibility
50–60%	Very thick STF, higher resistance	Better impact resistance but reduced flexibility

Despite its benefits, liquid body armor has several issues, including evaporation of the carrier fluid (e.g., EG), leading to weakened performance over time, sensitivity to humidity, leakage of carrier fluid, and poor breathability [78,96]. To address these limitations, researchers have taken a novel approach to identify the most suitable "liquid body armor" by developing and analyzing different STF compositions [97]. For this purpose, ten types of STF formulations were explored in the study to find better combinations of materials upon a comparison of performance. The combinations were achieved by varying the carrier liquid, such as 200 Da and 400 Da of PEG and 400 Da of polypropylene glycol (PPG). Similarly, the filler materials also varied, using silica nanoparticles (SiO_2) ranging from 20 to 40 wt%, with fumed silica (0.2–0.3 µm diameter) and Pyrogenic Silica (40 µm diameter). All ten STF formulations are listed in Table 4. The study tested different Kevlar and Twaron fabrics to evaluate how well they work with STFs. In addition, the interaction of STF with fabric was conducted in two different ways. In the first method, fabric was directly soaked in the STF, whereas the second method used a thick layer of STF placed between Kevlar to form a sandwich-like structure. Among the various tested configurations, the PEG400-based STF

with 27 wt% Pyrogenic Silica demonstrated the highest effectiveness in moderate-impact scenarios, absorbing 60% of the kinetic energy. However, in high-velocity impact tests, only one formulation, PEG400 with 30 wt.% Pyrogenic Silica, successfully prevented bullet penetration when strategically placed between the first and second layers of an 11-layer Kevlar XP panel, as presented in Figure 17. However, the issues of fluid leakage, evaporation, and reduced breathability remain practical concerns that need to be resolved before STFs can be widely adopted in the mass production of soft body armor.

Table 4. STF formulations chosen for experimental investigations [97].

Sample Code	Polymer Matrix	Fumed Silica (0.2–0.3 μm) [wt.%]	Pyrogenic Silica (>40 μm) [wt.%]
P1	PEG 400	20	-
P2	PEG 400	30	-
P3	PEG 400	-	20
P4	PEG 400	-	30
P5	PPG 400	20	-
P6	PPG 400	-	20
P7	PEG 200 [1]	-	40
P8	PEG 400 [1]	-	40
P9	PPG 400 [1]	-	40
P10	PEG 400	-	27
P-bk	PEG 400	-	-

[1] Ethyl alcohol was added to facilitate dispersion.

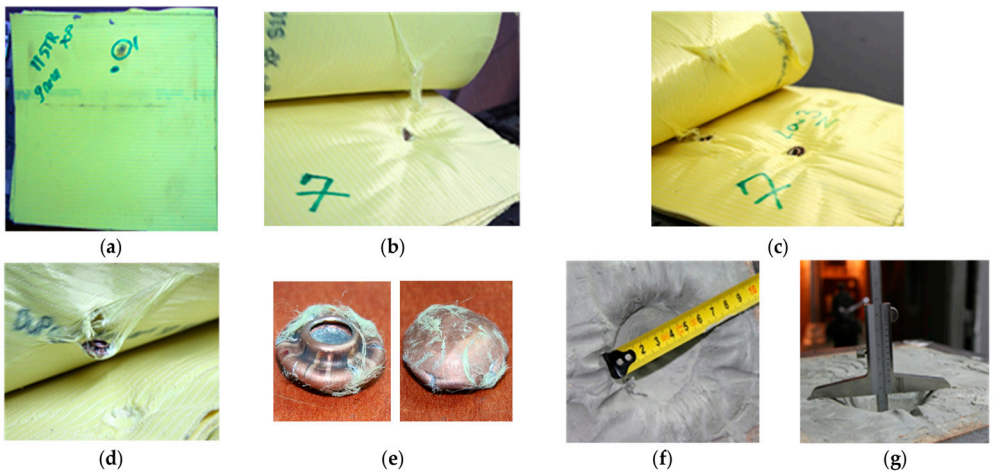


Figure 17. (**a**) Eleven layers of Kevlar: front view; (**b**–**d**) bullet stopped between 6th and 7th layers; (**e**) bullet recovered between Kevlar layers 6–7; and (**f**,**g**) measurement of the traumatic imprint in the ballistic clay [97].

With the same filler material, which is fumed silica, another study dispersed the nanomaterial in EG, which was used for the impregnation of Kevlar fabric to increase the stab resistance [91]. The impregnation was conducted by dipping and squeezing the fabric to ensure uniform penetration. In performance testing, the shear rate threshold was found to be around 200 s^{-1}, making it effective for impact protection. Quasi-static and dynamic stab tests confirm the significantly improved performance of STF-treated Kevlar than neat Kevlar, as shown in Figure 18. STF treatment did not significantly change fabric flexibility, and it only increased thickness, ensuring comfort and lightweight properties for wearers.

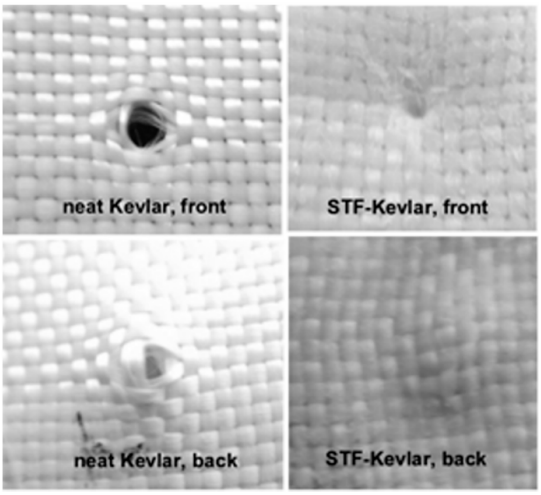


Figure 18. Photographs of neat Kevlar fabric and fumed silica/Kevlar composite fabric after quasi-static stab testing. Reprinted from ref. [91] with permission from Springer Nature.

Apart from these studies, other studies investigated the stab performance of body armor constructed with STF composites [92,96,98–102]. To improve projectile resistance, a novel approach was taken to develop an STF-composite soft body armor to withstand 7.62 NATO rifle rounds [82]. The aim was to replace the traditional NIJ Level III-rated armor typically made of steel, ceramic, or rigid composite plates. The researcher used fumed silica, silicon carbide, tungsten, and super-activated carbon particles as filler materials dispersed in PEG 400 to create a shear thickening suspension. The STF was applied to Kevlar 29 fabric, which is a bi-directional weave with yarn interlocked at 90 degrees. The results showed that tungsten-based fluid had a much higher viscosity than silica-based fluid, likely due to its density and uniform particle shape, which made it more effective in absorbing impact. In contrast, silicon carbide reduced the thickening effect and lowered performance. The treated Kevlar became about seventy percent stiffer, and in dynamic testing, it absorbed thirty-six to fifty-seven percent more impact force compared to untreated fabric. However, it did not perform well in knife or spike tests. Interestingly, the combination of silica and tungsten did not give the best results, suggesting that friction between fibers may play a more important role than the fluid's thickening behavior. Overall, the treatment improved impact resistance, but more research is needed to understand the exact reasons behind the improvement.

Similarly, another study developed STF/Kevlar composite body armor to withstand the impact of 9 × 19 mm lead core bullets [103]. Two panels of multiple layers (20–24) were created, where the first one is 500 nm silica particles and the other one is 100 nm silica particles. Both were tested against 9 × 19 mm bullets at a velocity of around 430 m/s, and Back Face Signature (BFS) was measured to assess impact performance. Back Face Signature (BFS) refers to the depth of the indentation or deformation on the rear side of a ballistic armor panel when it is struck by a bullet or projectile. The panel with 500-nanometer particles showed less BFS, meaning it absorbed more energy and offered better protection. This suggests that using larger silica particles improves impact resistance. Placing STF-treated layers at the back of the armor can help keep it lightweight while still providing strong protection. The same researchers used the same approach with unidirectional (UD) and 2-dimensional (2D) woven fabric impregnated with silica (500 nm)-based PEG 200 dispersion [104]. The fabrics were made of ultra-high-molecular-weight polyethylene (UHMWPE) and Very-High-Modulus Aromatic Polymer (VHMAP). In addition, fabric combinations of both materials were prepared to make the fabric flexible and highly protective, eventually showing better energy absorption than single-fabric panels. Furthermore, UD fabric

showcased lower BFS, which indicates better energy absorption than neat woven fabric. This research provides insights into next-generation armor design to maximize protection and mobility.

In another study, a unique approach was taken to ensure the uniform dispersion of silica nanoparticles with PEG through ultrasound irradiation. With the uniform dispersion of filler materials, STF-infused Kevlar and nylon fabric showed better quasi-static penetration performance [105]. Similarly, another study used ultrasonication and stirring methods to ensure uniform dispersion [106]. Researchers also tried to optimize the impact resistance performance of STF/Kevlar fabric by investigating the padding technique [107]. Kevlar comes with a Teflon coating that limits the absorption of STF. To overcome this issue, a new sequential padding technique has been introduced, which involves treating Kevlar twice using different pressure levels instead of a single-step application. This resulted in a higher "add-on percentage" of STF, which eventually increased the absorption of impact energy by 125% compared to neat Kevlar, resulting in improved impact resistance. In another study, researchers tried to find a solution by addressing an inevitable drawback of STF/Kevlar composite, which is sedimentation, by introducing shear thickening gel (STG) as a gel-like boron–siloxane polymer with a low degree of crosslinking, offering an alternative to traditional STF by avoiding the dispersion of particles in a viscous fluid [108]. In the study, three types of multi-layer fabrics (21-layer neat Kevlar, 20-layer uniformly stacked STG/Kevlar, and 20-layer gradient-stacked GS-STG/Kevlar) were tested under different impact heights; they contained a varied concentration of STG in different layers, as shown in Figure 19. The study established that GS-STG/Kevlar fabrics significantly outperformed conventional Kevlar and uniformly stacked STG/Kevlar fabrics in ballistic impact while maintaining a lightweight structure. By strategically varying the STG content across different layers, the material maximized energy absorption without increasing the overall weight, making it an ideal candidate for advanced body armor applications.

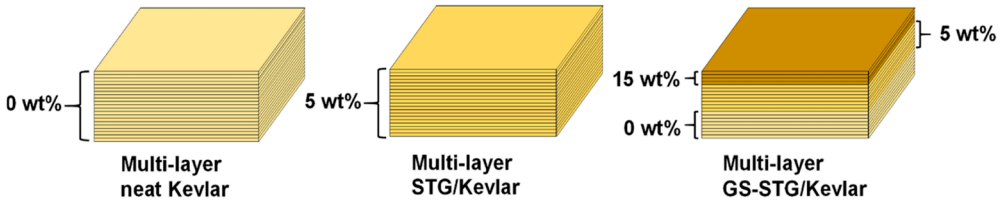


Figure 19. Schematic diagram of 21-layer neat Kevlar, 20-layer STG/Kevlar, and 20-layer GS-STG/Kevlar fabrics (the top 4 layers are 15 wt% STG/Kevlar, the middle 8 layers are 5 wt% STG/Kevlar, and the bottom 8 layers are neat Kevlar). Reprinted from ref. [108] with permission from ScienceDirect.

Due to the prospects of STF/Kevlar, this composite material has been extensively studied by several researchers [109–114]. A significant limitation of STG is its cold-flow behavior, which gradually deforms under gravity, limiting its long-term usability. To address this problem, researchers developed a polyurethane (PU)-based composite foam that integrates STG for impact absorption, carbon nanotubes (CNTs), and silicon dioxide (SiO_2) nanoparticles for superhydrophobicity and chemical resistance [115]. The integration of CNTs opened the door to multifunctional properties in the body armor since it endowed the body armor with impact resistance and strain-sensing properties [116]. As illustrated in Figure 20a, the composite foam is formed in two steps. In the first step, dip coating applies a mixture of CNTs and STG to the foam skeleton. In the next step, a mixture of silicon dioxide (SiO_2) and STG is sprayed onto the foam's surface. This layered coating process results in a new composite foam, called SiO_2/CNT/STG@PU (SCS@PU), that turns the

foam black and keeps it lightweight, as shown in Figure 20b. Compared to neat STG, the composite retained its shape over time, as shown in Figure 20c,d.

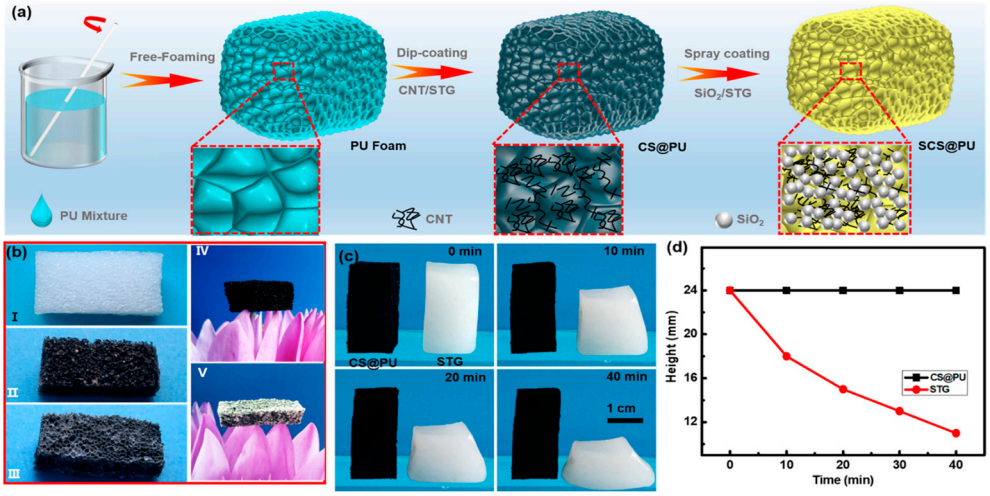


Figure 20. (**a**) Fabrication schematics of SCS@PU; (**b**) digital photos of PU (**I**), CS@PU (**II**), SCS@PU (**III**), CS@PU (**IV**), and SCS@PU (**V**) standing on the petals of a water lily; (**c**) cold-flow phenomenon of cuboid samples after 40 min; and (**d**) corresponding height−time curves. Reprinted from ref. [115] with permission from the American Chemical Society.

