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A REVIEW ON THE PERFORMANCE AND COMFORT OF STAB PROTECTION ARMOR

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Abstract:

Stab-protective clothing is the most important component of safety equipment and it helps to save the lives of its wearers; therefore, it is designed to resist knife, nail, or needle attacks, especially to the upper body. In this paper, the essential requirements for stab-resistant armor are investigated based on an in-depth review of previous research and prototype test results. The combination of protection and comfort in armor vests is a particularly challenging task. Review of the state of the art technology responsible for the manufacture of stab-resistant clothes has revealed that their design and development should encompass the elements of comfort, freedom of movement, permeability, absorption, evaporation, and weight reductions to ensure excellent ergonomics and high wear comfort. The design as well as the production, weight, thickness, material types and properties, and the arrangement of scales determine the level of protection and comfort offered by stab-resistant vests. Currently, the production of stab-proof gear-based 3D printing technology is evaluated, using lightweight materials (aramid) in the form of segmented scales inspired by nature. As the protection performance and wear comfort of stab-proof gear is enhanced, the willingness of security, control, transport, custom, and correction officers to wear them can be significantly increased in an endeavor to ensure that fatal injuries will decrease significantly.

Keywords:

Stab-protection and comfort, bio-inspired, lightweight, concealment, weapons

1. Introduction

Stab-protective clothing is a vital component of safety equipment that helps to save the lives of its wearers. A stab vest is a reinforced piece of body armor designed to resist attacks to the upper parts of the body (chest, back, and sides). It can be worn underneath or over clothing and offers protection against stabbing with sharp-tipped knives, needles, nails, and other sharp objects.

Early humans used comparatively primitive armors, which were manufactured out of metal, horn, wood, or leather lamellae [1, 2], but as civilizations developed and techniques advanced, body armor evolved. Then, in the last century, with its two world wars, various attempts were made to advance the technology of body armor [1]. It was reported that the first soft body armor was developed by the Japanese and, in that instance, was made of silk and was most effective against low-velocity bullets [3]. The first so-called bullet-proof vests were designed in America in the two decades following World War I [4, 5]. Modern police body armor was introduced into practice in the 1970s as a result of the US National Institute of Justice (NIJ)-funded research [6].

Research indicates that an officer who is not wearing body armor is 3 to 4 times more likely to suffer a fatal injury if stabbed in the torso than an officer who is wearing body armor. Thus, police officers, military, transport, and correction administrators should encourage their staff to wear stab vests during the whole duty shift [7].

The level of protection required in soft and sensitive body regions is determined by the type of attacks that are likely to be encountered [8]. Though corresponding guidelines exist, the design of appropriate stab vests with the desired level of protection can be challenging for a wide range of weapons that are used for puncture, and the stabbing techniques are different depending on assailants [9].

In addition to stab protection, body armors should be selected for comfort, flexibility, and other ergonomic issues for acceptance in accompaniment with coverage and service life [10–12]. The stab-protective vest should maintain body temperature through the thermal balance of heat generated by the body and transferring it to the environment [13, 14]. Thermal resistance, water-vapor resistance, moisture transfer, air permeability, surface friction, size, fit, locomotion, and flexibility are the most important comfort-determining factors [15, 16] to enhance the function of vests, when these factors are considered during designing.

Protection and comfort are always conflicting. It is a well-known fact that a high level of protection from attacks is typically achieved at the expense of physiological comfort [17], which reduces the working period and efficiency of the wearer [12].

The selection of advanced materials (both for performance and for comfort) and appropriate armor design should ideally allow the flow of excessive metabolic heat away from the body (thermo-physiological property), which can be reflected by a combination of air permeability, thermal resistance, and moisture evaporation [18–20]. The increase in the stab resistance was attributed to the coating that bound the reduced micro-porous nature of the cloth and its raw material, increased thickness, and bending resistance that resulted in reduced comfort properties [20].

To be thermally comfortable when the body is heating up and sweating, the stab-protective vest should be able to eliminate the excess heat generated within the body to the atmosphere [13, 15, 20, 21]. Tactile comfort, i.e., the feel or sensation on the skin when worn, is affected by the type of fiber and should be considered [22], as well as the chemical finish [23], type of fabric, and fabric structure [22].

The use of body armor has always been an issue in terms of ease of body movement and cognitive functions [24, 25], which should not be drastically compromised by the design of the protective armor [12].

2. Determinants of protection and comfort of armors

2.1. Concealment for protection and comfort

The compatibility of protective armors and other equipment should be evaluated in addition to freedom of movement and appropriateness of the design (overlap between jacket and trousers, arm length). Manufacturers should produce customized vests for wearers with different body types, to ensure that maximum benefit is achieved [26].

