



Review

Comprehensive Review of Endogenous and Exogenous Parameters Influencing Dynamic Stab Impact Performance in Protective Textiles and Fibrous Composite Materials

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Abstract: Dynamic stab resistance is a critical property for protective textiles and fibrous composites used in body armor and protective gear applications. This is also a very complex property that depends on various factors, including material properties, structural design, and external impact conditions. This review paper presents an in-depth investigation into the dynamic stab impact response and performance of textile and composite materials, focusing on the influences of various endogenous and exogenous parameters. Material-level factors, including material type and properties, fiber orientation, yarn density, textile architecture, chemical treatments, and coatings, are reviewed. In addition, the influence of external conditions, including impact velocity and energy, blade shape and type, impact condition, and impact angles on the stab resistance of the protective materials are discussed. The interplay of these factors significantly affects penetration resistance, energy absorption, and trauma mitigation. This paper further discusses different stab resistance testing methods and standards on various kinds of protective materials and relatively compared the efficiencies of each. Current challenges on flexibility versus protection and future research directions necessary to realize advances in protective textiles with dynamic stab resistance are debated. The present comprehensive analysis gives useful insights to engineers, manufacturers, researchers, and standard makers for selecting, developing, and testing protective textiles and fibrous composite materials with improved stab protection applications.

Keywords: protective textiles; fibrous composite materials; body armor; dynamic stab resistance; stab testing standards; penetration resistance; stab performance factor; impact conditions



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1. Introduction

Dynamic stab impact performance is one of the most important research areas for developing advanced materials in personal protection of textiles and fibrous composites [1–4]. Humans have used such protective materials throughout history, from ancient chainmail armor to modern high-performance textiles, continually evolving to enhance protection against edged weapons. In early times, they used textiles manufactured out of metal, horn, wood, or leather lamellae, 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 [5]. 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 [6]. The first so-called bulletproof vests were designed in America in the two decades following World War I [6,7]. Modern police body armor was introduced into practice in the 1970s because of US National Institute of Justice (NIJ)-funded research [8]. Currently, modern technologies such as 3D printing incorporated with 3D scanning are employed to develop comfortable armors without compromising the protection performance using lightweight and high-performance materials [9,10]. Besides, dynamic impact, including the stab and ballistic area, has received increased interest because of the pressing demands for high-performance protective gears, especially in law enforcement, military, and civilian applications [3,5]. Impact protection textiles are designed to resist sharp object penetration under dynamic conditions and thus help in preventing injuries related to ballistic and stabbing incidents [11–13]. They also provide a broad spectrum of personal defense, especially in applications where the material is to be subjected to dynamic stabbing impacts, such as in uniforms worn by police and security personnel [14]. However, the performance of such textiles against stab impact is governed by a complex set of parameters that control the effectiveness of the textiles in reducing injuries [15]. Generally, the dynamic stab impact response and performance in textiles involves the interaction of a complex material microstructure and is highly related to intrinsic factors such as fiber type, material composition, weave structure, areal density, weave pattern, etc., and extrinsic parameters, including stab velocity, blade geometry, angle of the stabbing force environmental conditions, etc. [16–21]. Therefore, understanding such parameters properly is required for optimum functionality and effectiveness [22]. Unlike static penetration, dynamic stabbing introduces rapid deformation and energy dissipation mechanisms that challenge the material's structural integrity [11,23]. As mentioned above, therefore, fibrous materials' ability to resist such dynamic impacts depends on both intrinsic as well as extrinsic factors. Understanding these parameters is of the utmost importance in designing textiles that provide protection reliably without compromising flexibility, comfort, or weight. In this respect, the current paper deals with the dynamic stabbing impact of textiles and discusses the effects of different intrinsic and extrinsic parameters on material performance under a stab threat. Research into dynamic stabbing impact response has undergone significant changes over the past few decades. The earlier studies focus on the fundamental mechanical properties of woven and nonwoven fabrics under static conditions. However, when the need for more realistic assessments began to grow, test methodologies were developed to better simulate real-world conditions under dynamic action [24,25]. These advances allowed researchers to investigate the behavior of materials under high-velocity impacts, which helped them to identify key performance issues like energy absorption, force distribution, and modes of failure. Besides, the development of high-performance fibers like aramids, ultra-high-molecular-weight polyethylene, and carbon fibers also formed important milestones in the development of impact resistance textiles [26–28]. Another important feature that characterizes the dynamic stab impact performance of the materials are using hybrid and multi-layer textile systems [29–31]. Combining different fiber types with the integration of additional protective layers, such as resin-coated fabrics or metal plates, has empowered fibrous composites to fulfill any specific protection requirements [32–34]. Examples of hybrid systems incorporating shear thickening fluids (STFs) and graphene-based materials have shown better energy dissipation and reduced deformation under dynamic loading [2,11,35–37]. Apart from experimental investigations of the physical materials, introduction of numerical simulations was a big milestone in this area [38,39]. Such computational models allowed product engineers and researchers to predict the behavior of fibrous materials under various stabbing conditions, offering insights into the influences of both material properties and external factors. Besides,