Experimental results demonstrated that the SCS@PU composite foam absorbed 81% of impact forces, significantly outperforming regular PU foams and previous STG–foam composites. Integrating CNTs into the shear thickening gel (STG) and PU foam matrix allows the material to function both as a protective and a smart sensing material. The CNT/STG layer enabled real-time monitoring of pressure and strain, allowing the foam to detect human body movements, such as pulse monitoring and blinking. Additionally, the SiO_2/STG coating created a highly water-resistant surface, protecting the material from rain, sweat, and corrosive chemicals. Researchers used carbon black (CB) in a similar study, combining STG with a PU sponge. The composite material is also abbreviated as STG-CB/PUS [117]. In another study, a composite known as Leather/CNT-SSG/PU was developed using leather combined with conductive shear stiffening gel (SSG) [118]. Carbon nanotubes (CNTs) and polyurethane (PU) were used as the filler materials for SSG. The composite has a three-layer sandwich structure: natural leather on the outside for strength and flexibility, CNTs mixed with shear stiffening gel in the middle for impact protection and sensing, and a polyurethane sponge on the inside, as shown in Figure 21a. This design was able to absorb bullet impacts up to 142.4 m/s and spread out the force effectively. As shown in Figure 21d, the impact on the outer layer is absorbed by the compression of the leather fibers. Importantly, the integrated CNT network provides the composite with intelligent sensing abilities, enabling it to detect and measure impacts through changes in electrical resistance. Under dynamic impact, the absorbed energy led to the destruction of the conductive networks of CNT-SSG, which resulted in a reduction in conductive paths with increasing resistance of the composite. The conductive networks gradually recover by reconnecting due to the viscoelastic CNT-SSG, as shown in Figure 21e–g. In a similar study, another composite was developed using the same process, except the PU layer was replaced by a sensor-equipped non-woven fabric (NWF), resulting in a Leather/CNT-SSG/NWF composite. This new structure was utilized to create a smart bulletproof vest prototype capable of detecting impacts and monitoring their exact location through real-time resistance changes. The vest's intelligent sensing capabilities make it particularly

valuable for protecting and alerting soldiers or law enforcement personnel during critical situations.

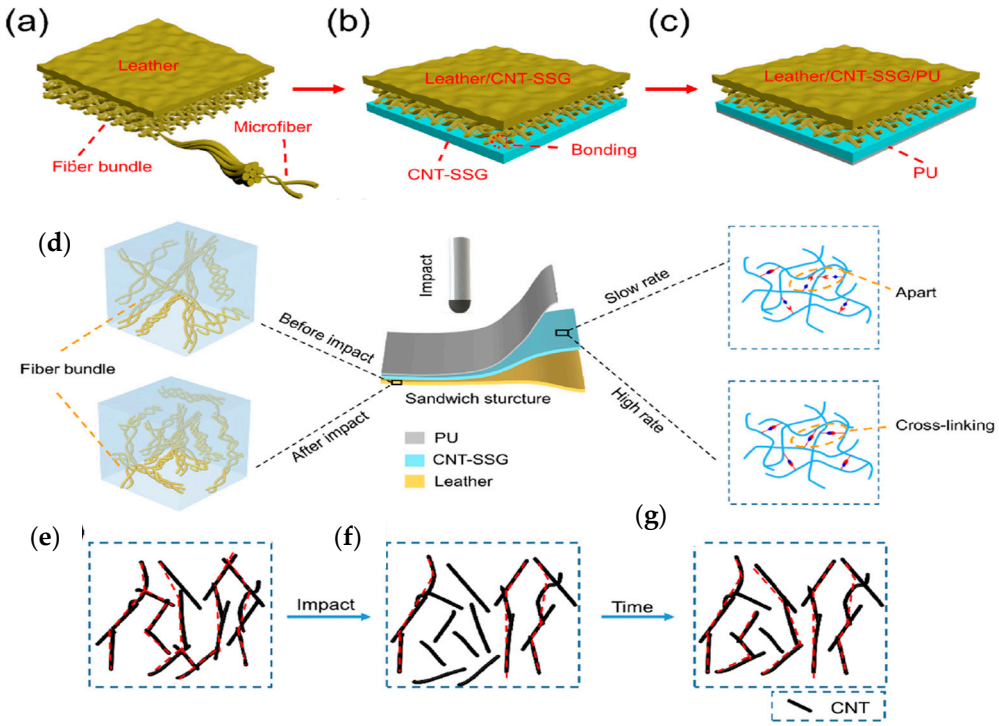


Figure 21. (**a**–**c**) Schematic synthetic process of CNT-SSG; (**d**) anti-impact mechanism diagram of Leather/CNT-SSG/PU; and (**e**–**g**) electrical property mechanism diagram of CNT-SSG. Reprinted from ref. [118] with the permission of ScienceDirect.

In another study, an advanced ballistic composite was developed by integrating carbon nanotube (CNT)-reinforced polystyrene-ethyl acrylate (PSt-EA)-based shear thickening fluid (C-STF) with Kevlar fabric [119]. In the study, the researcher primarily explored an alternative to silica-based STF for its limitation in weight optimization. Hence, the study utilized a polymer-based STF, specifically, a PSt-EA-based STF, offering lower density and strong shear thickening effects. CNTs were added to the STF to enhance the protective properties further, leading to an innovative CNT/PSt-EA-based STF/Kevlar composite (C-STF/Kevlar). The result of the study created a high-performance, lightweight, and impact-resistant fabric that provided the best balance of the viscosity fiber–matrix for 1.0 wt% CNTs while increasing the ballistic limit velocity (Vbl) from 84.6 m/s to 96.5 m/s and enhancing puncture resistance. In body armor design, buffer material is one of the common soft materials that is added behind the hard protective plates. It generally absorbs the material placed on the inner side of the body armor, as shown in Figure 22a. This helps reduce the impact on the wearer, and it can be made from traditional materials such as foam, rubber, and fabric. However, they fail due to their inadequate safety according to the modern threat and safety standard. A study was conducted to come up with an improved buffer layer that comprises shear stiffening gel (STG)-modified ethylene–vinyl acetate (EVA) foam, as shown in Figure 22b [120]. The study aimed to minimize the behind-armor blunt trauma (BABT), which occurs when a bullet is stopped by the body armor but still transfers force to the wearer, potentially causing severe injuries. To find an optimum composite, 3% and 5% STGs were used to make the buffer sample, which was tested in combination with ultra-high-molecular-weight polyethylene (UHMWPE) ballistic protection layers. These samples were tested using ballistic impact experiments with 7.62 mm bullets fired at 445 $\pm$ 10 m/s. The samples were mounted on ballistic clay,

which simulated the human body, allowing researchers to measure Back Face Signature (BFS), as shown in Figure 23a.

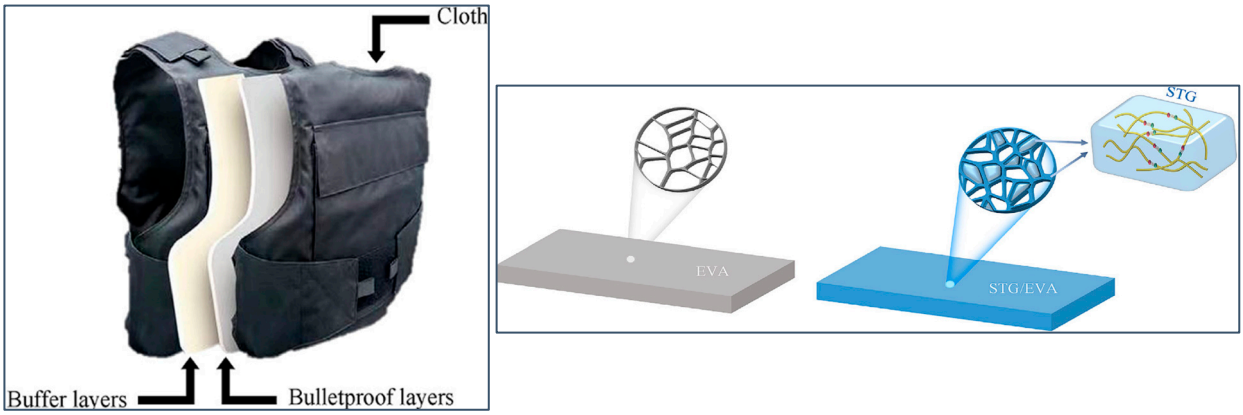


Figure 22. (**a**) Typical structure of contemporary body armor [120]. (**b**) Schematic diagram of EVA and STG/EVA foam [120].

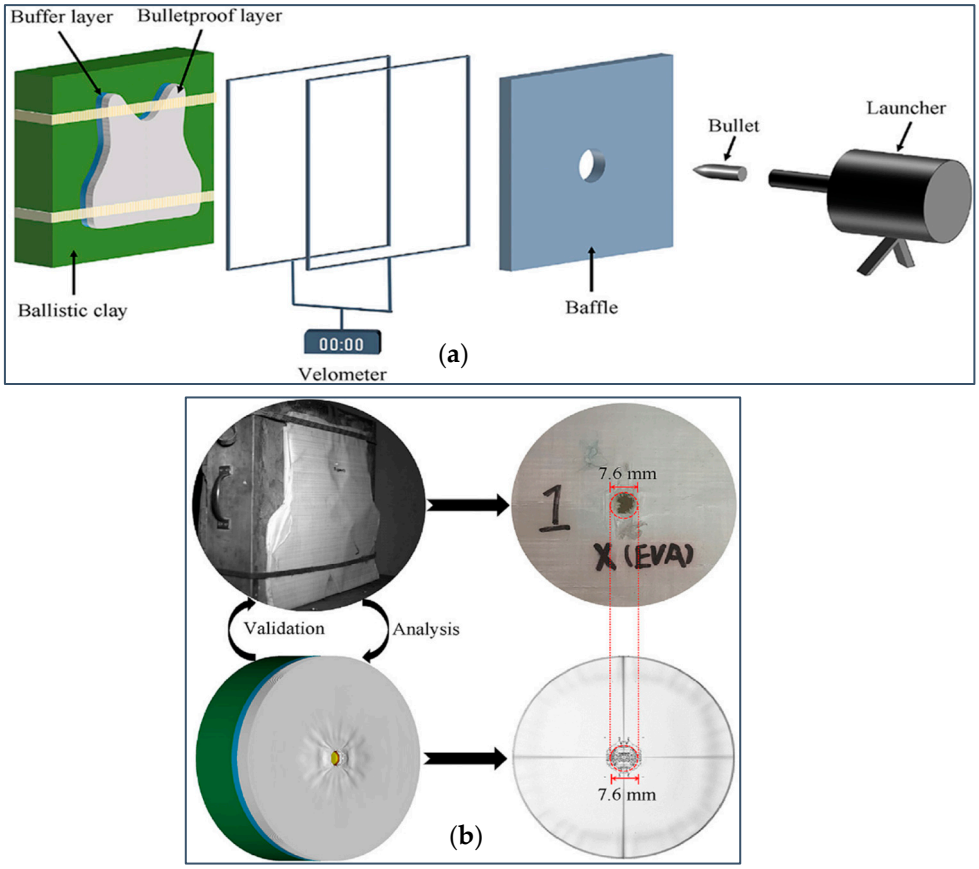


Figure 23. (**a**) Setup of the ballistic test and (**b**) comparison of a bullet hole in UHMWPE between the test and the simulation [120].

Additionally, finite element analysis (FEA) was conducted using LS-DYNA® to simulate ballistic impacts, analyzing how the buffer layers absorbed and distributed energy. Ballistic clay tests showed that STG-modified EVA foam significantly reduced Back Face Signature (BFS), lowering impact force transmission to the body. The STG/EVA-3% buffer reduced BFS by 39%, while STG/EVA-5% achieved a 42% reduction, demonstrating superior energy absorption. Finite element analysis (FEA), using LS-DYNA®, confirmed these

results, showing that STG-infused layers effectively dispersed impact energy, minimized stress concentration, and momentarily stiffened upon impact before returning to a soft state. As shown in Figure 23b, both experimental and simulation data validated STG/EVA foam as an effective buffer layer, offering enhanced protection against blunt trauma in body armor applications.

A study on multifunctional body armor integrated with strain-sensing and electro-heating functions to convert electricity into heat energy in soft body armor [116]. In the study, the researchers introduced a three-layered coaxial fabric composite, denoted as SiO_2/STG/RGO@Kevlar (SSG@Kevlar). As shown in Figure 24, this fabric integrates Kevlar fabric as the core protection layer coated with reduced graphene oxide (RGO) nanosheets, followed by a reduction process with 57% hydrochloric acid. A repeated deionized wash is performed to remove the excess acid until the pH is close to 7. This coating provides strain-sensing and electro-heating properties that make the armor multifunctional. In the next step, a mixture of STG-SiO_2 is applied onto the fabric's surface, ending the safeguarding performance. Compared to neat Kevlar, the SSG@Kevlar composite exhibits a 40% reduction in peak force under impact and a 12 mm reduction in penetration depth against stab threats.

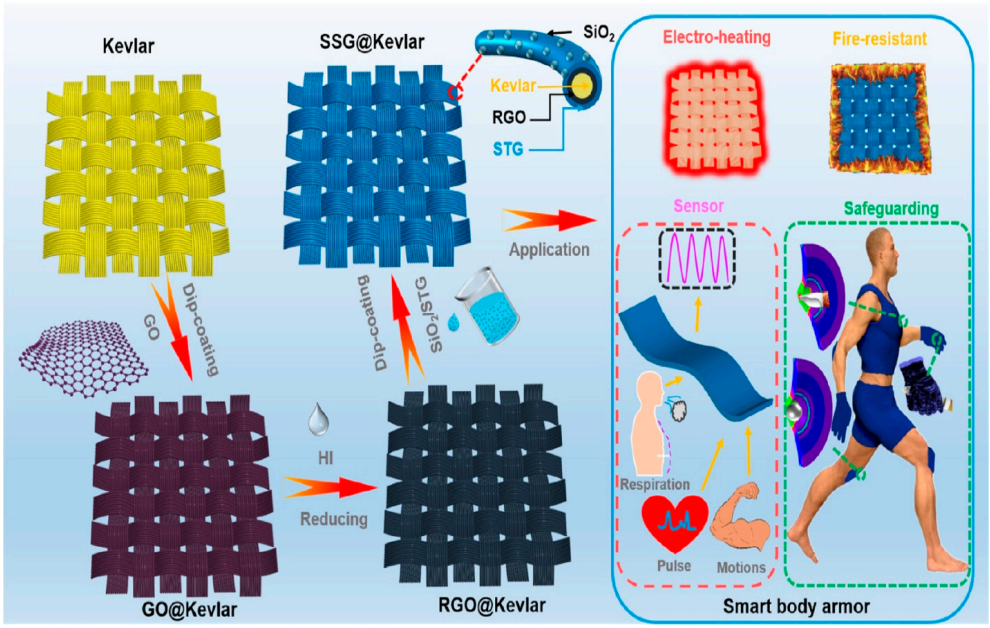


Figure 24. Schematics of fabrication and application of the SSG@Kevlar fabric composite. Reprinted from ref. [116] with permission from Elsevier.