The majority of stab attacks are directed at the chest and abdomen area, which can cause serious injuries, often leading to death [28–33], for which reason body armors are designed to protect these areas in particular, as shown in Figure 1 [34]. Besides the torso, head (including face), and arms are most likely to be attacked, followed by neck, shoulder, and legs that are also very vulnerable to stab attacks [35]. As shown in Figure 2, the neck and shoulder areas are not covered by armor vest because the currently available stab-resistant materials would lead to physiological and operational constraints [36, 37]. Therefore, advancements in materials and design are required, for example, based on 3D body scanning and 3D printing technologies.

2.2. Characteristics of weapons for stabbing

The majority of stabbing incidents are performed using domestic knives, such as kitchen knives, lock knives, sheath knives, pen knives, and other variations [19, 38]. Different types of stabbing and spiking domestic knives are presented in Figure 3.

Generally, each stabbing weapon has a blade and a handle designed to suit its intended purpose for medical procedures, domestic use, manufacturing, training, and attacking, whereby the overall performance essentially depends on the blade [39]. The physical condition and skill of the attacker in addition to the characteristic features of a blade, such as the material it is made of, thickness, profile of the tip (i.e., angle of the point), attacking angle, and sharpness of the edge, affect the severity of any attack and determine the type of armor to be designed [39–42]. Body armors that pass standard testing may still fail in case of a real attack due to changing parameters, for example, if knives are thrown manually or propelled mechanically at the target from different distances [43]. Moreover, the point and edge of a knife play significant roles during the basic mechanism of cutting (compressive pressure) [38, 44, 45]. Advanced stab-resistant armors protect their wearers against different types of knives.

Figure 1. Concealable body armor: stab-proof vest [27].

Figure 2. Shoulder and neck are not covered by standard stab vests [27].

Figure 3. Various stabbing weapons: **(a)** lock knife **(b)** sheath knife **(c)** combat blade **(d, f, h)** kitchen knives, **(e)** pointed weapon, **(g)** dagger, **(i)** awl, and **(j)** screw driver.

2.3. Design of stab-resistant armor types

Many biological systems possess hierarchical and fractal-like interfaces and joint structures that bear and transmit loads, absorb energy, and accommodate growth, respiration, and/or locomotion [46].

A diversity of geometrically structured interfaces and joints is found in biology, for example, in the form of bone and armored exoskeletons [47, 48], the cranium [49, 50], the turtle carapace [51] and algae [52]. Mechanical and biological activities such as growth, motion, protection, load transmission, and energy absorption are determined by their geometry [49, 50, 53].

Learning by imitation and further by linking of data has probably been one of the most productive ways of development to be deployed. In the case of bio-inspired flexible protection, segmented armors from fish (Figures 4a and 4b), alligators (Figures 4c and 4d), snakes, *Tonicella marmorea* (Figures 8 and 9), pangolin, scaly-foot gastropods (Figure 5), species of *Arapaima* (Figure 6), and armadillos (Figures 4e and 4f) are attracting an increasing amount of attention owing to their unique and highly efficient protective systems that resist mechanical threats from predation, while combining hardness, flexibility, breathability, thinness, puncture-resistance, and lightweight [53–58]. The extreme contrast between extremely stiff, hard scales and surrounding soft tissues gives rise to unusual and attractive mechanisms, which now serve as models for the design of bio-inspired armors. Despite this growing