these models have been instrumental in identifying design optimizations and enhancing the protective capabilities of textiles. For instance, early studies focused on theoretical and numerical models such as spring-mass systems to predict the impact force and penetration depth in soft body armor composed of aramid and ultra-high-molecular-weight polyethylene (UHMWPE) composites. These models demonstrated high accuracy, with errors within 3.2% for impact force and 1.7% for displacement, making them valuable for optimizing material composition while reducing experimental workload [40]. Finite element simulations using different version of LS-DYNA software including R11.0, R12.0, and R13.0 have been extensively used to replicate stab resistance tests, aligning with the NIJ 0115.00 standard. High-speed imaging and drop-test experiments on Twaron fabrics have validated these numerical models, showing their effectiveness in simulating material deformation and penetration behavior [39]. Similarly, shear thickening fluid (STF)-treated textiles have been modeled numerically to incorporate frictional effects, achieving a strong correlation (0.9691) with experimental results, thereby demonstrating their potential for stab-resistant applications [41]. The application of artificial intelligence (AI) and machine learning has further advanced computational modeling in stab-resistant textiles. Neural-network-based approaches have been employed to predict the ballistic performance of Kevlar 29 fabrics using material properties as inputs, with results closely matching experimental data [42]. Additionally, deep-learning-based damage prediction models have been developed to assess puncture impact parameters using real-time image processing, achieving an accuracy of 88.57% in predicting penetration layers. These AI-driven methodologies offer a promising direction for predictive analysis, real-time monitoring, and enhanced material design [43]. Overall, the integration of computational modeling in stab-resistant textile research has significantly improved the accuracy and efficiency of performance evaluation, reducing reliance on extensive experimental testing. As AI and machine learning continue to evolve, their application in optimizing protective textiles will further enhance both material resilience and wearer comfort. Further support has come from the development of standardized testing, such as that developed by the US National Institute of Justice (NIJ) and the UK Home Office Scientific Development Branch (HOSDB), which has given a real basis for measuring and evaluating stab-resistant material performance and allowed meaningful comparisons between studies. Besides, research also underlines the importance of interdisciplinary approaches among different fields, including combining material science with engineering and computational modeling to meet the complex challenges in designing effective protective textiles. For example, recent advances in nanotechnology, 3D printing, and smart materials have further expanded the scope of innovations of the new generation of stab-resistant fabrics with adaptive properties and enhanced durability [44–48]. Dynamic stab impact performance has been and will remain a focal point in the development of protective textiles. Researchers have also conducted computational and experimental investigations on the performance of body armor. As highlighted above, intrinsic parameters determine the baseline performance of the material, whereas extrinsic factors influence the real-world applicability of these materials. Therefore, understanding the combined effects of intrinsic and extrinsic parameters will be significantly helpful for advancement and continue to shape the future of stab-resistant textiles by forcing the innovations of safety and functionality. This paper reviews the intrinsic and extrinsic parameters that determine the stab impact resistance of the textile material regarding interaction and influence on its protective capabilities. Properties of the material, weave patterns, blade geometry, and velocity of stabbing are discussed here to provide a comprehensive approach for an understanding of these factors. Key developments in test methodology, computational modeling, and hybrid material systems are also explored in terms of performance enhancements. The emerging technologies discussed include

nanomaterials and smart textiles. Finally, the paper identifies challenges and proposes future research directions to optimize protective textile systems for high-risk applications.

2. The Endogenous Parameters in Stab Resistance of Textiles and Composite Materials

2.1. Effects of Raw Material, Types and Compositions

Impact-protective materials, including body armor, have been mainly made from fibrous materials since the Second World War [49]. The materials used in stab protection range from the micro level to the macro level in that they can be made from fibers, powders, liquids, fabrics, metallic plates, ceramics, composites, modeled geometries, 3D-printed hard-scaled items, etc. [5,50,51]. The performance of stab-protective armor elements depends on the mechanical behaviour of the raw materials.