In another study, researchers explored Polypyrrole (PPy), an intrinsically conductive polymer (ICP), to incorporate multifunctional properties in the soft body armor [121]. This polymer is formed through the oxidative polymerization of pyrrole monomers and is widely used as an electrical conductor. The study utilized the coating of PPy on aramid fabrics such as Twaron® to enhance stab resistance and introduce multifunctional properties such as electrical conductivity, anti-ultraviolet protection, and electrical heating capability. Simultaneously, the study aimed to enhance body armor adaptability to environmental conditions such as rain, snow, and UV exposure, which can gradually degrade aramid fabrics and reduce their protective performance. To make the PPy coating, the fabric was first cleaned in an acetone solution. Then, the fabric was soaked in a special solution to start the coating process, after which it was frozen for 3 h. The solution used for soaking contained ferric chloride ($FeCl_3$) and sodium 5-sulfosalicylate (NaSSA), which helped initiate the coating of the fabric, which was later frozen for 3 h. After that, a pyrrole solution was added, which formed a two-layer system. The fabric stayed in this cool mixture for

6 h so that the coating could form. Finally, it was washed and dried in a vacuum oven. An illustration of the process is presented in Figure 25. The composite showed 12.03% higher tensile strength than the neat fabric and better UV resistance by reducing strength loss by 6.7%. Inter-yarn friction rose 8.96 times, boosting stab resistance by 78.4%. The fabric also became highly conductive (6.183 Ω/sq), enabling stable heating from 26.6 °C to 65.7 °C (1 V–5 V). These improvements make it ideal for protective gear and smart textiles.

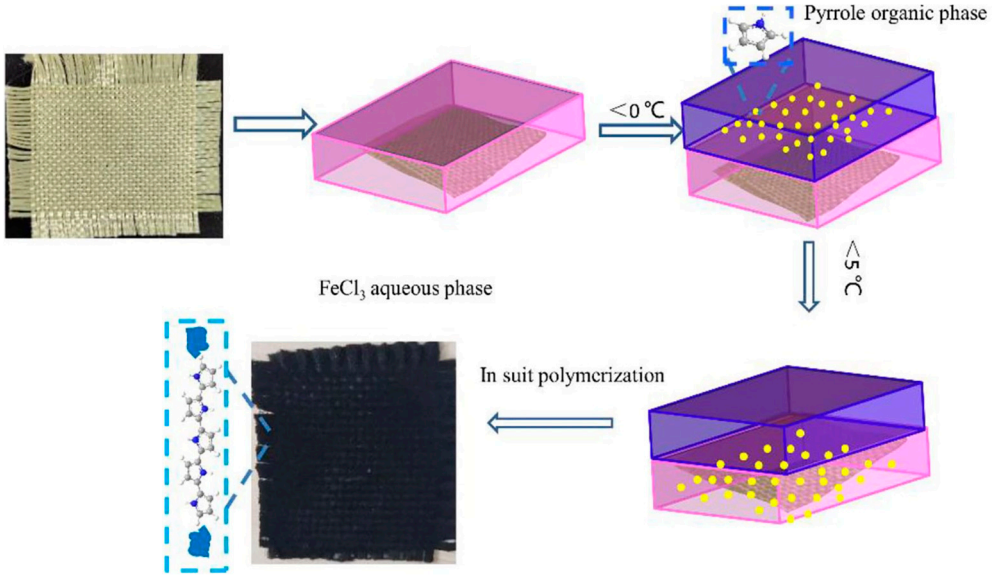


Figure 25. Schematic view of the preparation of PPy-coated aramid fabric [121].

The researchers developed a Kevlar composite by mixing silicon carbide (SiC), aluminum oxide (Al_2O_3), and graphene with epoxy resin and a hardener [122]. They applied this mixture to Kevlar fabric using dip coating, followed by hot pressing and cooling to solidify it. Test samples were prepared based on ASTM standards, as shown in Figure 26. Silicon carbide improved the fabric's strength, impact resistance, and heat tolerance, although it absorbed some moisture. Aluminum oxide increased tensile stiffness, provided top-level fire resistance (V-0 rating), and added strong wear protection. Overall, the composite showed better strength, insulation, and durability, making it suitable for ballistic and industrial uses.

In another study, researchers looked at aramid fabrics (modified with polyethylene and graphene) under extreme conditions, like high temperature and humidity [123]. They used Twaron, a well-known para-aramid material known for its high strength, thermal stability, and chemical resistance. Polyethylene (PE) softens at extremely high temperatures, reducing its effectiveness for ballistic protection by weakening the connections between fibers and allowing more fiber slippage. Similarly, high humidity leads to moisture absorption, weakening fiber bonds, lower structural integrity, and lower impact resistance. However, adding graphene helps solve these problems by enhancing structural stability, preventing excessive softening, and minimizing moisture penetration, ultimately making the fabric more resilient to environmental stressors. In another study, researchers explored developing hybrid soft ballistic panel packages that integrate graphene-modified para-aramid fabrics with different ballistic Kevlar textiles. The goal was to enhance soft armor's durability and ballistic performance by optimizing how the fabric layers are arranged and incorporating advanced materials [124]. The researchers used liquid-phase exfoliation (LPE) to integrate graphene into para-aramid fabric layers to achieve these improvements. This process involved dispersing graphite flakes in a solvent, breaking them apart through sonication, and stabilizing the mixture. The solvents and additives they chose, such as N,

N-Dimethylacetamide (DMAc) and trisodium citrate, were carefully selected to improve how well graphene sticks to Kevlar fibers. They applied multiple layers of graphene coatings to the fabrics to increase friction between yarns, which helps disperse energy when hit by a bullet. They evaluated ballistic performance using Back Face Signature measurements and pressure sensors. The results showed that graphene modification significantly improved energy absorption, enhancing impact resistance while maintaining flexibility and reducing weight. The optimized layer design ensured toughness in the front layers and shock absorption in the rear layers. Increased friction between yarns from the graphene stabilized the fabric, improving its overall strength. These findings suggest that graphene-enhanced Kevlar panels offer a lighter and more efficient solution for body armor. To improve energy absorption, impact resistance, and ballistic performance, researchers also explored graphene-based multi-layer polymer nanocomposites (MLPs) [125]. By integrating graphene nanoplatelets (GNPs) into polyvinyl alcohol (PVA), polyurea (PU), and acrylonitrile butadiene styrene (ABS) layers, the researchers achieved enhanced stiffness, toughness, and dynamic mechanical properties of body armor. Testing confirmed that graphene-reinforced MLPS offers superior protection compared to traditional armor materials, making it a lightweight and highly effective solution for military and law enforcement applications. Researchers also explored the potential of graphene nanoplatelets as reinforcements in multi-scale polymer composites for ballistic shielding [126]. Researchers combined high-strength three-dimensional woven aramid fiber fabrics with vinyl ester resin, incorporating varying concentrations of GNPs (0.1%, 0.2%, and 0.3% by weight). The panels were fabricated using compression molding and tested for their impact, tensile, and flexural strengths, along with dynamic mechanical analysis and Hopkinson split bar tests. The results indicated that the composite containing 0.1% GNP performed best in terms of dynamic mechanical properties, maximizing stress absorption while maintaining structural integrity. The inclusion of GNPs improved stiffness and impact resistance, but higher concentrations (0.3%) led to particle clumping, reducing overall efficiency. The study's findings suggest that incorporating low levels of GNPs enhances ballistic resistance while keeping weight minimal, making it a promising approach for advanced body armor applications. In another study, researchers investigated how to improve shear thickening behavior and elastic strength in polyvinylidene fluoride (PVDF) by adding zinc oxide (ZnO)–grafted graphene. ZnO-G, synthesized via the rapid microwave method, was incorporated into PVDF nanocomposites using a mixed solvent approach, significantly improving β-phase crystallinity due to strong polar interactions between PVDF chains and ZnO-G. Rheological analysis revealed that ZnO-G doping transformed PVDF's discontinuous shear thickening behavior into continuous shear thickening, reducing frictional forces and delaying hydrocluster formation. This modification extended the linear viscoelastic region, increased elastic modulus, and improved mechanical strength, suggesting potential applications in soft body armor and mechanical protective materials [127]. Similarly, integrating graphene nanosheets into Kevlar-29 was studied to enhance ballistic resistance in bulletproof vests, addressing the material's poor compression strength under high-velocity impacts. The introduction of graphene laminates between Kevlar layers demonstrated improved fabric strength, reduced deformation, and enhanced energy absorption, as measured through dynamic ballistic analysis [128]. Another investigation into multi-layer graphene (MLG) subjected to high-speed microbullet impacts highlighted graphene's exceptional energy delocalization properties, exhibiting a 300% improvement in energy dissipation under vacuum conditions compared to previous air-based tests [129]. The study found that MLG's quasi-plastic behavior suppressed brittleness, while delamination and wave propagation mechanisms played a critical role in impact resistance. The inclusion of graphene reinforcement in bulletproof vests further demonstrated reduced stress upon impact, improved

flexibility, and lower weight than conventional Kevlar-based armor. These findings collectively indicate that graphene-based nanomaterials have the potential to revolutionize protective gear by offering lighter, stronger, and more effective ballistic-resistant solutions for military, aerospace, and law enforcement applications.

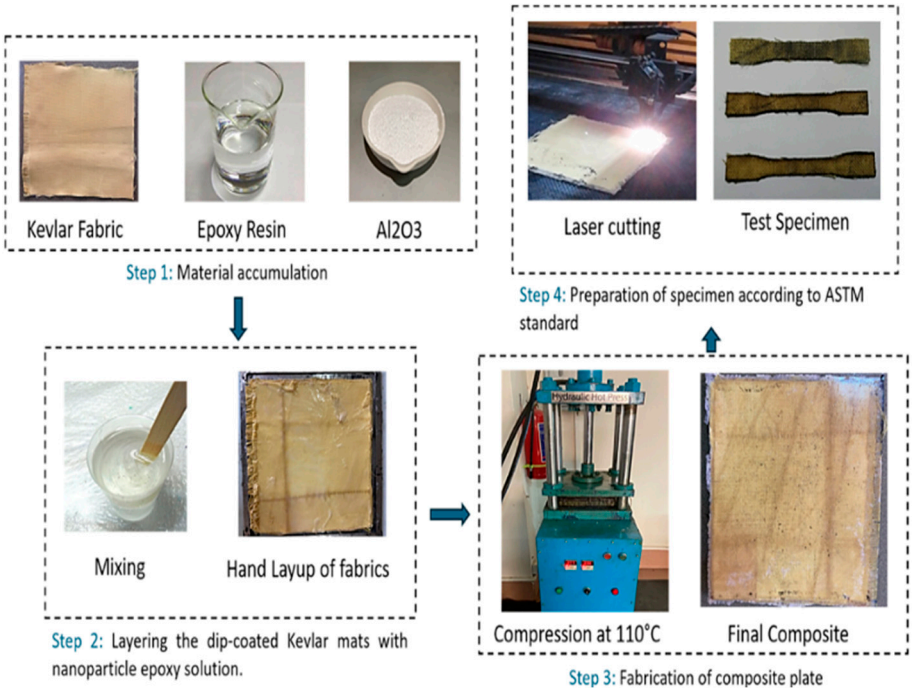


Figure 26. Composite manufacturing process [122].

In a novel approach, researchers combined both multiwalled carbon nanotubes (MWCNTs) and graphene nanoparticles (GPNs) to make a Kelar/epoxy matrix [129]. The purpose of this approach is to enhance the interfacial adhesion of Kevlar-based composite to address the limitation of weak fiber–matrix adhesion. Such limitations can lead to delamination and fiber pullout upon impact, reducing the composite's ability to absorb and dissipate energy effectively. When a high-velocity projectile strikes the composite, stress is not evenly transferred between the polymer and Kevlar fibers, causing premature failure at the interface. As a result, cracks can propagate easily, and the fibers may separate from the matrix rather than contribute to impact resistance. To improve the interfacial bonding of Kevlar with epoxy resin (diglycidyl ether of bisphenol-A) as a polymer matrix, an acid treatment with sulfuric acid and nitric acid was used to create a functional group on the fibers. The MWCNTs and GNPs were also dispersed into the epoxy resin using ultrasonication and high shear mixing to prevent agglomeration and ensure uniform distribution. The researcher made four Kevlar/epoxy composite panels with different combinations of materials to evaluate and identify the optimum combination by comparison. They were identified as P1, P2, P3, and P4. The baseline panel (P1) contained only Kevlar and epoxy, while P2 had 0.5 wt% MWCNTs, P3 had 0.5 wt% GNPs, and P4 (hybrid composite) had 0.5 wt% MWCNTs and 0.5 wt% GNPs. The hybrid composite (P4) outperformed all other samples, with 20% higher tensile strength and 54.49% greater energy absorption in low-velocity impact tests. In high-velocity ballistics tests (9 mm FMJ rounds at 430 m/s), P4 exhibited the lowest penetration depth, confirming superior impact resistance. Fractographic analysis revealed that P4's nanofillers prevented fiber pullout and crack propagation, making it tougher and stiffer. The study successfully created a lightweight, high-strength, and impact-resistant material that properly fits the soft body armor component. In another study, researchers focused on enhancing the ballistic performance of soft body armor by using hydrogel

as an alternative material [130]. Traditional armor made from multiple layers of aramid or ultra-high-molecular-weight polyethylene fabrics absorbs bullet energy by stretching and breaking fibers, but this often creates inward bulging that can lead to serious internal injuries. While adding more fabric layers or using shear thickening fluid can offer some improvement, they also introduce limitations, such as added weight, leakage, and reduced effectiveness at high impact speeds above 300 m per second. To overcome these challenges, a new bicontinuous hydrogel was developed using methacrylic acid, acrylamide, and vinyl imidazole. This hydrogel was infused into chemically treated ultra-high-molecular-weight polyethylene fabric to improve bonding. The resulting composite showed enhanced mechanical strength and impact resistance. Testing demonstrated that it reduced impact force by 36 percent, effectively lowered acceleration, and minimized bulging. Ballistic tests confirmed that the hydrogel-treated fabric could stop bullets traveling faster than 300 m/s while remaining flexible and lightweight.

Another related study introduced a nanocomposite hydrogel with high toughness and high strength using Pluronic F127 Diacrylate (PF127DA) as a crosslinking agent, acrylamide as the monomer, and nano silica as an additive [131]. When applied to aramid fabric, this composite significantly improved stab resistance. Compared to untreated fabric, it increased the spike stab force by over 759.84% and the knife stab force by more than 162.04%. These findings show that hydrogel-based materials can greatly enhance both ballistic and stab protection while keeping the armor light and flexible. Other researchers developed a new type of soft body armor that works well in extreme cold, down to −30 °C [132]. Traditional Kevlar armor becomes stiff and weak at very low temperatures, which reduces its ability to absorb impact. To resolve this issue, the researchers combined Kevlar with a tough and flexible hydrogel known as PSGN, made from polyvinyl alcohol, sodium alginate, glycerol, and salt. This composite was treated through freezing and thawing, followed by soaking in salt, to improve its strength. The resulting Kevlar/PSGN-10 material showed much better puncture resistance, over 285% higher puncture force, and 302% better energy absorption than regular Kevlar at −30 °C. Despite these improvements, it remained flexible and wearable, with only a small reduction in flexibility and a moderate weight increase. It also had strong strain-sensing abilities, making it useful as both protective gear and a wearable sensor. A similar study also worked on the development of a hydrogel-based composite for soft body armor designed to enhance puncture resistance and maintain flexibility in freezing conditions. In the study, a hydrogel matrix was formed by integrating polyvinyl alcohol (PVA), sodium alginate (SA), and glycerol [133]. This mixture was laminated onto aramid fabric, enhancing energy absorption and puncture resistance, even at −30 °C. The freezing–thawing fabrication method strengthens the hydrogel structure, ensuring durability and cold stability.