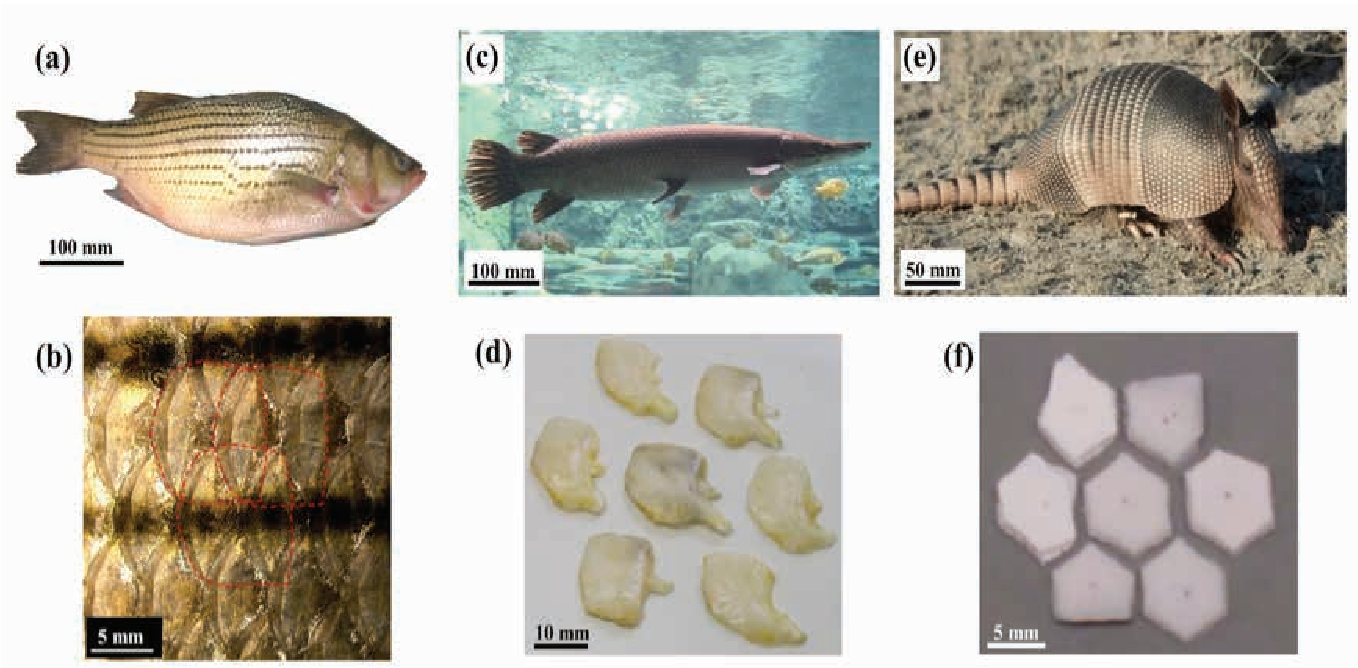

Figure 4. Examples of segmented armors found in nature: **(a), (b)** Striped bass with detailed arrangement of scales and geometry **(c), (d)** Alligator gar with details of scales; **(e), (f)** Armadillo with details of bony plates [59].

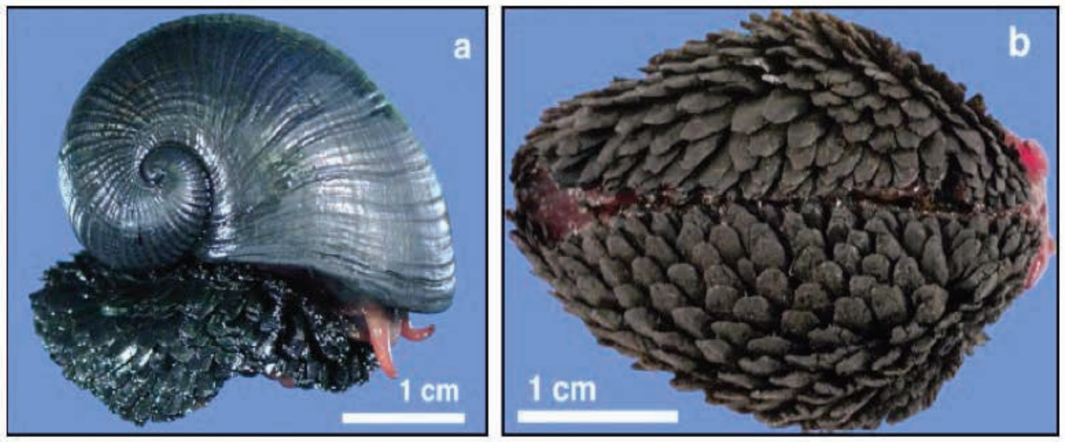

Figure 5. “Scaly-foot” gastropods top **(a)**, and underside **(b)** [60].