For example, fibers to be used for stab-protective armor must have high compression strength, high tensile modulus, low elongation at break, high tenacity, low density, and high flexural strength. Though its performance depends on the thickness and orientation of the materials, some high-modulus and -strength fibers are presented in Figure 1 [3,35]. The mechanical properties of the fibers depend on the chemical characteristics of the polymer made up of the fibers [52]. On the other hand, the same fibers might exhibit different mechanical properties and exhibit different impact resistance because of the different manufacturing processes of specific materials [53]. In the first case, it makes the materials suitable for specific applications, while in the second case useful for different applications. For example, p-aramid fiber, Kevlar 49 (elastic modulus, 113 GPa; tensile strength, 2.96 GPa), is recommended for use in ropes, cables, and composites for marine, aerospace, and sport goods applications, whereas Kevlar 129, which has the relatively lower modulus (96 GPa) and higher tensile strength (3.39 GPa) and lower elongation (3.5%), is recommended for impact and armor applications [7,54]. The Twaron® aramid fibers (tensile strength, 3.1 GPa, and modulus, 121 GPa) and Tech-nora® (tensile strength, 3 GPa, and modulus, 70 GPa) are also suitable for armor applications [24,55]. The common reason for security officers not using armor during their duty in the whole shift is the mass of the armor, and UHMWPE fibers have a significantly lower density (0.97 g/cm^3) as compared to aramid fibers (1.44 g/cm^3) [56]. Carbon fiber is superior because of its high modulus but is not suitable for impact resistance of its brittle behavior from its very low strain/break ratio [57]. On the other hand, the important behavior of the materials used for stab-protective armor elements is their resistance to environmental factors such as sunlight, rain, and wind. For example, aramid fiber (Kevlar) loses up to 25% when exposed to UV rays, whereas UHMWPE (Dyneema) loses only about 5% of its strength [14]. Another option over the above-mentioned fibers (p-aramid and UHMWPE) with high resistance to impact energy is Zylon for its high tensile properties (tenacity, 5.8 GPa). However, its performance is dependent not only on its high tenacity but also its fracture and flexural strengths, so it needs experimental investigation for the stab-protective armor. Zylon also needs additional treatment to improve its accelerated rate of degradation behavior from photolytic and hydrolytic reactions during usage and storage [14]. Another fiber for withstanding impact energy, which has a greater modulus (310 GPa) than most of the commercially available carbon fibers and higher tenacity than aramid fibers, is M5 [58]. As reviewed by some researchers, the performance of materials may not always depend on the type and properties of the materials. The shape and sharpness of knives will also determine the impact level on the protective armor beyond the material characteristics [59]. Some research results report surprising results for their argument against already set theories. It has been known that stab resistance armor materials need to be resistant to compression over tensile force. Carbon fiber has a lower elongation than Kevlar and should show better

resistance to stab force. However, the results reported by other research are opposite to this theory because of the sharpness of the knives [59]. Stab-resistant materials acquire lower elongation at break for lower deformation during the static puncture resistance and bursting strength measurements [60]. The yarns also play a significant role in the stab protection performance of the protective armor because the performance of the fabrics is determined by its yarn component [61]. As shown in Figure 2, axial and transverse waves propagate simultaneously as a transversely projectile load applied on a single fiber since the yarn defects in the impact direction.

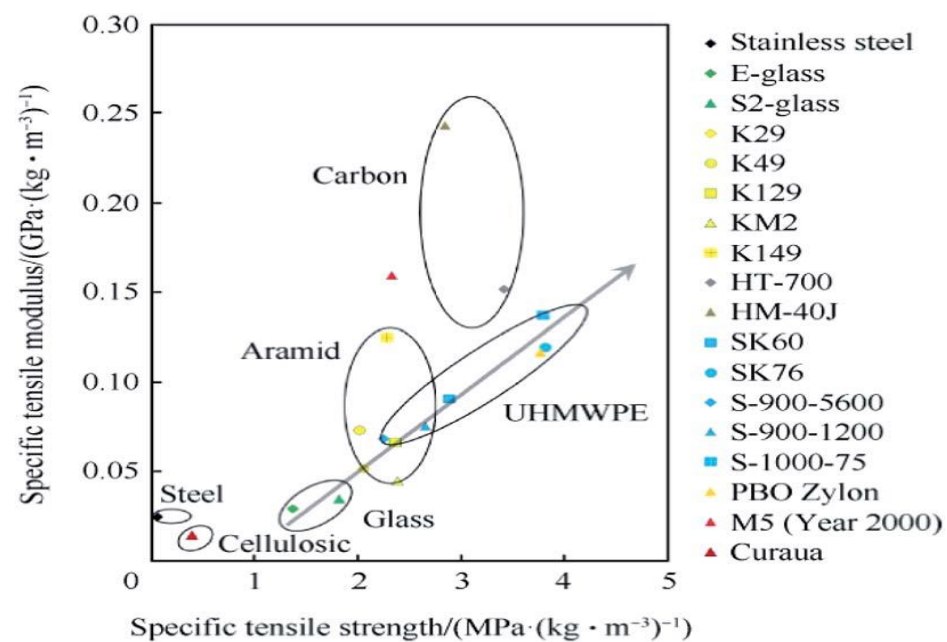


Figure 1. The modulus and strength of high-performance fibers, reprinted with permission from © 2019 Elsevier [35].