Traditional strain-sensing protective clothing often comes with limitations, such as failing to maintain both protection and sensing mechanisms since most impact resistance materials focus only on protection, making them stiff and uncomfortable. On the other hand, materials for incorporating sensing properties (like carbon nanotubes, MXene, silver nanowires, and liquid metals) that are mostly expensive often compromise protection. In a recent study, researchers developed a new Kevlar/hydrogel composite that addressed the limitations described above [134]. Unlike many smart PPE materials, which focus on either protection or sensing capabilities, the study successfully integrated both features in a single composite using a cost-effective and scalable fabrication method. The inspiration for this approach was the microstructure of Rhinoceros skin, which is extremely tough because it contains 85% collagen fibers tightly packed and linked together, making it highly resistant to punctures, as shown in Figure 27a,b. Similarly, the composite fabric developed in the study combined Kevlar and hydrogel made of gelatin and ammonium sulfate ($(NH_4)_2SO_4$),

which is a soft, yet tough, material that mimics the soft tissue of skin, as shown in Figure 27c. The preparation of hydrogel starts with dissolving the gelatin in water at 65 °C for 1 h and then crosslinking it in a Teflon mold at 25 °C for 24 h, followed by soaking it in ammonium sulfate for 12 h to increase strength. The Kevlar/hydrogel composite was created by coating Kevlar with gelatin, crosslinking it for 24 h, and soaking it in ammonium sulfate again to reinforce its structure. This composite is referred to as the KGA composite (Kevlar–gelatin–ammonium sulfate). This method is low-cost and scalable because it uses a salt solution immersion method to strengthen the hydrogel and enhance its protective properties. Unlike rigid body armor, this composite remains flexible (36.76% reduced stiffness), breathable (56.81% air permeability retained), and moisture-resistant, making it comfortable for extended use. Along with these properties, this composite is a sensor capable of detecting bending movements at different angles and frequencies. This allows real-time monitoring of body motions, which is useful for intelligent PPE applications.

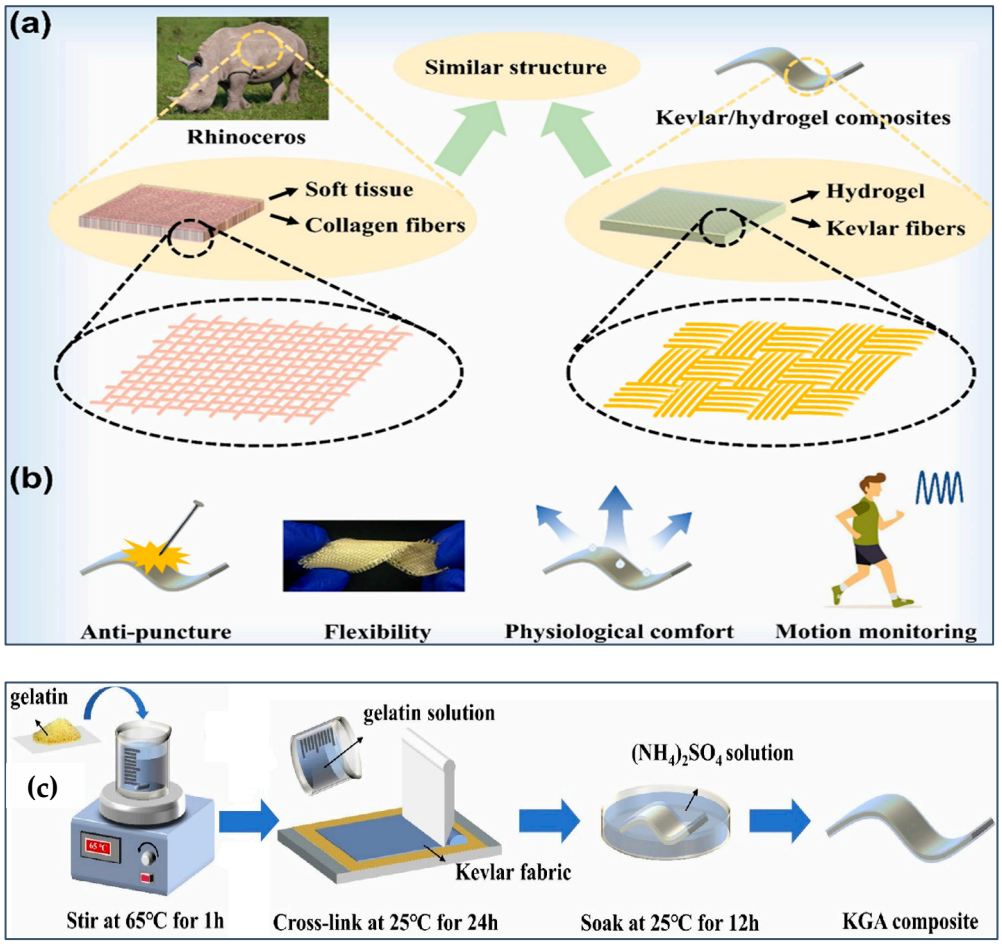


Figure 27. (**a**) Bioinspired design of Kevlar/hydrogel composites; (**b**) multifunctional properties of the Kevlar/hydrogel composites: anti-puncture, flexibility, physiological comfort, and motion monitoring; and (**c**) schematic diagram of the preparation process of gelatin/$(NH_4)_2SO_4$ hydrogels and Kevlar/hydrogel composites. Reprinted from ref. [134]. with permission from the American Chemical Society.

A novel study developed a self-growing armor using an innovative hydrogel material inspired by the natural armor of starfish [135]. The hydrogel in this armor is formed by mixing polyacrylamide (PAM) and polyacrylic acid (PAA), which is later infused with sodium acetate. When the hydrogel is exposed to external stimulation (such as temperature changes or dehydration), sodium acetate starts to crystallize on the outer layer of the

hydrogel, forming a solid protective armor. The construction of the armor is illustrated in Figure 28. This armor can repair itself after damage through a process called stimulated precipitation, where new sodium acetate crystals naturally grow on the surface of the hydrogel. This happens because the hydrogel contains dissolved sodium acetate, which can reform into solid crystals when exposed to external triggers such as temperature changes or moisture loss. When the protective layer is damaged, the hydrogel responds by allowing sodium acetate to recrystallize in the affected area, restoring the armor without the need for additional materials or intervention. This self-healing ability significantly improves the durability and longevity of the hydrogel, making it more effective for use in harsh environments.

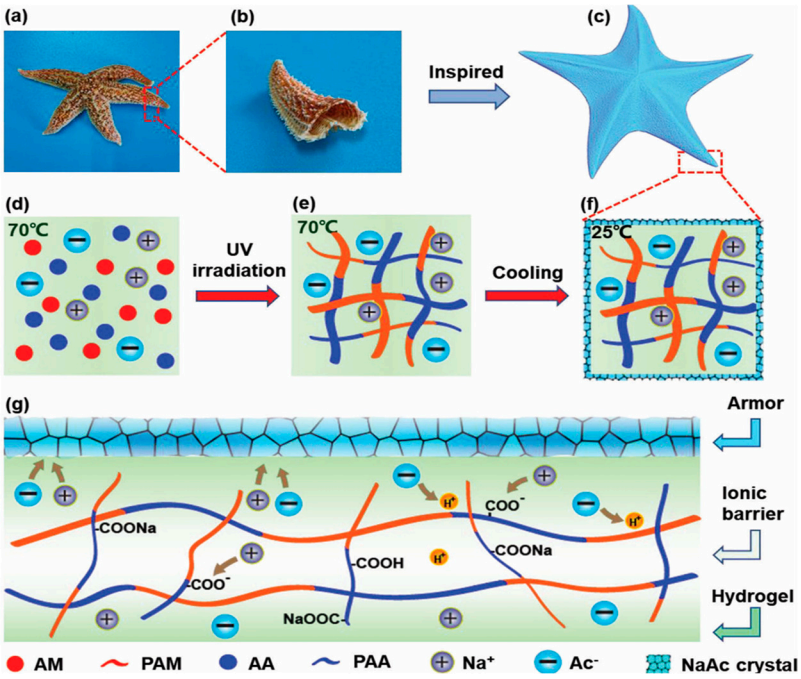


Figure 28. (**a**) Photographs of a starfish. (**b**) Photographs showing the armor of the starfish. (**c**) The armor-protective hydrogel is in the shape of a starfish. (**d**–**f**) Schematic diagram of the preparation process of armor-protective hydrogels. (**g**) Mechanism of the armor formation. Reprinted from ref. [135] with permission from Wiley.

In addition to these studies, research on hydrogel-based protective armor has been conducted [136]. In a study, green sodium lignosulfonate was mixed with polyvinyl alcohol hydrogel, creating a microphase separation structure that enhanced silver ions' adsorption. The adsorption of silver ions to hydrogel uplifts the toughness of the hydrogel to 50.7 MJ m^{-3} and enhances the ballistic performance of armor for further utilization. In another study, a hydrophobic soft body armor was developed. The mechanism of this armor works by applying a layer of hydrogel on the surface of the armor; the layer contains catechol groups that prevent the interfacial bonds with water after penetration, making this armor effective in humid conditions [137]. Another study applied (3-aminopropyl) triethoxysilane (APTES) as a binding agent to form a two-layer hydrophobic coating on the hydrogel, as shown in Figure 29 [138]. The inspiration for this approach is to mimic mammalian skin. Traditional hydrogels often suffer from water loss when exposed to air, limiting their long-term functionality in applications such as soft electronics, wound dressing, and biomedical materials. As mentioned, this limitation is addressed by a layer of a hydrophobic polymer and a layer of hydrophobic oil. This dual-layer structure acts as a shield, significantly reducing the rate of water evaporation and extending the hydrogel's usability in dry conditions. The binding agent APTES creates a strong and durable chemical

bond with the first layer of hydrogel that later reacts with steric acid (STA), forming a continuous hydrophobic second layer on the surface. To further enhance water resistance, hydrophobic oil is infused into the polymer coating, which reduces evaporation and extends its stability in dry environments. This double-hydrophobic coating effectively protects the hydrogel from drying out while maintaining its flexibility and mechanical properties.

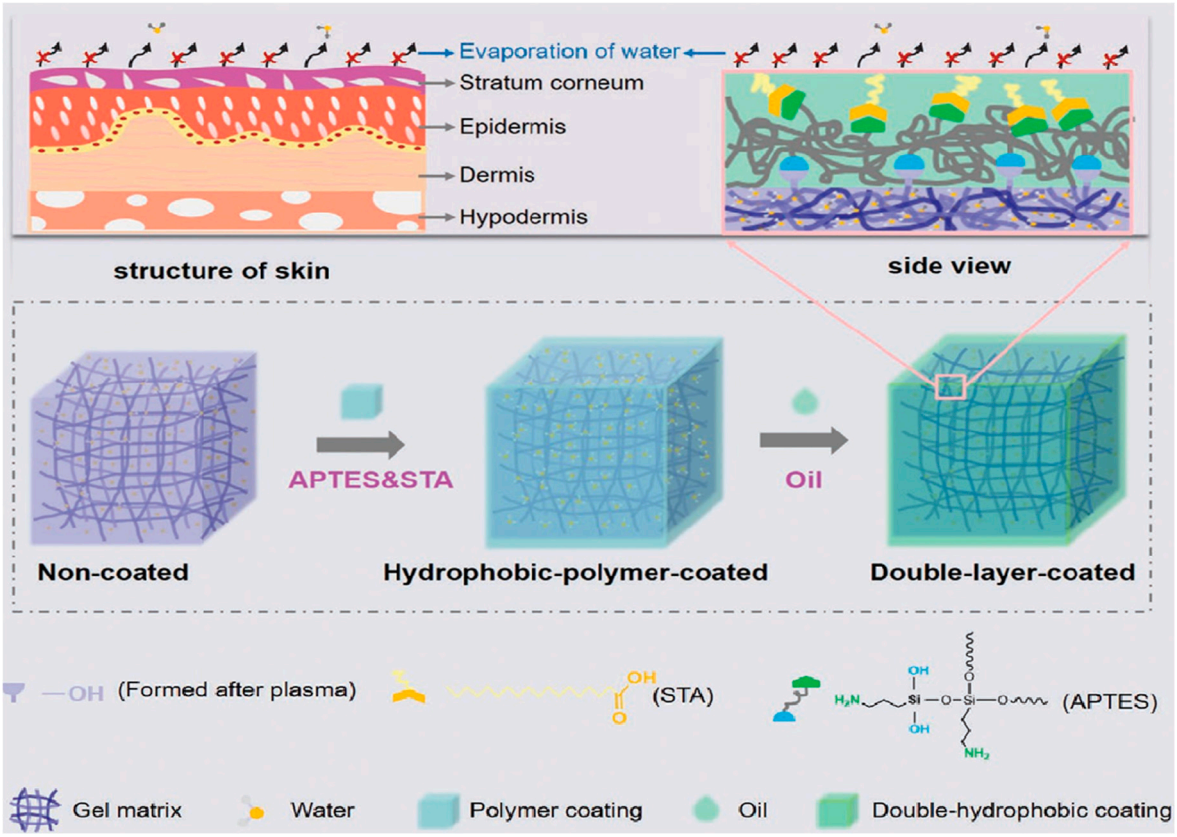


Figure 29. Schematic illustration of the skin-inspired double-hydrophobic coating encapsulated by hydrogel. One layer of oil and one layer of APTES&STA polymer coating bonded to the hydrogel surface can effectively prevent the evaporation of water from the hydrogel. Reprinted from ref. [138] with permission from Wiley.

The inclusion of self-healing properties in body armor has received attention in another study utilizing a self-healing polymer. This research utilized polyurea, a material that can repair itself through a new curing process activated by moisture at room temperature. Unlike other polymers, it does not require heat, ultraviolet light, or chemical triggers to cure [139]. This polymer forms special molecular networks that align with the tightly arranged hydrogen bonding structure within polyurea to improve its performance [140]. It increases strength, toughness, puncture resistance, and the ability to absorb energy under stress [141]. In addition, this approach also facilitates the self-healing functionalities that make it a suitable alternative for creating lightweight soft body armor. However, the current polyurea systems cure too quickly due to a fast reaction between isocyanate (-NCO) and amine (-NH_2) groups, which makes it difficult to regulate the curing process [142]. In a study, researchers addressed the limitations by designing a one-component self-healing polyurea that remains stable by introducing moisture-activated mechanisms, as illustrated in Figure 30 [143]. The study utilized polypropylene glycol-toluene diisocyanate terminated polymer (PPGTD) as the base material due to its high flexibility, durability, and strong reactivity with curing agents. This polymer consists of polypropylene glycol (PPG) for elasticity and toluene diisocyanate (TDI) to form strong polymer chains upon crosslinking.