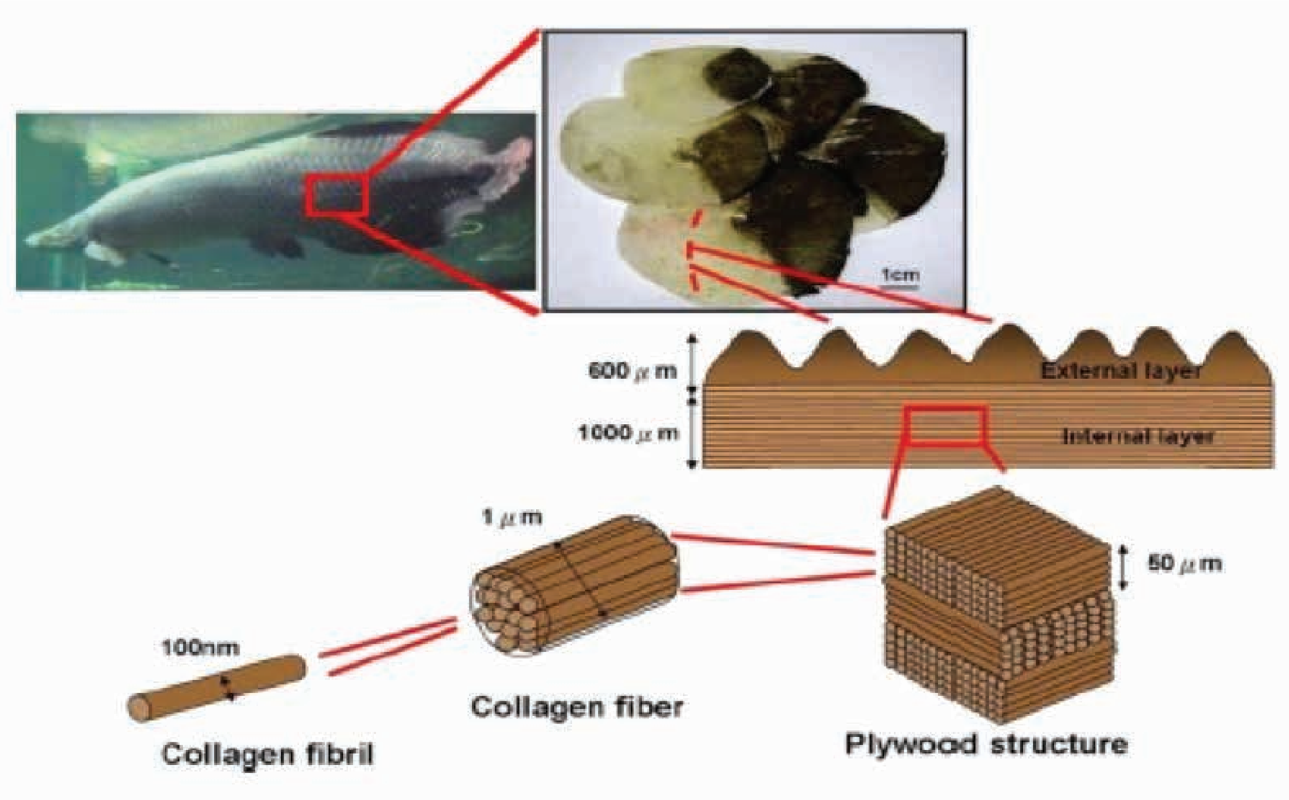

Figure 6. Hierarchical structure of *Arapaima* scales [57].

interest, currently limited guidelines are available for the choice of materials, thickness, size, shape, and arrangement for

Figure 7. Demonstrating the flexibility of pangolin armor [61].

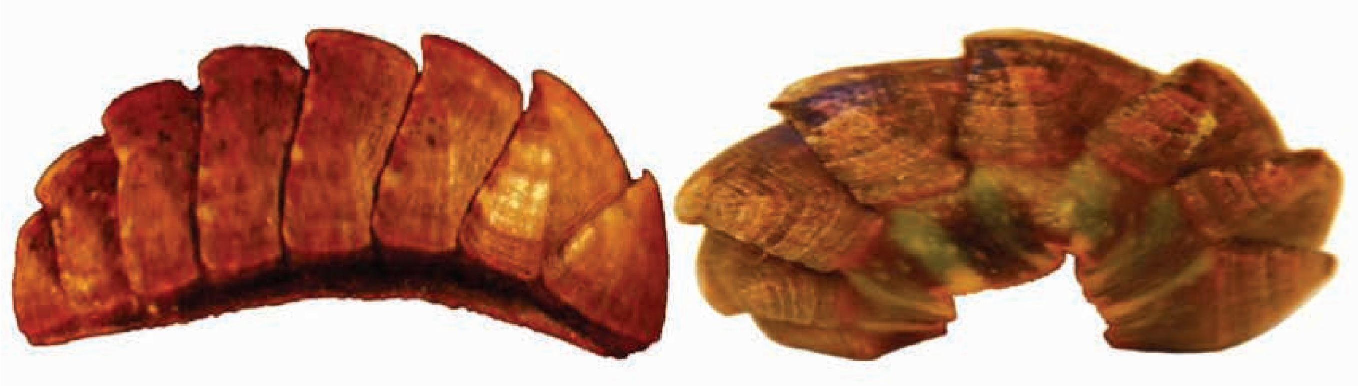

Figure 8. Images of Chiton *Tonicella marmorea*: **(a)** side view optical microscopy image of a dried shell; **(b)** side view photograph of a recently thawed chiton in a defensive, curved posture [58].