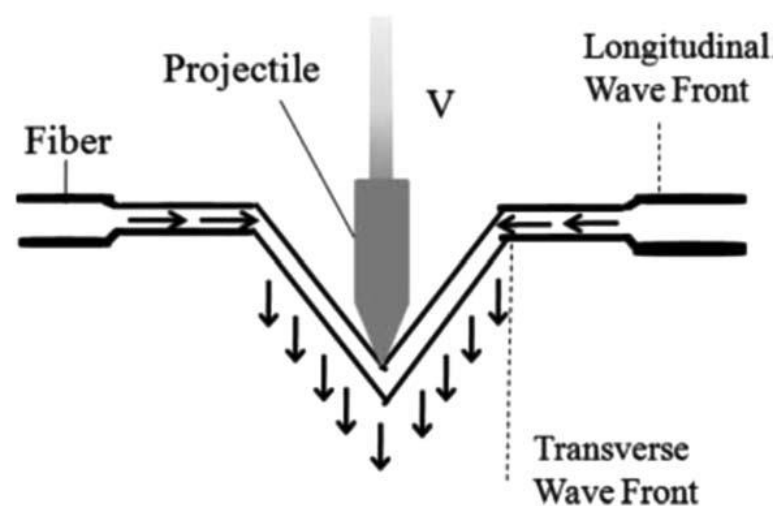


Figure 2. Pictorial representation of projectile impacting a single, yarn reprinted with permission from © 2003 Elsevier [62].

The impacted fiber of the yarn generates a velocity by the longitudinal strain wave, which can be estimated by the following equation [5,49]:

$$C = \sqrt{\frac{E}{\rho}} \quad (1)$$

where C is the speed of the longitudinal wave, E is the initial modulus, and ρ is the density of the fiber.

The tensile strain (ε) of the filament or yarn during impact determines the transverse stress wave speed (u), which is related to the longitudinal stress wave velocity in Equation (2):

$$u = C \sqrt{\frac{\varepsilon}{1 + \varepsilon}} \quad (2)$$

The ultimate tensile strength of fiber (U) in Equation (3) shows the tensile strength and modulus of fibers must be high in a low fiber density [63]:

$$U = \frac{\sigma \varepsilon}{2\rho} \sqrt{\frac{E}{\rho}} \quad (3)$$

where U is the ultimate tensile strength of the fiber, and ε is the ultimate tensile strain of the fiber. Besides, the fibers intended for body armor applications should also have properties like low moisture retention, high resistance to heat, high limiting oxygen index, etc. Friction between the yarns in contact and between the yarn and the impacting object decides the impact performance of fabrics [64] in which high inter-yarn friction improves the pull-out force and its energy absorption [65–71] because the dissipation of energy increases in the high pull-out force zone [66]. The function of friction is to enhance energy absorption through increased yarn kinetic energy, improved yarn strain energy, and frictional sliding [67]. The coefficient of friction can be classified into three ranges, as low (0.0–0.06), moderate (0.06–0.2), or high (0.2–1) [68]. The energy absorption increases with an increase in friction up to 0.2 and tends to fall above it.

2.2. Effects of Textile Structural Parameters

The yarn and filament performance can be managed by various factors, including twists. Twists increase the strength of materials up to a limit of the material-breaking elongation through the number of turns per unit length and twisting angle [72]. The insertion of a twist above a certain limit tends to make an oblique angle, reducing the strength. On the other hand, a twist is not inserted into all materials. For example, most high-performance materials are non-twisted; rather, they come in the form of bundles or single filaments [73].

2.2.1. Effects of Fabric Structures

The influences of fabric structures against the impacting energy of the stabbing knife are defined by the coverage, which is described as the type of structure, cover factor, the yarn integration direction and integration point, formation technique, and its dimension as unidirectional, biaxial (2D), three dimensional, multi axial, warp knitted, or bonded (nonwoven) [74–79]. Balanced fabric structures, such as in basic and derivative 2D weaves with crimps at the interlacement points, are suitable for under and outer cover of the protective armor elements with reduced weight and better flexibility [14,80]. The fabric cover factor has a significant influence on the absorption of impact energy as the fabrics with a large number of filaments or yarns per unit area limit the penetration of the knife to organs by avoiding movement of yarns during impact [14,57]. On the other hand, fabrics can be produced by bonding of filaments linearly and at varied angles without interlacement or intermeshing using resins [81,82]. Here, the protection is not only from the structure but also from the resin, which reduces porosity for permeability. The protection performance of the fabric structures is determined by the thread density of the fabrics. In general, the fabric with high thread outperformed to absorb the impact energy. The other factor is the fabric thickness, which depends on yarn count and type of fabric structural dimension.

Apart from its excellent forming ability [83–85], 3D fabrics have better resistance to impact energy due to their structural integrity and thickness as compared to unidirectional and 2D fabrics with high tensile properties [86–88]. As discussed in the above paragraph, fabrics can have crimps when formed by interlacement or intermeshing. A low yarn crimp helps to slow down the speed in stab impact [87], while a high crimp tends to stretch, and the sharp object penetrating the large crimp yarns means it takes more time to stop the load [87,89]. The crimp level of warp and weft yarns is a debated topic against the protection performance. Some researchers have said that a balanced optimum crimp between warp and weft provides better protection, while others reported a crimp-balanced structure reflected higher back wave energy from the side of impact, which affects the resistance performance to impact energy [14,90].