To enable latent curing and self-healing properties, the researchers incorporated a Schiff base reaction, where amine (-NH_2) groups in the curing agents are temporarily blocked using an aldehyde (e.g., isobutyraldehyde). This prevents premature polymerization, keeping the material stable until application. The self-healing mechanism activates when the material absorbs moisture, reinitiating the Schiff base reaction and reforming broken bonds, allowing up to 98% strength recovery within 48 h. The study paved the way for next-generation self-healing materials to enhance personal protection and advanced technology integration.

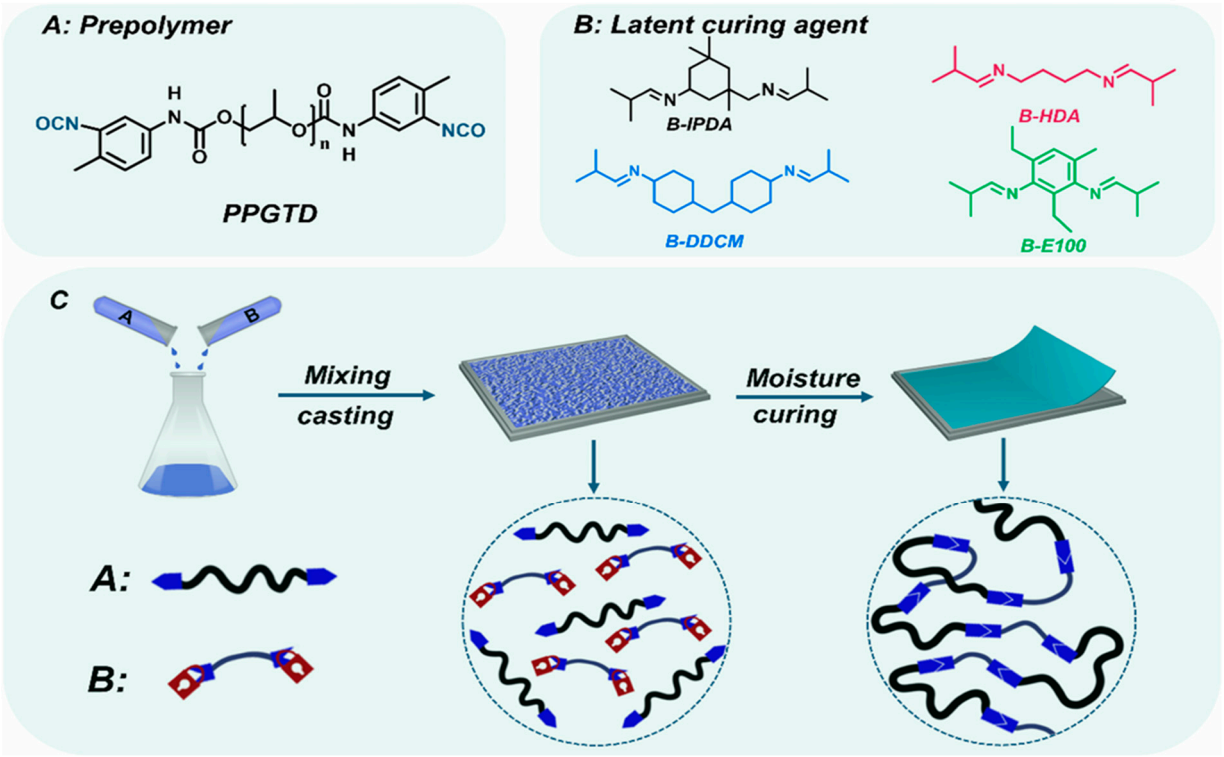


Figure 30. Preparation of one-component polyurea. (**C**): (**A**) and (**B**) mixing. Reprinted from ref. [143] with permission from the American Chemical Society.

Usually, a typical soft body armor made of high-performance fibers like Kevlar works effectively for around five years [144]. Over time, the protective ability of soft body armor panels deteriorates because the coating material, like resins on fibers, wears out, causing a reduction in ballistic and protective performance [145]. However, in a novel study, researchers explored a practical solution to restore the performance of aged Kevlar-based body armor rather than discarding it [146]. The study involved coating old Kevlar panels with polyaspartic polyurea and comparing them against both untreated aged panels and newly manufactured ones. Three sample types were used: untreated old Kevlar, coated old Kevlar, and new Kevlar panels. Each was prepared in single- and multi-layer configurations by bonding fabric layers with a polyurea film. The coated panels showed improved puncture resistance, mechanical strength, and water resistance compared to the untreated ones. Although the coating increased thickness and weight, flexibility remained acceptable, and stretchability saw only a minor reduction. New Kevlar samples performed the best overall, but the coated old panels closely matched their performance, suggesting that polyaspartic polyurea is an effective treatment for renewing soft body armor. With a similar approach, another study also evaluated the polyurea coating's performance on ultra-high-molecular polyethylene (UHMWPE) [147]. The primary focus was reducing Back Face Deformation (BFD), which occurs due to the inward deformation toward the

wearer upon impact, causing injuries even if a bullet does not penetrate the armor. Four test specimens were prepared as target plates by varying the positions of polyurea coating, such as front-face coating, where polyurea was applied only on the side facing of the projectile, back-face coating, where polyurea applied on the side closest to the wearer, coating on both surfaces, where polyurea was applied on both sides of the UHMWPE panels, and control samples, which were created without any polyurea coating, as shown in Figure 31a–d. The impact performance test of these armors was conducted by shooting small steel balls of 8 mm diameter at speeds varying from 200 m/s to 450 m/s using an air-powered gun. The high-speed photography images analyzed the target plates' deformation, as shown in Figure 31e. While the front-face coating showed a better bulletproof effect, absorbing more impact energy, a large deformation appeared on the plate.

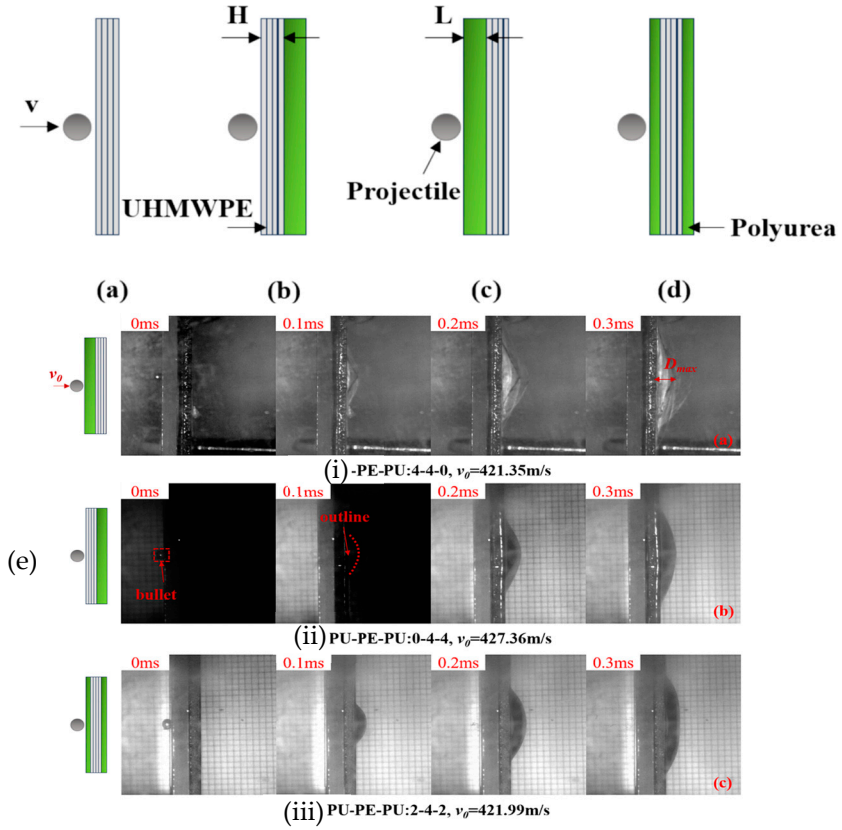


Figure 31. Classification of target plates: (**a**) control group; (**b**) back-face coating; (**c**) front-face coating; (**d**) coating on both surfaces; and (**e**) high-speed photography pictures of typical times of different polyurea coating positions at similar penetration speeds. Reprinted from ref. [147] with permission from ScienceDirect.

On the other hand, both the back-face and surface-coated target plates showed less deformation on the plate, providing better protection to the wearer from blunt force trauma. However, the front-face-coated plates resisted the higher-speed bullet from penetration, unlike the back-face-coated plates, as shown in Figure 32a,b. The study's findings were strengthened by conducting post-impact computed tomography (CT) scans to clearly see internal structures and damage inside the armor without physically cutting it open, as shown in Figure 32c.

An innovative approach to creating lightweight body armor is the integration of STF and polyurea [148]. The newly designed composite is prepared with Kevlar fabric coated with a diluted polyurea solution made from aromatic isocyanate and amine resin, creating strong composite layers. STF infused with silica nanoparticles (PEG) is carefully filled into

paper honeycomb structures, sealed, and placed behind the Kevlar/polyurea composites to enhance impact resistance. This composite with a thin single-layer STF-filled honeycomb panel with 2 mm thickness showed a performance equivalent to that of ten standard Kevlar layers. The findings were supported by stab resistance testing via drop hammer puncture tests and standardized ballistic evaluations in accordance with NIJ 0101.06 Classes II and IIIA, followed by measuring the Back Face Deformation upon bullet impact. Overall, the new hybrid armor demonstrated a 17% reduction in thickness and weight compared to traditional armor while maintaining equivalent protection levels.

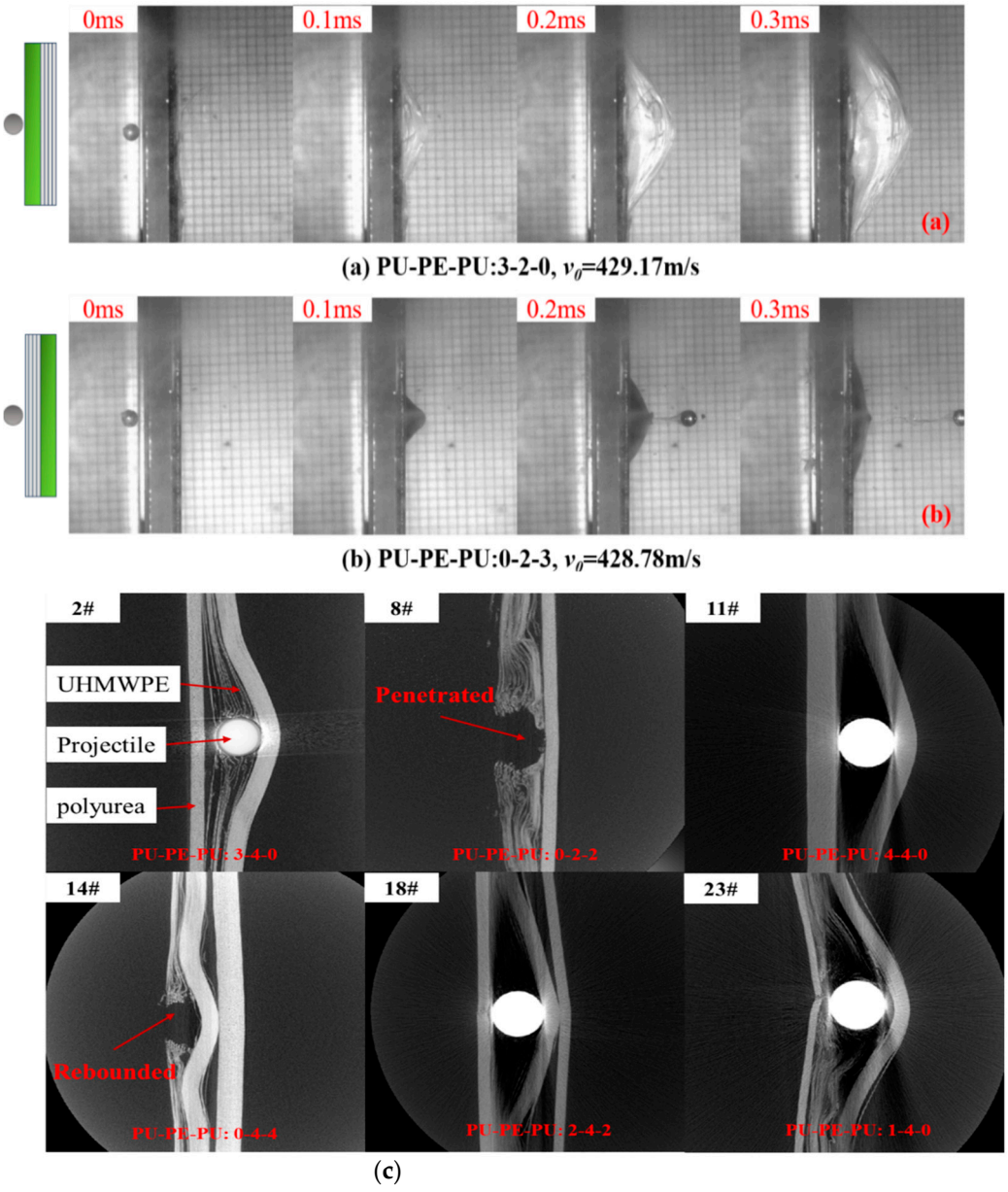


Figure 32. (**a**,**b**) Typical high-speed photography images of different polyurea coating positions at similar penetration speeds and (**c**) CT scanning of the target plate under typical working conditions. Reprinted from ref. [147] with permission from ScienceDirect.

To consolidate the insights from recent developments in composite materials for body armor, a conceptual diagram is illustrated in Figure 33. It represents the relationship between material types, fabrication techniques, and performance outcomes in body armor systems. Materials such as shear thickening fluids (STFs), hydrogels, polypyrrole (PPy), nanocomposites, and self-healing polymers offer distinct functional benefits when applied

using appropriate techniques, like multi-layering, coating, infusion, three-dimensional shaping, or moisture-activated curing. These methods facilitate enhanced ballistic resistance, flexibility, self-healing, stab protection, and even environmental adaptability in soft body armor. To further contextualize these developments, Figure 34 provides a generalized summary of the current maturity levels of key material technologies used in soft body armor. This visual analysis categorizes innovations such as shear thickening systems, hydrogel-based composites, conductive polymers, and smart textile systems based on their advancement and level of integration in existing designs. While shear thickening systems and certain nanocomposites are approaching technological maturity, other promising approaches, such as sensor-integrated fabrics, hybrid foam composites, and multifunctional smart textiles, remain in the early stages of development, highlighting clear research gaps. These include the need for improved multifunctionality, long-term durability under extreme conditions, and adaptive performance in varied environments. As research continues to evolve, such integrated material and structure strategies are expected to play a pivotal role in shaping the next generation of lightweight, adaptive, and high-performance body armor solutions.