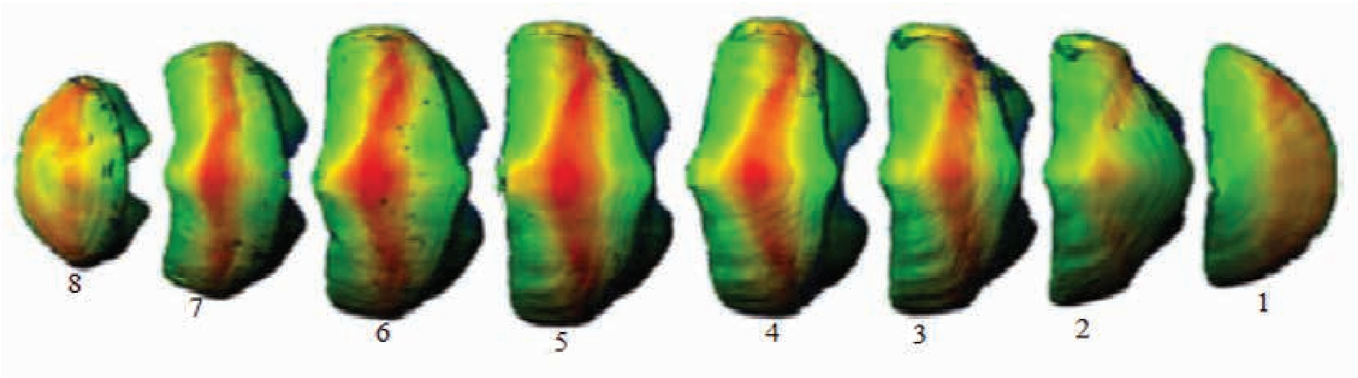

Figure 9. Thickness distribution of the armor plate assembly of *Tonicella marmorea* presented in dorsal view of the spatial distribution of thickness for each plate (1–8) [58].

protective scales [59].

Researchers studied the structure of individual scales and their arrangement (scalation pattern), using the example of a striped bass (*Mimetes Saxatilis*), a common teleost fish originating from the Northern Atlantic Ocean, which provides basic knowledge for future biomimetic “artificial scales” such that the resistance to puncture of individual scales is equally as important as their overlap and arrangement in providing efficient protection [56]. Similarly, protective gear for the human torso should be designed for ultimate protection, while providing the required flexibility, locomotion, and permeability to air and moisture.

2.4. Interactions between scales and segmentation

Segmented armors allow for much greater flexibility of movement, and they are therefore found in animal species with relatively fast locomotion; however, such armors still provide high surface hardness to prevent the teeth of potential predators from penetrating the soft underlying tissues and vital organs [59, 62], in which individual segments display highly efficient structures and mechanisms. Shape optimization may be coupled with material choice, size and thickness of the scales, and attachments of the scales to design, thus producing high-performance bio-inspired flexible armors [59].

The scale–scale interactions can significantly increase the resistance to puncture due to the improved stability, and these interactions can be maximized by tuning the geometry and arrangement of the scales [63]. Interestingly, the designs that offer the best combinations of puncture resistance and flexural compliance are similar to the geometry and arrangement of natural teleost and ganoid scales (see Figure 10), which suggests that natural evolution has shaped these systems to maximize flexible protection [64, 65].

Structured interfaces are prevalent throughout nature and give rise to many remarkable mechanical properties in a number of biological materials [46, 53, 63, 66–68]. The materials, shape, size, and arrangement of the scales also influence the flexural response of the whole scales of skin, in which the scales surrounding the puncture redistribute the puncture force over large surfaces and volumes in the soft tissue [54, 66, 69]. This mechanism of scale interaction and force dispersal prevents unstable localized deformation of the skin and damage to underlying tissues [56, 70]. Due to additive manufacturing technologies that enable printing on individually assembled soft base materials, the geometric design of interlocking structures combined with material elongation allows for overlapping effects [37].

Therefore, protective gear involving segmented scales (see Figure 11) will provide better protection and comfort to a human torso than a vest made of a single piece of stab-resistant material, e.g., ceramics, polycarbonate sheet, or other metals. However, the performance of segmented scales for stab protection depends on the thickness of scales and the type of materials used for 3D printing. A research study presented the