2.2.2. Effects of the Number of Fabric Layers and Stitching

The fiber types, yarn structure, and fabric architectures are discussed in detail in the above sections. Their performance does not mean that these materials are used without construction for the specified energy level. The stabbing energy can be absorbed if the armor is rigid and thicker [5], but a single layer of high-performance fabrics is insufficient to resist the intended impact energy [7]. Rather, the protective element against the impact energy is made of either several layers of high-performance fabrics connected or stitched [76,91–93], or the fabrics are used as a reinforcement of the composite with the polymer or resin [75]. Therefore, the change in fabric layers greatly affects the dynamic stab resistance of the target. Generally, increasing the number of layers enhances the overall areal density of the fabric, resulting in different mechanical behaviors of the final materials [34,94,95]. Expectedly, as the number of layers increases, the trauma depth and diameter decrease. As shown in Figure 3, although it depends on the amount of impact energy, the trauma depth and trauma width of the stabbing are significantly influenced by the number of layers of protective parts [96].

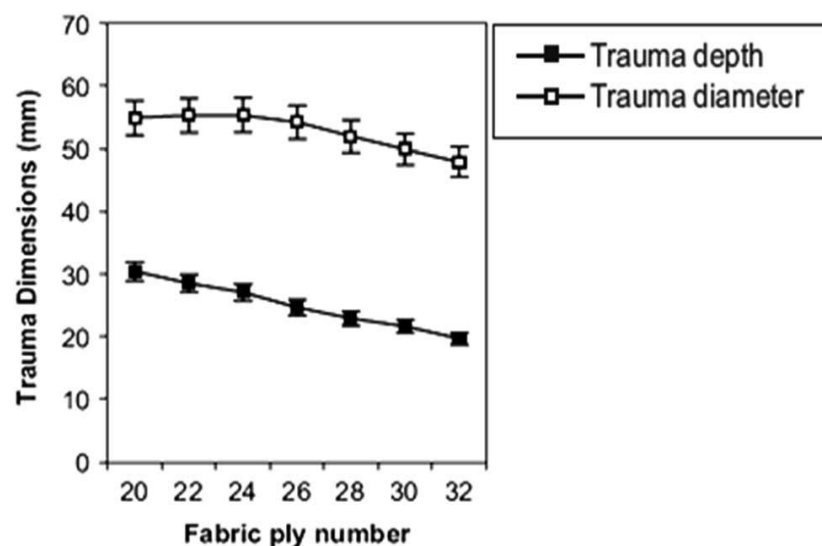


Figure 3. Effect of the number of fabric layers on the trauma depth and diameter, reprinted from ref. [96] with permission from Elsevier.

On the other hand, the number of layers, while enhancing the protection performance, at the same time reduces comfort. This leaves the wearer to become negligent to use it during their shift, as it reduces mobility, increases weight, reduces ventilation [97], and limits locomotion and cognitive functions of the wearer [5]. The other limitation of multiple layers is that the point of connection of fabrics creates paths for sharp objects

to penetrate through, which can be avoided by hiding with treatments and coating the stitching line [93,97]. The impact energy absorbed by the protective armor increases as the number of layers increases [8]. As shown in Figure 4, the number of layers determines the amount of maximum force required to puncture the protective material. In all three energy levels, the highest maximum puncture force is exerted to the sample with the maximum number of layers of fabric for the protective armor.

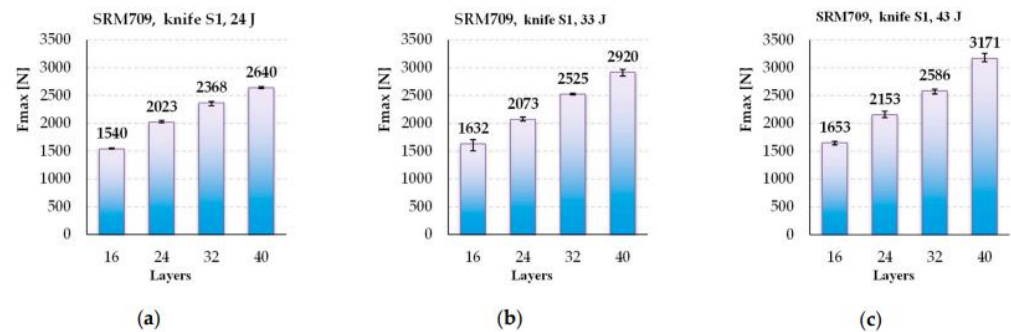


Figure 4. Average values for Fmax, depending on the number of layers in a panel, for different strike energy levels: (a) 24 J, (b) 33 J, and (c) 43 J. Reprinted with permission [8]. Copyright under open access publication (CC BY/4.0).

In another study, different fabrics, one, a 2D woven fabric, and the other three, 3D-woven fabrics: {f1}, {f2}, {f3}), both in single and four-layer arrangements, were subjected to dynamic stabbing, and trauma deformation was measured on the back of the tested specimen [98]. The three 3D fabric structures were designed with different warp yarn composition systems inside their structure. For example, {f1}, {f2}, and {f3}) are composed of 100%–0%, 50%–50%, and 35%–65% of warp-weft ratio, respectively, inside their structures. According to the obtained results, the number of layers is of crucial importance for energy dissipation in the case of every fabric type and composition. As can be seen in Figure 5a,b, increasing the number of layers in the specimen results in an increase in the maximum trauma deformation along the width of the blade for any fabric type.