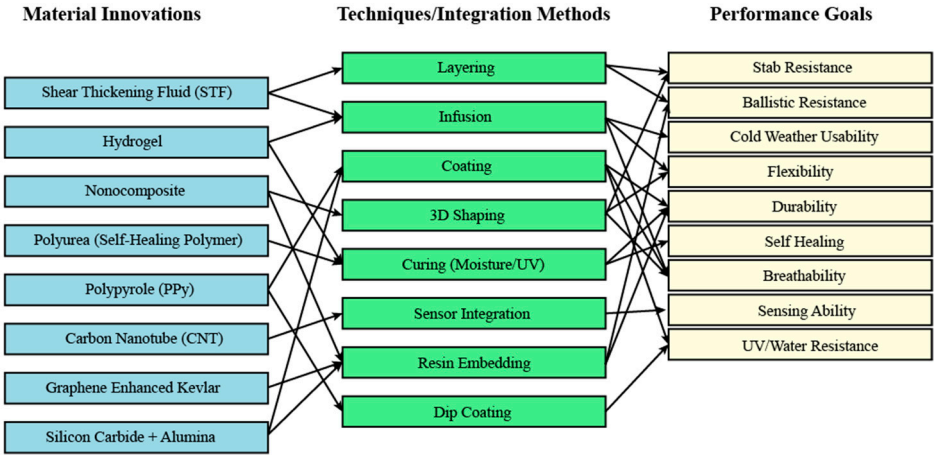


Figure 33. Conceptual map linking material innovations, fabrication techniques, and key performance goals in soft body armor development.

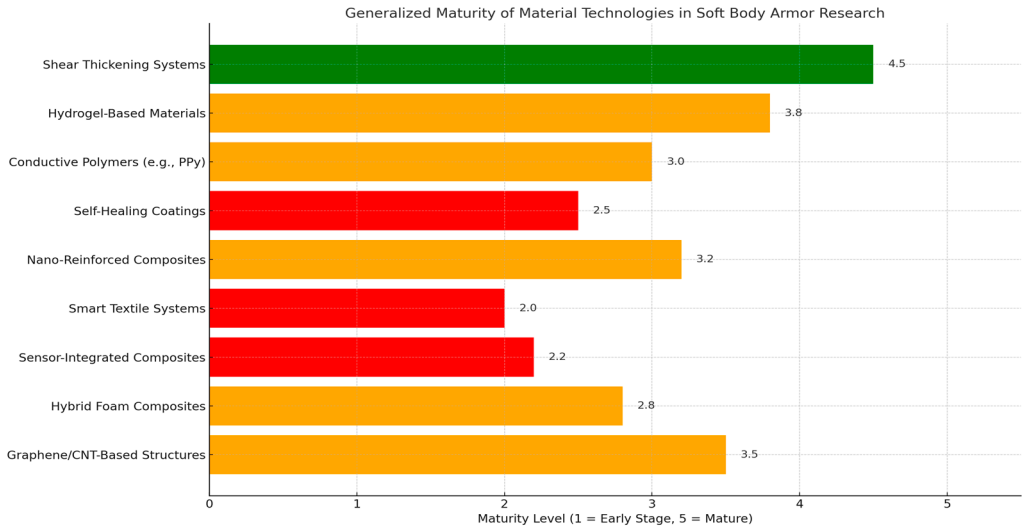


Figure 34. Summary of emerging material technologies in soft body armor, showing current development stages and highlighting research gaps in multifunctionality and durability.

5. Evolutions of Standards and Regulations for Ballistic Testing

5.1. Overview of Different Body Armor Standards

Body armor testing standards are fixed procedures that are created to evaluate the performance of protective clothing under certain realistic threat conditions. These standards are formulated to establish minimum performance requirements and test methods for the ballistic resistance of body armor [149]. These tests typically assess protection against ballistic, stab, and spike threats, where national or international bodies set the assessment criteria and procedures.

5.1.1. National Institute of Justice (NIJ) Standards

NIJ is a US-based organization that mainly focuses on advancing public safety and the justice system through scientific research and evidence-based practice. This institute first introduced its official standards for body armor testing in 1972 and set the groundwork for the evaluation method of ballistic impact-resistant materials for safety and effectiveness. Since then, the standard has been updated more than five times to cope with the evolution of body armor and test methods [150].

NIJ Standard 0101.01 and NIJ Standard 0101.04

The first updated and formal version was published in 1982 as NIJ Standard-0101.01 to measure the performance of ballistic body armor, typically dedicated to helmets. A major advancement occurred with the release of NIJ Standard-0101.04 in 2000, which became one of the most widely used standards for testing the ballistic resistance of body armor [151]. This standard was developed with six levels of protection, as shown in Table 5, with Levels I, IIA, II, and IIA for protection against handgun threats and Levels III and IV for protection against high-velocity rifle rounds. In this standard, Roma Plastilina No. 1 clay is used as backing material for a homogenous block of nonhardening clay, and an oil-based modeling clay is placed in contact with the armor panel during ballistic testing. This backing material simulates a human who is strapped with body armor in a fixed way, as shown in Figure 35a. Upon firing the bullets at the body armor, an indentation is formed on the backing material. As shown in Figure 35b, a test barrel is set up for the ammunition, and the baling material and electronic materials are mounted on the stand. The shooting location on the vest is predefined, as shown in Figure 35c. The depth of the backing material is measured by Back Face Signature (BFS), and a value under 44 mm was considered acceptable. NIJ-0101.04 also included V50 ballistic limit velocity testing, which measured the velocity at which 50% of the bullets penetrated the armor and 50% were stopped. Despite being outdated, this standard is still used internationally due to its simpler structure and the inclusion of ammunition types relevant to military applications [152].

Table 5. Ballistic-resistant armor threat level for NIJ Standard 0101.04 [151].

Threat Level	Caliber	Bullet	Mass (g)
I	0.22 long rifle; 0.380 ACP	Lead round nose; FMJ round nose	2.6; 6.2
IIA	9 mm; 0.40 S&W	FMJ round nose; FMJ	8.0; 11.7
II	9 mm; 0.357 Magnum	FMJ round nose; jacketed soft point	8.0; 10.2
IIIA	High velocity 9 mm; 0.44 Magnum	FMJ round nose; jacketed hollow point	8.0; 15.6
III	7.62 mm rifle	Full metal jacket	9.6
IV	0.30 caliber rifle	Armor-piercing	10.8

ACP, automatic Colt pistol; S&W, Smith and Wesson; and FMJ, full metal jacket.

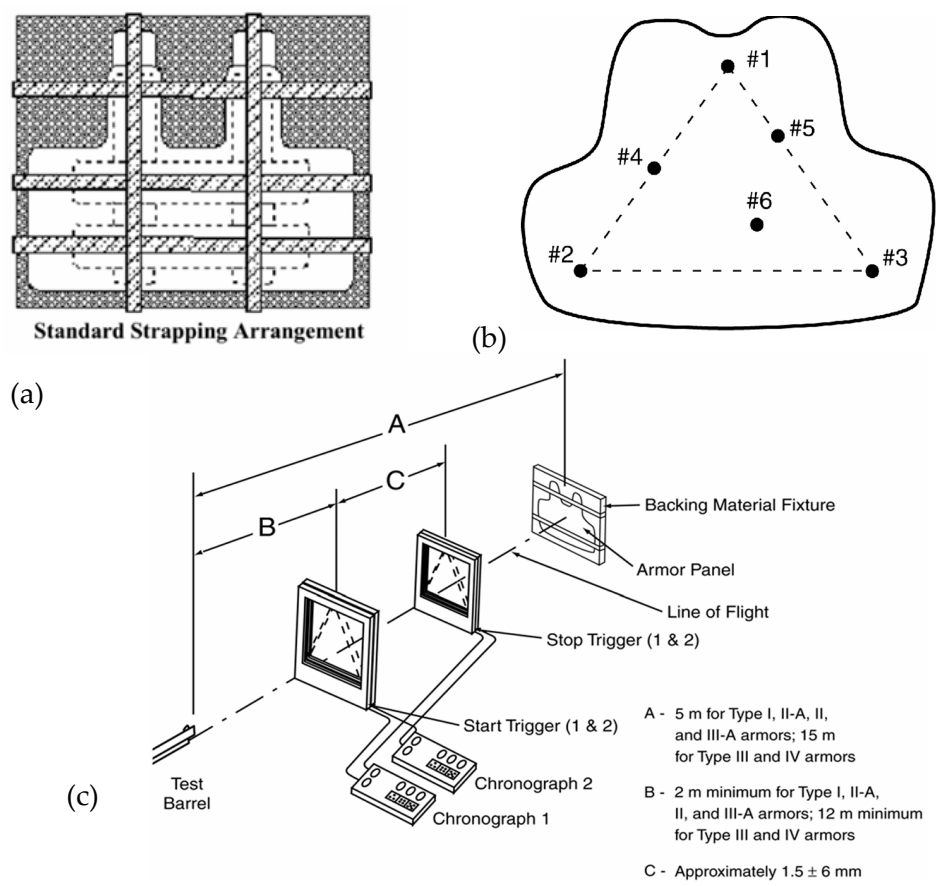


Figure 35. (**a**) Acceptable strapping method [151], (**b**) general armor panel impact locations (front and back) [152], and (**c**) test range configuration [151].

NIJ Standard 0101.06

In 2008, the NIJ Standard 0101.06 was introduced to improve the accuracy and reliability of body armor testing [149]. One of its key updates was the addition of pre-conditioning requirements for soft body armor. Under this protocol, armor must undergo ten days of exposure to heat, humidity, and mechanical wear before ballistic testing. Specifically, the armor is conditioned at 65 degrees Celsius with 80 percent relative humidity and subjected to mechanical tumbling or drop testing to simulate real-life usage and aging. In contrast, hard body armor is exposed to more rigorous procedures, including thermal cycling, impact drop tests, and durability evaluations to assess long-term structural integrity. A notable change was also made to the threat level classification. For example, in Levels IIIA, the 9 mm full metal jacket was replaced with a 357 full metal jacket round, aligning the standard more closely with law enforcement needs rather than military threats. The standard refined the armor classification system into five protection levels: Type IIA, Type II, Type IIIA, Type III, and Type IV, where these levels range from protection against low-velocity handgun rounds to armor-piercing rifle threats. Another significant addition was the inclusion of a "Special Type" category. This allows users to request armor tailored to non-standard threats such as foreign ammunition, custom high-velocity rounds, or unique environmental conditions. While the user can specify the type of ammunition and velocity, all other testing protocols must still follow the standard guidelines. In terms of testing methodology, the standard placed greater emphasis on precise velocity control, accurate shot placement, and detailed procedures for evaluating both perforation and Back Face Signature, commonly referred to as P-BFS. For the armor to pass, the Back Face Signature must not exceed 44 mm, ensuring that even if the bullet does not penetrate, the wearer is protected from severe blunt force trauma. Additionally, like previous versions, this standard includes the V50

ballistic limit velocity test, which helps determine the velocity at which a projectile has a 50 percent chance of penetrating the armor.

NIJ Standard 0101.07

NIJ Standard-0101.07 is the latest version that was introduced in 2023 [144]. Significant changes have been made to the previous testing methodology, classification system, and laboratory practices. Unlike previous versions, this standard incorporates new shot placements, including angled or oblique shots such as the 45° shot at the top center of soft armor, to simulate threats that may bypass protection at vulnerable edges, as shown in Figure 36. These placements simulate realistic scenarios where bullets might strike vulnerable areas of the armor. For hard armor, the standard now requires testing at the top curved section of the plate, also known as the crown, which is a common structural weak point. These changes allow more complete understanding of how armor behaves under actual use.

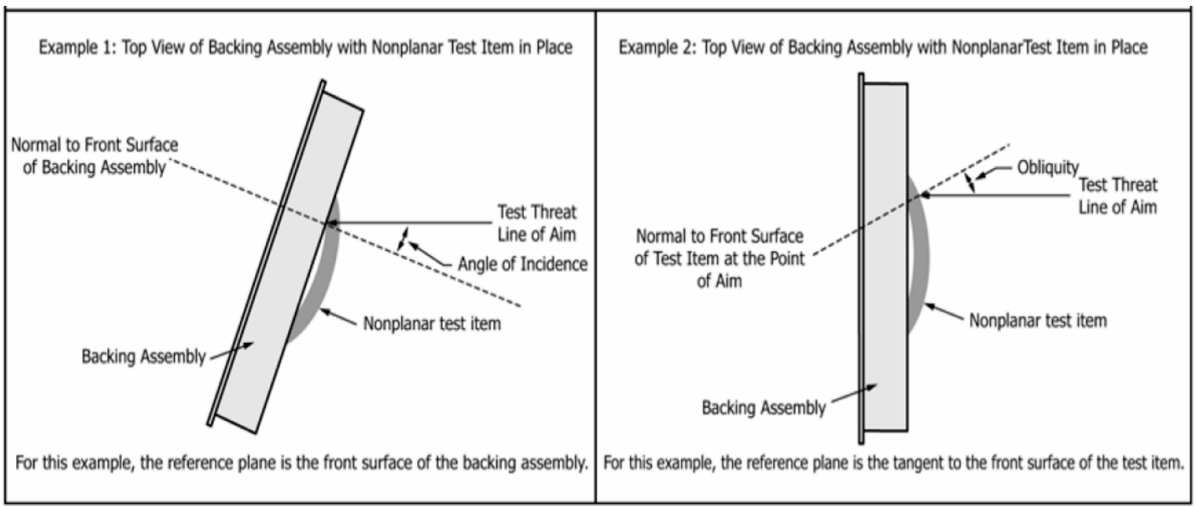


Figure 36. Examples showing angle of incidence and obliquity using a clay block backing assembly [144].

The classification of the ammunition types and corresponding velocity requirements has been moved to separate but related documents called NIJ Standard 0123.00. The traditional armor levels, such as Levels IIA, II, IIIA, III, and IV, were replaced with a simplified system, as shown in Table 6. The handgun threats are now classified as HG_1 (designed to stop lower-energy handgun rounds, such as 9 mm) and HG_2 (which protects against higher-energy rounds like the 0.44 Magnum). In addition, rifle threats are grouped under RF_1, RF_2, and RF_3. RF_1 covers protection against standard rifle rounds, such as 7.62 mm NATO FMJ, and RF_3 addresses high-level threats such as 0.30-06 armor-piercing ammunition. The newly added RF_2 level bridges the gap between RF_1 and RF_3 by offering protection against intermediate rifle threats that are too powerful for RF_1 but do not require the heavy protection of RF_3. The standard aligns more closely with ASTM testing protocols, especially those from Committee E54, which governs protective equipment standards for homeland security. The National Institute of Justice (NIJ) has also worked along with ASTM Committee E54 to unify ballistic body armor testing standards, as outlined in NIJ Standard 0101.07, which references several key ASTM E54 committee standards. These protocols specify detailed procedures for sample preparation, shot placement, backing material calibration (e.g., Roma Plastilina clay or equivalent), and environmental conditioning, such as temperature, humidity, and impact simulation. For example, published ASTM standards include E3004-22 (clay block preparation), E3017-17a (penetration and Back Face Deformation), E3110/E3110M-22 (ballistic limit data collection), E3112/E3112M-20

(ballistic-resistant product testing), and E3005 (body armor terminology). These criteria help to meet NIJ's objective for consistent and predictable ballistic resistance testing from facility to facility. Furthermore, gender-specific testing (which will be discussed in Section 4.2 in detail) is now supported using molded clay appliques that better replicate female body shapes, helping ensure that female-specific armor designs are evaluated under anatomically realistic conditions.