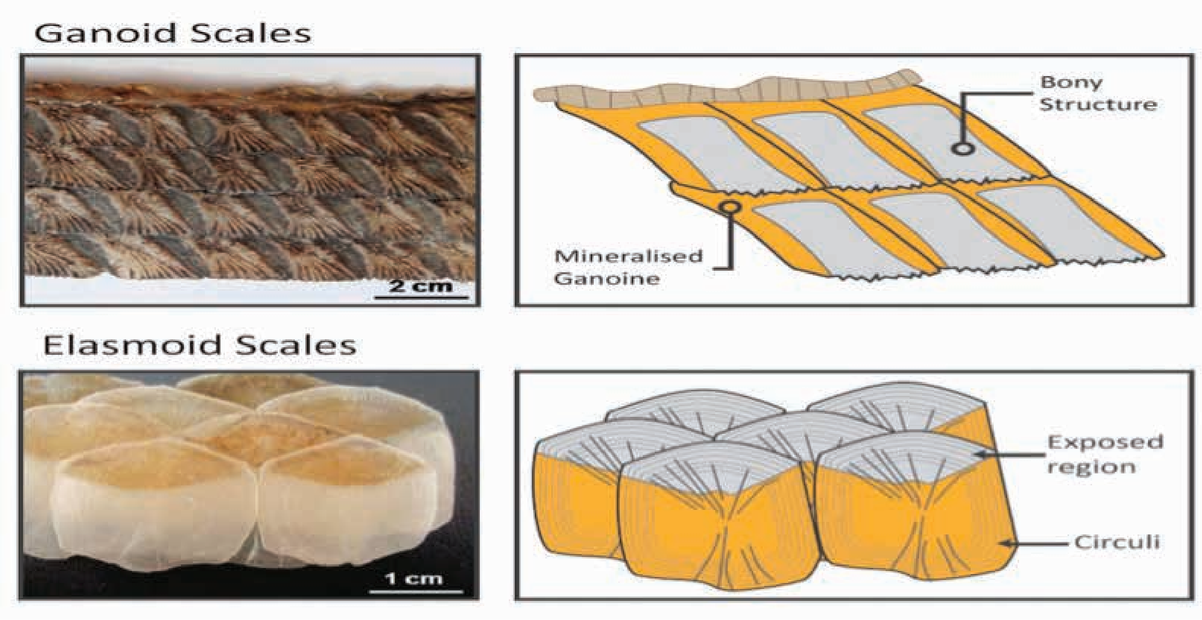

Figure 10. Examples of ganoid and elasmoid scales [65].

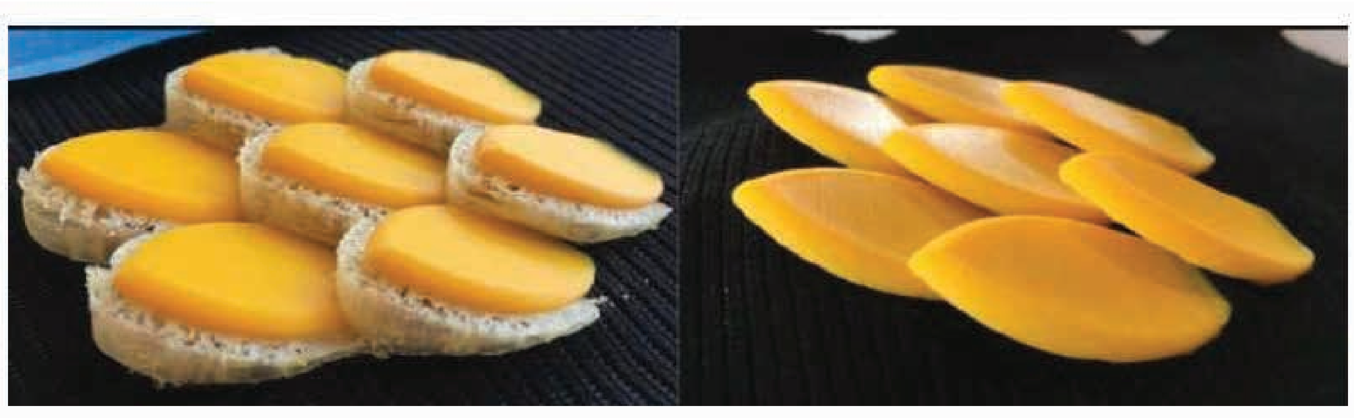

Figure 11. Scale-like elements with water-soluble support (left) and overlapping effects (right) [37].

scales of 3D printed from aramid fiber with different thicknesses, and the result revealed that a scale with 2 mm thickness failed to resist the stabbing blade, whereas the scales with 4 mm and 6 mm thickness resist the puncture of a knife at impact energy of 25 joules [37]. Segmented scales increase thermal comfort by allowing the transport of moisture away from the body [14, 71]. The human body requires elimination of excess heat from the body through the dry heat losses and perspiration from the body to the environment, which depend on the air gap between the skin and garment layers. These air gaps should be determined during designing and attachment of segmented scales to improve the comfort of body armors [14, 21, 72, 73].