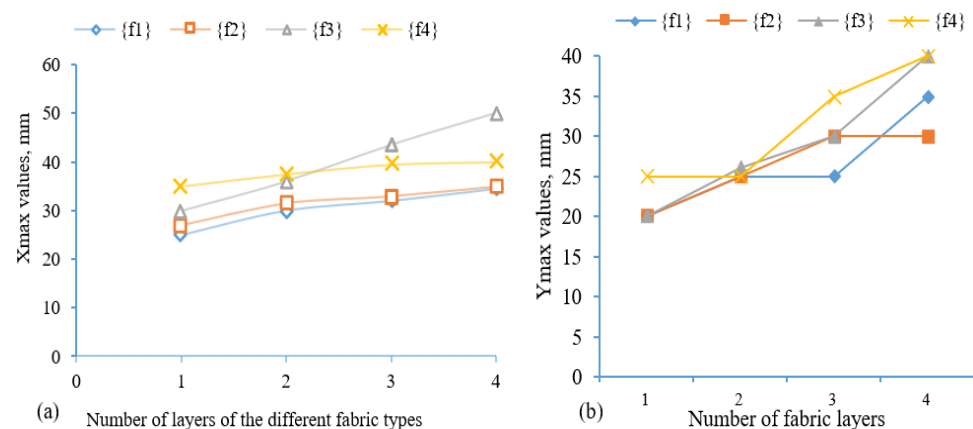


Figure 5. The effects of the number of plies involved on the maximum trauma deformation on the back of target specimen measured at the surface of the backing material in the (a) knife blade width (Xmax) and (b) knife blade thickness (Ymax) directions. Reprinted with permission [98]. Copyright under open access publication (CC BY/4.0).

The study also investigated the impact of the number of fabric layers on Depth of Penetration (DoP) and Depth of Trauma (DoT). In general, the samples provided different values of DoP and DoT, as shown in Figure 6a,b, respectively. For example, in Figure 6a,

in general, DoP of the knife blade of the impact into the backing material decreases with an increase in the number of layers in the multi-layer specimens. Specimens based on one layer of the two 3D WIFs {f2} and {f3}, having various stuffer warp yarns, as well as the 2D woven fabric {f4}, resulted in DoP values that were less and comparatively uniform. Still, as evident in Figure 6b, the Depth of Trauma, DoT, did not follow a clear trend, as was seen along the tested specimens from various configurations.

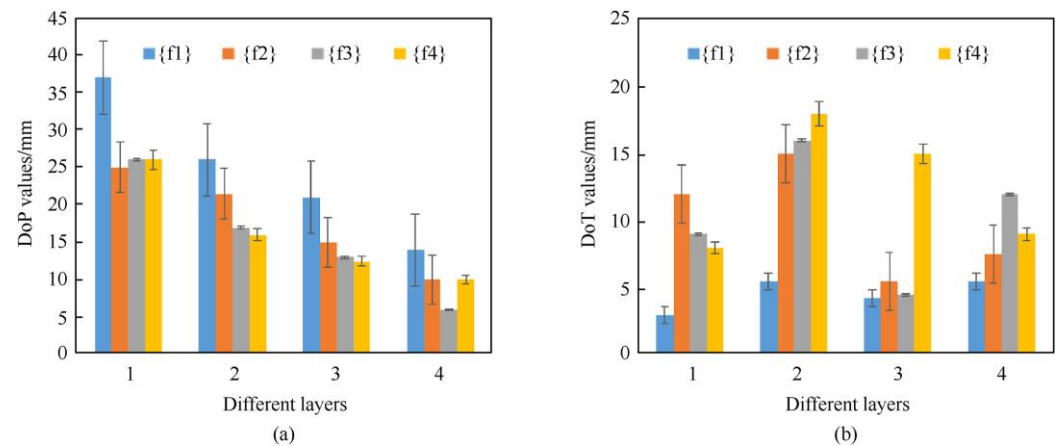


Figure 6. (a) The effects of the number of layers/plies involved on the (a) Depth of Trauma (DoT) and (b) Depth of Penetration measured on the back of target specimen at the surface of the backing materials for different layers of fabrics. Reprinted with permission [98]. Copyright under open access publication (CC BY/4.0).

2.2.3. Effects of the Orientation of Reinforcement Layers

The arrangements of multiple layers of protective elements can be performed in different ways and are described as the orientation of individual layers throughout the whole thickness [5]. Researchers have reported that the orientation of the protective elements plays a significant role, where laying all slices of a product in the same direction results in fatal injury of the user while the arrangement of layers of slices of a particular thickness of a protective part improves the resistance against the intended impact energy (Figure 7) [99,100].