Table 6. Ballistic-resistant armor threat level for NIJ Standard 0101.07 [144].

Threat Level	Designation	Caliber	Bullet	Mass (g)	Velocity (m/s)
Handgun Level 1	HG_1	9 mm; 0.40 S&W	FMJ round node: FMJ	8.0; 11.7	332; 312
Handgun Level 2	HG_2	0.357 Magnum; 0.44 Magnum	Jacketed soft point: SJHP	10.2; 15.6	427
Rifle Level 1	RF_1	7.62 mm NATO	Full metal jacket (M80)	9.6	838
Rifle Level 2	RF_2	Intermediate rifle calibers	Steel core or enhanced FMJ	--	--
Rifle Level 3	RF_3	0.30-06 caliber rifle	Armor-piercing (M2 AP)	10.8	878

5.1.2. HOSDB/CAST (UK) Standard

In the United Kingdom, the Home Office Scientific Development Branch (HOSDB), now known as the Centre for Applied Science and Technology (CAST), issued standards and testing methods for body armor intended for UK law enforcement [153]. This standard provides minimum performance requirements for body armor to protect UK law enforcement officers against threats from firearms (ballistic), knives (edged weapons), and spikes (non-edged weapons). The most recent version of this standard was published in 2017 and reflects the latest operational needs and technological developments since the original standard in 1993, with revisions in 1999, 2003, and 2007. The standard categorizes the threat level as a lower level, as shown in Table 7, which includes HO_1 and HO_2, which address common handgun threats. In contrast, higher levels (HO_3, HO_4, and SG_1) represent more extreme threats, such as rifles or shotguns.

Table 7. Classification of protection levels for ballistic body armor of the CAST standard [152].

Level of Protection	Ammunition Type	Bullet Mass (Grams/Grains)	Test Velocity (m/s)	Test Distance	Maximum Allowed BFS (Indentation)	Intended Threat Level
HO_1	9 mm FMJ (Full Metal Jacket) 9 mm JHP (Hollow Point)	8.0 g (124 grain)	365 ± 10	5 m	Mean: 44 mm	Low-velocity handgun threats (standard pistols)
HO_2	9 mm FMJ 9 mm JHP	8.0 g (124 grain)	430 ± 10	5 m	Single shot: 44 mm	Higher-velocity handgun threats
HO_3	7.62 mm NATO Ball (Radway Green $L_{44}A_1/L_2A_2$) 7.62 × 39 mm surrogate (e.g., AK-47)	9.3 g (144 grain) NATO	NATO: 830 ± 15	10 m	Mean: 44 mm	Intermediate rifle threats (military-grade rifles)
HO_4	SAKO 0.308 Winchester (Barnes TSX BT or similar)	7.9 g (122 grain) Surrogate	Surrogate: 705 ± 15	10 m	Single shot: 44 mm	High-threat rifle ammunition (sniper rounds) must also meet HO_3 criteria

Table 7. *Cont.*

Level of Protection	Ammunition Type	Bullet Mass (Grams/Grains)	Test Velocity (m/s)	Test Distance	Maximum Allowed BFS (Indentation)	Intended Threat Level
SG_1	12-Gauge Shotgun Slug (Winchester 1 oz. Rifled)	10.7 g (165 grain)	820 ± 15	10 m	Mean: 25 mm	Heavy shotgun projectile threats
Special Levels	Examples: 0.357 Magnum (Soft Point) 5.56 × 45 mm NATO SS109 Federal Tactical Bonded 5.56 mm	28.4 g (1 oz.)	435 ± 25	Specific per ammunition type	Single shot: 30 mm	Customized or unique operational threats

The standard categorizes body armor into unformed armor (flat panels commonly used for male users), formed armor (shaped panels typically designed for female anatomy), plates (rigid armor offering higher ballistic protection, including rifles and shotguns), and extended coverage panels (additional protection for the shoulders, groin, and neck). Critical performance metrics, notably the Back Face Signature (BFS), include using Roma Plastilina® No. 1 clay as the backing material. During testing, the armor is mounted with the backing material, where a 45° angle shot is first performed, followed by rotating the armor to the right angle, as shown in Figure 37.

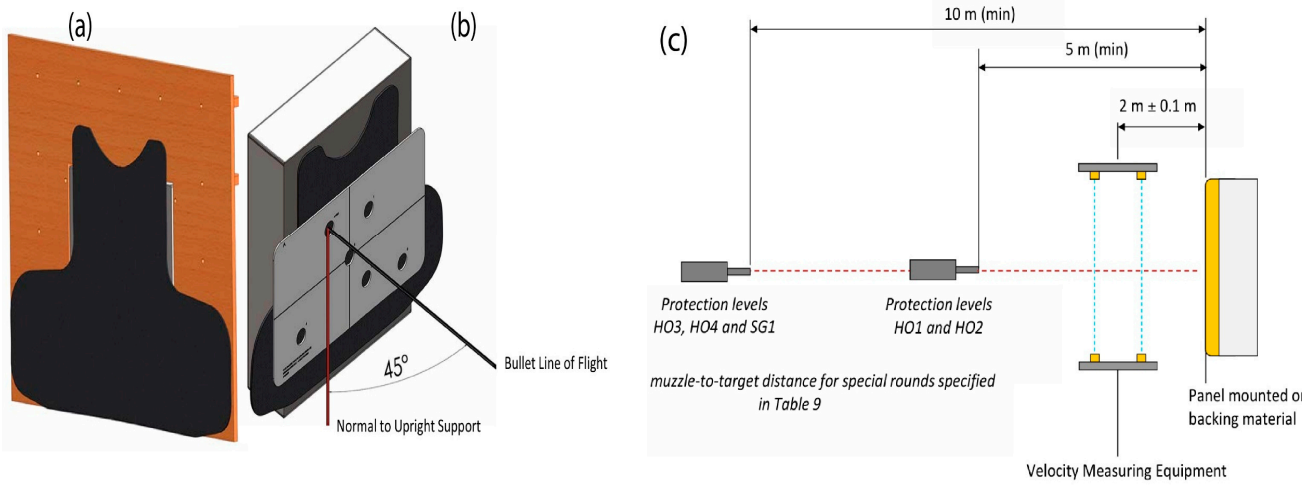


Figure 37. (**a**) Ballistic tray mounted with extension support. (**b**) Images showing the rotation of the protective panel and backing material about the shot normal to achieve a 45° angle. (**c**) Schematic showing a standard ballistic test configuration [152].

For handgun protection (levels HO_1 and HO_2) and stronger threats like rifles and shotguns (levels HO_3, HO_4, and SG_1), the allowed average BFS values are 44 mm and 25 mm (with a single-shot limit of 30 mm), respectively. These limits help provide complete protection against both bullet penetration and blunt force trauma.

5.1.3. VPAM Standard

The German-based VPAM standard, first introduced in 1999, is widely accepted in Europe, offering a comprehensive and realistic approach to evaluating ballistic protection. Unlike some standards that rely only on fixed testing conditions, VPAM emphasizes real-world weapon threats by considering projectiles' type and energy and how frequently they are encountered in actual scenarios. It encompasses testing for both soft and hard armor and evaluates different threat levels using defined projectile types and velocities. The standard

categorizes weapons into four threat levels based on bullets' energy and energy density, recognizing that materials react differently depending on the type of impact, as shown in Table 8. VPAM is unique because it also emphasizes the protection probability, which is the likelihood that the armor will stop a bullet at a given speed. It uses mathematical models to predict outcomes based on many tests, not just pass/fail shots. This is especially useful for manufacturers aiming for high safety margins. The standard also outlines how many shots are required for reliable results and how test objects should be set up, including details about the shooting distance and projectile velocity [153].

Table 8. Classification into threat classes [153].

Threat Class	Energy	Energy Density	Common Calibers
I up to 250 J or up to 5 J/mm^2	22 short 22 long 22 L.R. common calibers 32 S.&W. 32 S.&W. long 6.35 Browning 7.65 Browning 9 mm Brown. short	22 short 22 long 32 S.&W. 32 S.&W. long 44 S.&W. Spl. 6.35 Browning 7.65 Browning 9 mm Brown. short	22 short 22 long 32 S.&W. 32 S.&W. long 6.35 Browning 7.65 Browning 9 mm Brown. short
II up to 500 J or up to 8 J/mm^2	22 Win. Mag. 38 Spl. 44 S.&W. Spl. 45 Auto 7.65 Parabellum 9 mm Brown. long 9 mm Luger 9 mm Makarov	22 L.R. 38 Spl. 40 S&W 45 Auto 45 Colt 9 mm Brown. long 9 mm Luger 9 mm Makarov	38 Spl. 45 Auto 9 mm Brown. long 9 mm Luger 9 mm Makarov
III up to 750 J or up to 11 J/mm^2	10 mm Auto 357 SIG 38 Super Auto 40 S &W 45 Colt 7.62 × 25 Tokarev 9 × 21	10 mm Auto 357 SIG 38 Super Auto 7.65 Parabellum 9 × 21	10 mm Auto 357 SIG 38 Super Auto 9 × 21
IV higher than 750 J or higher than 11 J/mm^2	357 Magnum 41 Rem. Mag. 44 Rem. Mag.	357 Magnum 41 Rem. Mag. 44 Rem. 7.62 × 25 Tokarev 22 Win. Mag.	357 Magnum 41 Rem. Mag. 44 Rem. Mag.

5.1.4. ISO/FDIS 14876-1

The ISO/FDIS 14876-1 standard [154], first developed in 2002, is a globally recognized framework that outlines the general requirements for body armor. This standard is part of a larger system developed by the International Organization for Standardization (ISO) in collaboration with the European Committee for Standardization (CEN). It is divided into four parts: bullet resistance, knife stab resistance, needle/spike resistance, and general requirements. ISO 14876-1 defines what body armor is, how it should be labeled, what kind of threats it should protect against, and how to test it. It includes details on sizing, ergonomic design, areas of required protection, and product marking. The standard also classifies armor into performance levels based on the threat level it can withstand. It also provides methods for testing the armor in realistic conditions using bullets, knives, or spikes. Importantly, this ISO standard emphasizes that body armor cannot guarantee full protection in every situation, but rather effectively reduces the severity of injuries. One of the key features of this standard is its focus on both functionality and comfort, ensuring that

body armor is not only protective but also wearable during routine tasks. The document also acknowledges the need to update and adapt testing methods as new types of threats emerge. Additionally, while military and police-specific armor may fall outside some European regulations, this standard still guides the assessment of their performance [155].

The comparison of global body armor standards presented in Table 9 helps to clearly understand the differences in classification, protection levels, testing procedures, and material requirements. Standards from the United States, the United Kingdom, Germany, and international bodies like ISO each follow unique methods and assessment criteria based on the type of threats they are designed to counter. For example, while the NIJ standards are widely used in the United States, with clear updates across decades, the UK CAST standard focuses on law enforcement needs, and the VPAM standard in Europe emphasizes realistic scenarios and mathematical probability. The ISO standard provides a balanced and globally accepted guideline that also values comfort and usability, along with protection. This comparison highlights how different testing approaches have evolved to match the demands of safety, usability, and technological progress.

Table 9. Comparison of key international body armor standards.

Standard	Origin	Year Introduced	Protection Levels	Key Features	Backing Material
NIJ 0101.04	USA	2000	Level I to IV	Six levels, V50 test, BFS < 44 mm, widely used	Roma Plastilina No. 1 clay
NIJ 0101.06	USA	2008	Type IIA to IV + Special Type	Pre-conditioning, Special Type, refined threat levels	Roma Plastilina No. 1 clay
NIJ 0101.07	USA	2023	HG_1, HG_2, RF_1 to RF_3	Oblique shots, new level system (HG/RF), gender-specific testing	Molded clay appliques
HOSDB/CAST	UK	1993 (latest 2017)	HO_1 to HO_4, SG_1, Special Levels	Covers ballistic, knife, and spike threats; shaped panels; BFS < 44 or 25 mm	Roma Plastilina No. 1 clay
VPAM	Germany	1999	Class I to IV (based on energy and energy density)	Energy density-based classification; protection probability modeling	Custom setup depending on the threat
ISO/FDIS 14876-1	International (ISO/CEN)	2002	Bullet, knife, and spike resistance are defined	General requirements; ergonomic design; realistic testing methods	Flexible (realistic simulation)

5.2. Improved Body Armor Standards for Female-Oriented Body Armor

The increasing number of female personnel as first responders and the demand of making gender-specific body armor also prompted the modification of the standards to address the evaluation of female body armor [155]. It is evident that the latest version of NIJ standard 0101.7 incorporates specific testing methods for nonplanar (curved) soft armor panels designed for female wearers. Unlike the traditional flat panel testing, NIJ 0101.07 now includes clay appliques to simulate the curvature of the female torso better. This ensures that curved panels make proper contact with the backing material during testing, allowing for more realistic evaluations of ballistic performance. In addition, NIJ 0101.07 introduced new shot placements aimed at identifying unique vulnerabilities to shaped panels, such as oblique-angle shots near the top center of the panel, as shown in Figure 38. This responds to evidence showing that bullets hitting the top edge of curved

armor at certain angles might deflect into unprotected areas if all layers are not properly engaged. NIJ standards also now explicitly recognize three categories of armor based on gender: male, female, and gender-neutral. Female-specific soft armor often features curved ballistic panels to accommodate the bust and reduce underarm gaps. These design changes improve comfort and ensure that the armor offers full protection across critical zones.