2.5. Materials for the production of stab-protection armor

Stab- and puncture-resistant soft body armor commonly employs multiple layers of densely woven fabrics or closely spaced laminated layers to dissipate the energy of an impact [74]. A stab-resistant body armor panel should afford protection against injury from penetration, while ensuring that the movement of the wearer is not excessively restricted. The impact force should be effectively spread from the point of impact over a greater area of the armor [75–77]. Materials designed for stab protection should absorb all the stab energy prior to penetration [69, 76, 77]. A typical stab-resistant system used for industrial protection is several millimeters thick and composed of knitted aramid fabric impregnated with thermoplastic polymers [78].

Some research studies encourage the use of much harder materials, such as high-density ceramics, to prevent bodily injury arising from impacts caused by sharp objects made of steel or other hard materials penetrating the protective armor [59]. Modern soft body armor consists of multiple layers of fabrics made from expensive high-performance fibers, for example, aramid, glass, polybenzoxazole, light para-aramid, and high-performance polyethylene, as an outer cover, while cotton, polyester, or wool are used to ensure good breathability and durability [78–81]. Most of the flexible protective systems used today are based on advanced textiles involving aramid and polyethylene fibers [82].

Shape optimization may be coupled with material choice, thus producing high-performance bio-inspired flexible armors [59]. Suitable yarns and fibers for making body armor fabric for multi-threat vests are available [4, 83–87]. Moreover, natural fibers such as wool and cotton are combined with aramid material for enhanced wear comfort in terms of thermal conductivity,

Table 1. Description of some testing standards of stab-protective body armor

No	Standard and Owner	Description	Protection Level	Energy Level (Joules) and Penetration Depth (mm)			
				E1	**Maximum Penetration Depth**	**E2**	**Maximum Penetration Depth**
1	ISO 13998, EU [103]	This applies to protective aprons, trousers, and vests for use with hand knives, and related garments for protection in accidents. It specifies requirements for the design, penetration resistance, cut resistance, sizing, ergonomic characteristics, innocuousness, water permeability, cleaning, and disinfection, marking and information to be supplied by the manufacturer.	Level 1	2.45	10 mm and no single penetration exceeds 17 mm	-	-
			Level 2	4.9	12 mm and no single penetration exceeds 15 mm		
2	US Department of Justice Office of Justice Programs National Institute of Justice-Stab Resistance of Personal Body Armor NIJ Standard–0115.00[6]	The scope of the standard is limited to stab resistance only. The standard does not directly address slash threats; however, testing has shown that stab threats are by far the more difficult to defeat, and that body armor capable of defeating stab threats will perform satisfactorily against slash threats.	1	24±0.50	7	36 ± 0.60	20
			2	33±0.60		50 ± 0.70	
			3	43±0.60		65 ± 0.80	
3	Home Office Scientific Development Branch (HOSDB) Body Armor Standards for UK Police (2007) Part 3: Knife and Spike Resistance [97]	The standard contains requirements for body armor intended to provide torso protection to officers exposed to assaults by knives (K) and spikes (SP). Body armor capable of defeating stab and ballistic threats will perform satisfactorily against slash attacks.	KR1+SP1	24	KR1 = 7, SP1 = 0*	KR1 = 36, SP1 = N/A	KR1 = 20*, SP1 = N/A
			KR2 + SP2	33	KR2 = 7, SP2 = 0*	KR2 = 50, SP2 = N/A	KR2 = 20*, SP2 = N/A
			KR3 + SP3	43	KR3 = 7, SP3 = 0*	KR3= 65, SP3 = N/A	KR3 = 20*, SP3 = N/A
4	Association of test laboratories for bullet resistant materials and constructions-VPAM KDIW 2004 Edition: 18.05.2011 [98]	The standard describes the requirements, classifications, and test procedures for stab (K), spike (D), and needle impact-resistant equipment. The standard ensures reproducible results and provides customers and users with a better market transparency to objectively compare the products of various providers.	K1 + D1	25	<20	-	-
			K2 + D2	40			
			K3 + D3	65			
			K4 + D4	80			

vapor transportation, air permeability, high moisture content, and insulation [88, 89]. Another research study concluded that inserting wool into a twill woven protection panel can lead to achieving acceptable stab depth values with fewer layers because wool is prevents yarn from sliding on the aramid layer below. This leads to weight reduction and improved wear comfort of the soft panels [90]. A suitable material selection is essential to design and develop armors with high protection performance for a specific energy level and wear comfort.