An increased number of layers of the stab-protective element with varied angles of orientation significantly increases the potential to withstand the impact energy from sharp objects [101]. This is because the different layers are oriented along different axes distributing the impact energy and the isotropy assembly approaches. The symmetric orientation helps the protective elements to have improved protection performance through balanced energy absorption [51]. In general, stab-protective armor, as safety equipment, must provide comfort without compromising its protective performance. This can be achieved through the integration of various factors, including materials, structures, processes, treatments, finishes, and storage. The stab-protective armor element needs to be hard-scaled, thinner, and lightweight with permeability, heat transfer, locomotion, and full cognitive functions of the body. 3D printing technology offers a promising approach for manufacturing stab-protective armor elements using functional materials in liquid, powder, and filament forms. Other research also investigated four different panel orientations based on the angles 0° , 22.5° , 45° , and 67.5° to represent a range of impact orientations and simulate varied loading conditions on the material, as shown in Figure 8 [98].

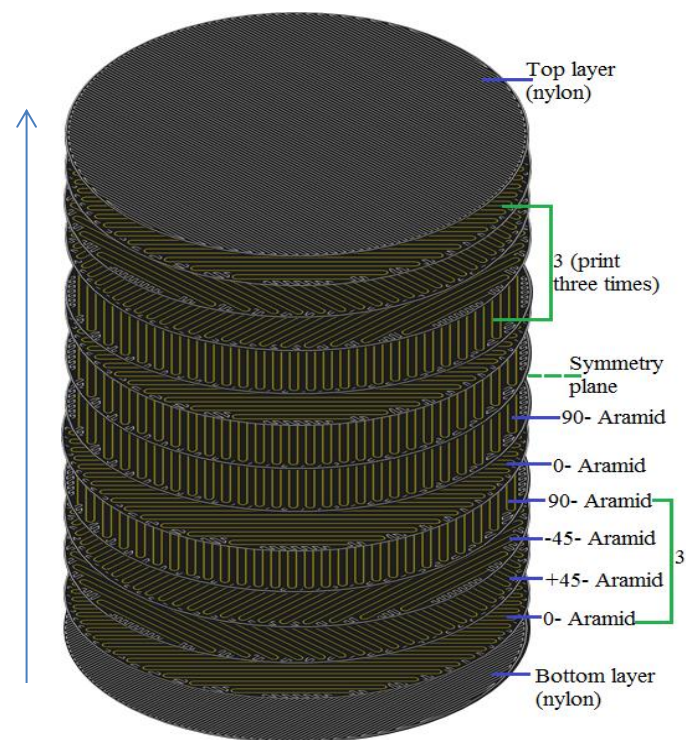


Figure 7. Ply orientations of ballistic panels. Reprinted with permission [99]. Copyright under open access publication (CC BY/4.0).

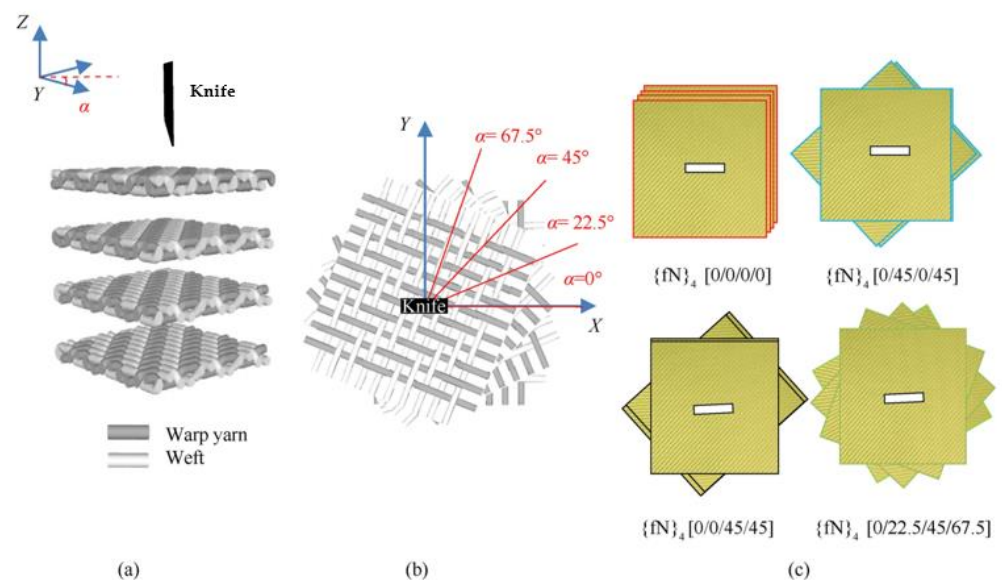


Figure 8. Schematic view of (a) fabric layer arrangements and knife positioning, (b) the coordinating system of the fabric ply with different angle orientations, and (c) the arrangements of aligned and angled panels. Reprinted with permission [98]. Copyright under open access publication (CC BY/4.0).