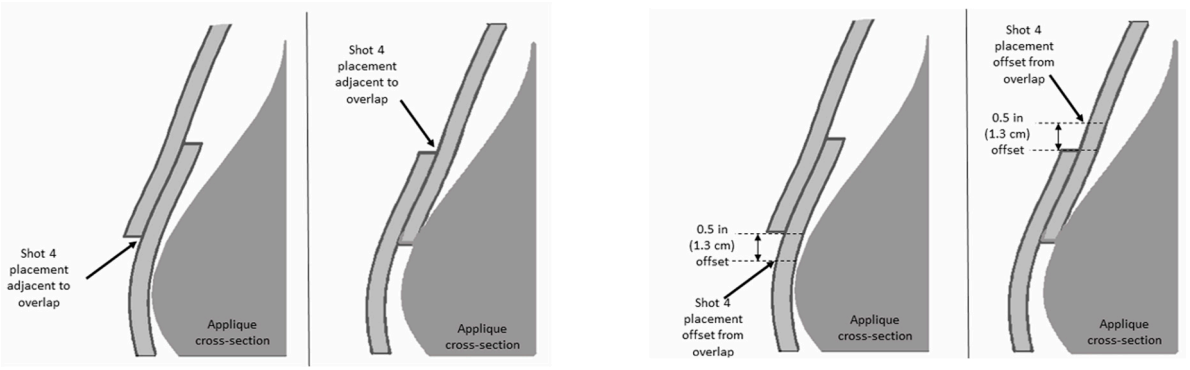
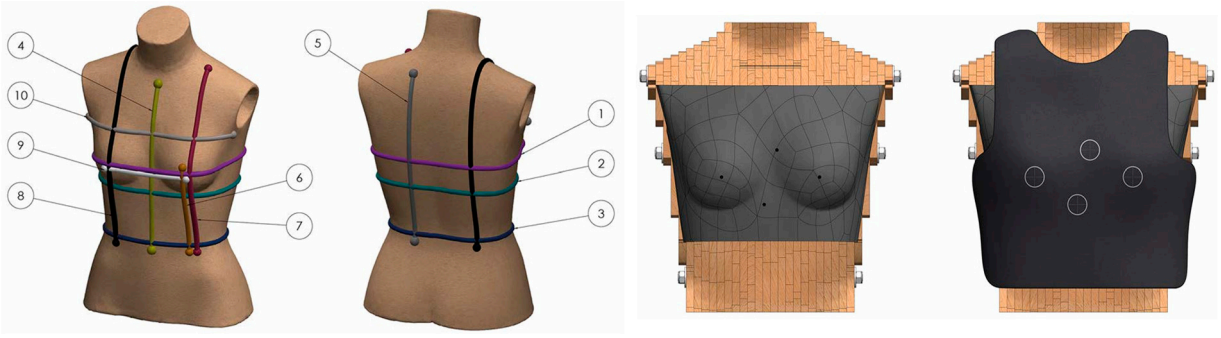


Figure 38. Examples of shot placement in regions of horizontal overlap [144].

Gender-specific testing methods are also prioritized in HOSDB/CAST standards, where the testing sample has a specific armor shape that is used for female users. The standard provides detailed dimensions for both small and large female torso forms, including bust circumference, shoulder height, and waist-to-waist measurements, as shown in Figure 39a. Additionally, formed armor is tested differently from unformed (flat) armor. While unformed armor is evaluated on flat clay blocks, formed armor is assessed using shaped backing materials using Plastiline® 40, which better mimics the female anatomy. The specimen is mounted on a wooden bust holder that simulates the female torso, as shown in Figure 39b. This provides more accurate Back Face Signature (BFS) readings and other safety metrics, which are essential for gauging blunt trauma effects [152]. In terms of VPAM Standards, although it was not originally designed for gender-specific testing, its flexible and data-driven approach allows for adjustments based on female anthropometric needs, making it a valuable tool for inclusive armor development. VPAM acknowledges that materials respond differently to projectile energy and density, making it especially useful for tailoring armor to the unique body shapes and mobility needs of female users.



(**a**) (**b**)

Figure 39. (**a**) Dimensioned female torso and (**b**) standard shot pattern locations marked on formed armor [152].

6. Challenges and Future Implications

6.1. Challenges

6.1.1. Challenges of Female Soft Body Armor Panel Design

Historically, soft body armor design has been dominated by male-centric standards, with initial designs primarily based on anthropometric data from military service members [59]. These anthropometric data set the fundamental guiding principle for the development of the product to ensure compatibility between the body armor and the user's body dimensions [156]. Typically, these dimensions include the measurement of height, chest circumference, bust circumference, waist circumference, and hip circumference [157]. This list expands with continuous studies, adding more anthropometric measurements like upper arm length and circumference, hip circumference, and waist circumference. The addition of these measurements enhances the fit of vest components, such as arm protectors, cummerbunds, thigh protectors, and groin locks [59]. While these anthropometric measurements serve as the foundation for body armor design, they primarily reflect male body proportions [158]. The gradual inclusion of females into the profession that used to be male-only, where protective clothing was mandatory, has brought attention to critical issues regarding the design and fit of body armor [15]. Females exhibit distinct anthropometric characteristics and measurements compared to their male counterparts [159]. The anthropometric differences between males and females significantly impact the design and fit of body armor. Males are, on average, 13 cm taller and 14–18 kg heavier than females [37,38]. Females have a greater overall fat percentage, with more fat distributed in the abdominal and hip areas, resulting in a wider waist-to-hip ratio.

In contrast, males exhibit a higher muscle-to-fat ratio [160]. Female chest measurements require adjustments for bust prominence, while males have a broader and more uniform chest structure [19]. Torso length, shoulder width, and limb proportions also vary, with males having longer torsos, broader shoulders, and larger upper arm circumferences due to greater muscle mass. In contrast, females have shorter hip heights, wider pelvic structures, and more curvature between the front and rear waist [30]. Apart from differences based on gender, the female anatomy exhibits significant variability in body proportions, including differences in bust size and shape, waist-to-hip ratio, and torso length. Unlike male-specific body armor, which has been refined over decades using standardized measurements, female-specific armor requires much more detailed data collection [161]. Women's bodies have unique dimensions, movement patterns, and pressure points that standard designs fail to accommodate [31]. While current production techniques such as cut-and-sew fabrication, fabric folding, and stretch molding have helped address gender-specific differences to some extent, they still do not fully account for the wide range of female body shapes [162]. One major reason for this is the lack of extensive anthropometric research focused on women. As a result, manufacturers often rely on scaled-down versions of male armor rather than designing body armor that properly conforms to the female form. This leads to poor fitness, discomfort, and even reduced protection in critical areas [31]. Customization could help solve many of these issues, but it comes with its own set of challenges. Unlike mass-produced armor, which can be made in bulk at lower costs, customized female armor is often made to order. This means longer production times, higher costs per unit, and difficulties in managing inventory [163]. Although there has been a significant advancement that offers promising solutions, there are challenges in scaling personalized body armor for mass production [58]. Many manufacturers still rely on traditional patterning techniques, which limit customization options. In addition, integrating personalized armor into existing procurement systems requires policy changes and further research to make these solutions more accessible [48]. Furthermore, for agencies responsible for

equipping large teams of female first responders, balancing cost-effectiveness with the need for proper fit becomes a significant concern [164].

6.1.2. Challenges of Soft Body Armor Materials

Soft body armor systems are widely employed for ballistic and stab resistance in police and military personnel. Despite technological advances, several material and structural problems continue to limit their performance, comfort, and overall usability. The primary issue is balancing protection, flexibility, and weight [165]. While ballistic protection is provided by high-performance fibers like aramid (e.g., Kevlar®) and ultra-high-molecular-weight polyethylene (UHMWPE); however, these traditional materials typically compromise flexibility, breathability, and thermal comfort, especially with long-term wear [22]. Furthermore, multi-threat protection remains an issue, as most soft armor systems are ballistic-optimized but lack sufficient resistance to other threats, like spikes, knives, or fragment impacts [166–168]. Being able to achieve an integrated system with protection against all forms of threats without excessive bulk is an ongoing materials engineering challenge. Another challenge is bringing materials that are environmentally durable and resistant. Materials used in soft body armor degrade with exposure to sunlight, UV, water, and increased temperature, compromising structural integrity and long-term ballistic resistance [169]. It could limit usage time to 5–7 years, on average. The unpredictability of performance under combined environmental conditions, like humidity or extreme heat, then multiplies reliability issues in the field. Another significant issue is the ergonomic mismatch for individuals of varying body types. Most soft armor is designed using male anthropometric data, which results in poor fit and mobility for women and smaller individuals. Unlike male armor, which primarily needs to cover a flatter chest and broader shoulders, female armor must adapt to curves around the bust, waist, and hips [162]. Currently used rigid and semi-rigid materials often struggle to mold to these areas, leading to discomfort and gaps in coverage [170]. While using softer materials can help with flexibility, it often comes at the cost of reduced protection [171]. Adding extra layers may improve safety, but it also makes the armor bulkier and heavier, restricting movement and making it harder to wear for long periods [172]. Researchers have been exploring innovative materials such as shear thickening fluid, carbon nanotubes, graphene, hydrogels, polyurea, and impact-absorbing foam to address this. These materials have the potential to make body armor lighter, stronger, and more adaptable to the female form without compromising protection. However, they are still in the early stages of development and require extensive testing, cost reductions, and scalable manufacturing before they can become widely available. Advances in smart textiles, nanotechnology, and adaptive materials could be game changers in the future, ensuring that female first responders have armor that is not only protective but also comfortable and practical for real-world use [173]. Additionally, existing testing requirements (e.g., NIJ 0101.06) frequently cannot duplicate actual impact angles, body movement, or multiple dynamic loads, restricting the predictive validity of laboratory tests [174]. From a sustainability perspective, end-of-life recycling and disposal are problems that remain to be addressed. The soft armor's multi-layer composite architecture makes it difficult to recover materials, with environmental and cost factors. Furthermore, innovative protection materials such as shear thickening fluids (STFs), auxetic yarns, or 3D warp interlock fabrics, while promising, are characterized by high production prices and poor scalability [175]. In summary, soft body armor development is constrained by a combination of material limitations, ergonomics, environmental deterioration, test gaps, and sustainability challenges, all of which call for multidisciplinary solutions to future developments.

6.2. Future Implications

The future of female-specific soft body armor lies at the intersection of technological innovation, material science, and human-centered design. Despite notable advancements, several technological barriers remain, including limitations in achieving optimal fit, comfort, and mobility without compromising ballistic and stab protection. Anthropometric diversity among female first responders presents a complex challenge for universal design, necessitating the development of adaptive and size-inclusive solutions. Furthermore, there is a need to reconcile material performance with industrial scalability, sustainability, and economic feasibility to ensure widespread adoption [25].

6.2.1. Technological Advances and Research Priorities

Emerging technologies such as 3D scanning and virtual modeling have shown strong potential for creating tailor-made body armor that conforms to individual body shapes. These technologies allow manufacturers to optimize protection zones across the chest and other anatomical regions by integrating advanced scanning and parametric modeling techniques [21,48]. However, integrating these tools into large-scale production remains a key challenge, requiring further research into automated and cost-effective digital workflows. Three-dimensional textile structures and warp interlock fabrics have been identified as promising solutions for molding body armor directly to the female form, enabling a better anatomical fit without excessive weight or bulk [40]. The seamless knitting process eliminates fit issues and enhances protection, addressing problems associated with seams in traditional cut-and-sew fabrication methods [57]. Research into dart rotation techniques and CAD-based pattern engineering has also opened pathways for better customization; yet, additional studies are needed to ensure these methods can be adapted across diverse body types [32,57]. Advances in materials science are also pivotal for the next generation of body armor. Lightweight composite materials such as Kevlar/epoxy matrices infused with shear thickening fluids (STFs), graphene nanoplatelets (GNPs), and carbon nanotubes have demonstrated significant potential in improving ballistic resistance and energy dissipation [115,120,129]. However, scaling the production of these high-performance materials while maintaining affordability and sustainability remains a research priority. Gradient shear thickening gels (STGs) integrated with flexible foams have further enhanced shock absorption and impact mitigation, suggesting promising avenues for soft armor systems that provide high protection without sacrificing mobility [108]. Likewise, graphene-based multi-layer polymer composites emerge as viable alternatives to traditional aramid fibers, offering exceptional toughness and lightweight properties [128,129]. Research should focus on green synthesis methods, end-of-life recyclability, and life cycle assessments to ensure these materials are environmentally responsible.

6.2.2. Smart Textiles and Functional Coatings

Incorporating smart functionalities into soft body armor offers exciting possibilities for real-time protection and monitoring. Developments in conductive carbon nanotube-infused shear thickening gel and polyurethane composites enable strain-sensing and motion detection, providing wearers with enhanced situational awareness through real-time data on body armor performance [129]. However, ensuring reliability, durability, and signal integrity under harsh operational conditions remains a critical research gap. Functional coatings such as hydrogel-based fabrics have introduced self-healing and extreme temperature tolerance capabilities, while advanced coatings have improved stab resistance, UV protection, and electrical conductivity, enhancing the versatility of soft body armor [134]. Future research must investigate the scalability of these coatings, their long-term stability, and their compatibility with existing armor systems.

6.2.3. Industrial Scalability, Economic Feasibility, and Sustainability

For these technological advancements to translate into real-world impact, addressing industrial scalability is essential. Many advanced materials, such as graphene or carbon nanotubes, present cost and supply chain challenges that hinder mass production. Research into low-cost synthesis methods, alternative raw materials, and process optimization is vital to bridge this gap. Moreover, sustainability must be central to body armor innovation. The environmental impact of current materials (e.g., aramid fibers and resins) underscores the need for biodegradable alternatives, renewable feedstocks, and closed-loop manufacturing systems. Incorporating life cycle assessments and techno-economic analyses into early-stage research will enable informed decisions regarding feasibility and market readiness. Finally, economic feasibility remains a barrier, especially for small-scale manufacturers or resource-constrained organizations. Balancing material costs, processing complexity, and end-user affordability is crucial to ensure equitable access to advanced protective solutions for diverse first responder populations.

7. Conclusions

The development of female-specific soft body armor (SBA) represents an unprecedented advancement in the reward systems for women's work in high-risk occupations. This review points out that most of the existing SBA systems still fail to address female users' anatomical, ergonomic, and biomechanical needs. On the other hand, significant advances have been made in paneling techniques, from traditional darting to seamless molding and digital contour fashioning, which better accommodate the bust area. CAD-based virtual modeling, 3D scanning, and 3D warp interlock weaving have revolutionized the issue of fit versus element balance and dependence. The development of new materials also resulted in the production of ultra-lightweight and high-performance panels. Bolt-and-cap composite fiber-reinforced systems developed with aramid fibers, UHMWPE fibers, and STF treatments exhibit superior ballistic and stab resistance while remaining feather-light and compact. These changes significantly improve user mobility, comfort, and safety. The development of smart material composites with carbon nanotubes and shear thickening gels (STGs), as well as the ability to respond to shear stress, greatly enhances the functionality of SBA by enabling impact detection and changes to its form. Despite these advances, challenges persist. Testing standards continue to evolve but often do not provide gender-specific and detailed evaluation standards. Additionally, cost, manufacturing capacity, and the need for larger anthropometric databases hinder the complete realization of custom armor. Accordingly, future research must emphasize the optimization of manufacturing processes, female-specific standardization of testing, and integration of sustainable and recyclable materials in SBA design. Combining composite science, computer-aided design, and user-centered development will play an essential role in creating the next generation of high-performance, efficient, and inclusive female body armor.

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