2.6. Weight of stab-resistant armor

Various factors affect the freedom of movement of individual body parts, including the number of layers, thickness of each fabric layer, clothing system design, and the relative ease of fitting between body dimensions and clothing [42, 91]. As the number of layers, physical bulk, and overall weight of the clothing system tend to increase, mobility is reduced, which can cause pain in several body parts, e.g., neck, back, and shoulder. The design might include front pockets for extra equipment, an adjustable abdominal belt, zippers, or adjustable straps for convenient wearability, which additionally increase weight. A stab-proof body armor panel that is made of a multilayered fabric assembly might exceed 40 layers and have a total weight varying from 1 kg to 10 kg depending on the armor type and protection level required [35, 92]. For low-energy threats, the number of layers can be reduced, which makes it easier to assemble a complete multilayer garment.

It was reported that users were reluctant to wear an uncomfortable protective vest [93]. Therefore, the interaction between the protective vest and the body is an important factor that needs to be considered when designing body armor. Advanced body armor technologies aim to reduce body armor vest weight to enhance the wearer's comfort level [73, 75, 94]. Evaporation of sweat over a large percentage of the body area could be improved by reduced weight and thickness of body armor vest [95].

The addition of advanced materials to the material mix improved stab resistance due to the improved mechanical properties of the end product and a high aspect ratio. For example, a stab-proof material made of laser-sintered polyamide/carbon fiber with a plate thickness of 6.5 mm and a pyramid angle of 30° appeared to be the optimum composition for the desired application. Its area density was 6.58 kg/m^2, leading to a 43% weight reduction compared to conventional stab-resistant body armor [96]. Lightweight, free motion, flexibility, improved breathability as well as a high protection performance of armor materials can be achieved in future research projects.

3. Evaluation of stab-resistant armors

The performance of stab-protective armors is assessed for its protection and comfort using testing standards. This helps to determine the protection level of armors for a specified impact energy applied by attackers. The widely used test standards are US Department of Justice, NIJ-Stab Resistance of Personal Body Armor NIJ Standard–0115.00 [6], Home Office Scientific Development Branch (HOSDB) Body Armor Standards for UK Police (2007) Part 3: Knife and Spike Resistance [97], and Association of Test Laboratories for Bullet Resistant Materials and Constructions-VPAM KDIW 2004 [98]. These standards present the scope and evaluation procedures of the protection level, striking energy (see Table 1), number and size of specimens, backing material, maximum allowable penetration depth of knife through each specimen, and test conditions.

The main comfort parameters of body armor such as air permeability, thermal transmission, water resistance, and flexibility of armor are evaluated according to ASTM-D737:2004 [99], ASTM-D5470:2017 [100], ISO-811:2018(en) [101], and ASTM-D1388:2018 [102], respectively.

4. Conclusion

Stab-resistant body armors are crucially important for saving the lives of police officers, correction officers, transport officers, and customs officials. Although the vast majority agrees on the importance of protective gear, there are considerable issues pertaining to their weight, bulkiness, thickness, limited flexibility for free body movement, restricted permeability, and metabolic respiration, thus decreasing the willingness of potential users to wear protective clothing. Therefore, protection as well as comfort should be considered during the design and development of body armor. Hence, important factors, such as the types and characteristics of materials, design, thickness, concealment, integration between plates, protection class, and body armor weight must be taken into consideration throughout the whole process – from the concept of design to the product development itself. A high-performance material such as aramid is highly suitable to fulfill these requirements for bio-inspired vests, which help saving the lives of officers and ensure the desired comfort. The described body armor is under prototype development and will be subjected to testing to determine the optimal combination of comfort and protection. Thicker, bulkier, rigid, and larger/single plated armors can provide higher protection levels at the expense of comfort, in turn reducing acceptance by potential users. Although comfort is a legitimate concern, protection is always the prime requirement for stab-resistant gear.

Currently, our team of researchers is studying the design and development of 3D printed stab-resistant armor based on the example of naturally occurring scales using aramid fibers due to their lightweight, durability, and high strength. Optimization of protection performance with the lowest possible thickness of scales and weight of the overall armor will be the main focus of the current research. All future research efforts in this field should simultaneously address comfort and protection performance, thereby increasing the willingness of armor users to wear armor frequently and regularly. 3D body scanning and 3D printing technologies can be employed to improve comfort by providing the necessary concealment, full flexibility, and great freedom of movement. The protection level and comfort of armors can be further improved by means of hybrid materials. For example, by the 3D printing of wool fiber and aramid or carbon fiber, two essential properties of the resulting stab-proof material can be guaranteed; this is because wool provides permeability and absorbency, whereas aramid or carbon ensures high impact resistance to puncture force.

The optimization of protection and comfort of body armor requires further research in terms of materials, design, technological flexibility including 3D printing technology, and the integration of electronic devices for communication, sensing situations, recording, and viewing of attackers from all directions. As a result, the wearers of protective gear could detect potential attacks earlier, thus giving them the chance to escape or prepare mentally for their defense.

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