As shown in Figure 9, the test results illustrate that specimen with aligned multi-ply fabric layers ($\{sN\}_4 [0/0/0/0]$ or $[(0)4]$) have generally lower DoP values compared to the angled configurations. This is because the aligned layers optimize resistance by placing the warp yarns directly along the path of the knife, thus allowing the shear force to be effectively distributed. On the other hand, angled multi-ply fabric panels present different values of DoP and DoT due to changing ply orientations. For instance, the angled configuration $[0/22.5/45/67.5]$ generally has lower DoT than that of aligned configurations $[0/0/45/45]$ and $[0/45]$, which better dissipate the energy through the panel. This can be

explained by the fact that the higher angle of fabric orientations includes larger resistance from weft yarns and stuffer warp yarns against the shearing force of a knife blade.

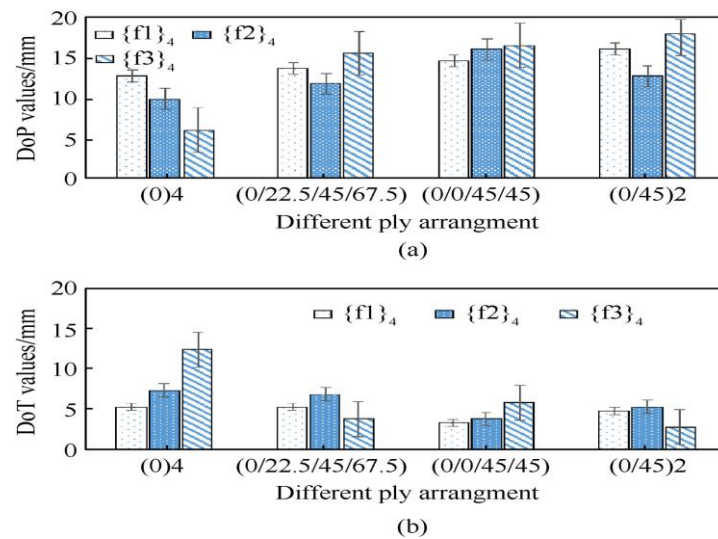


Figure 9. The effects of different fabric layer orientation systems within the specimens on the (a) Depth of Trauma (DoT) and (b) Depth of Penetration measured on the back of target specimen at the surface of the backing materials for different layers of fabrics. Reprinted with permission [98]. Copyright under open access publication (CC BY/4.0).

2.2.4. Effects of Textile Finishing and Treatment

Apart from the effects of multiple fabric parameters, including the number of fabric plies and their stacking sequence, and fabric architecture, the finishing of the materials also greatly contributed to the stabbing performance. Such finishing mainly creates friction between yarns, and such a phenomenon plays a critical role in the energy dissipation mechanism of woven fabrics under impact. This is closely dependent on the mobility and friction between the yarns, which relates to the fiber-fiber interfacial property of the fabric. In such interactions of yarns during an impact event, the friction generated plays a vital role in dissipating energy and is hence crucial for impact resistance. To enhance this energy dissipation mechanism, much research has been directed toward different fiber surface modification techniques. In particular, the effectiveness of fiber surface modifications, such as lubrication [65,102], coatings [103–105], and interphase design [106,107], depends on the nature of the impact and the characteristics of the weapon. While these treatments enhance frictional energy dissipation and restrict fiber mobility, they do not provide absolute resistance against fiber rupture, especially under extreme conditions. For example, the lubrication technique reduces unwanted resistance with controlled friction levels and is hence an effective way to optimize inter-yarn friction. Coatings add a protective layer to the fibers, which can enhance their interaction and improve energy dissipation, whereas interphase design extends this further by functionally tailoring the interface between the fibers for enhanced frictional performance. Very good improvements using these methods in enhancing the impact response of the woven fabric have lately been reported. These modifications lead to increasing the amount of inter-yarn friction to enhance dissipation capability but, more so, improve fabric durability and performance as well. Accordingly, for better performance, development using weaving technology would therefore still put special focus on increasing inter-yarn friction in this advanced material design when high impact resistance is necessary. Once the influence of friction is clearly defined, materials with very low and low friction levels need to be improved through the above-mentioned and other finishing techniques for more energy absorption [3]. Additionally, research has

shown that the effectiveness of such treatments varies based on the type of penetrating object. For instance, shear-thickening fluids (STFs) integrated with Kevlar fabrics have demonstrated improved resistance against dynamic stab threats by increasing inter-yarn friction and restricting fiber movement. However, studies also indicate that while STF-treated fabrics reduce yarn slippage and enhance stab resistance, fiber-level penetration may still occur when facing extremely sharp or high-velocity blades [70,71]. Polymeric coating on tow pull-out responses of Kevlar showed enhanced friction [108]. On the contrary, some materials have a high friction coefficient and need to be reduced using humidity for hydrophilic materials and softening treatments [109,110]. As shown in Figure 10, the high inter-yarn friction of STF/Kevlar fabric could strengthen the resistance relative motion of yarns so that more surrounding yarns participated in the impact energy dissipation and maximized the role of high-performance Kevlar fabric [111].

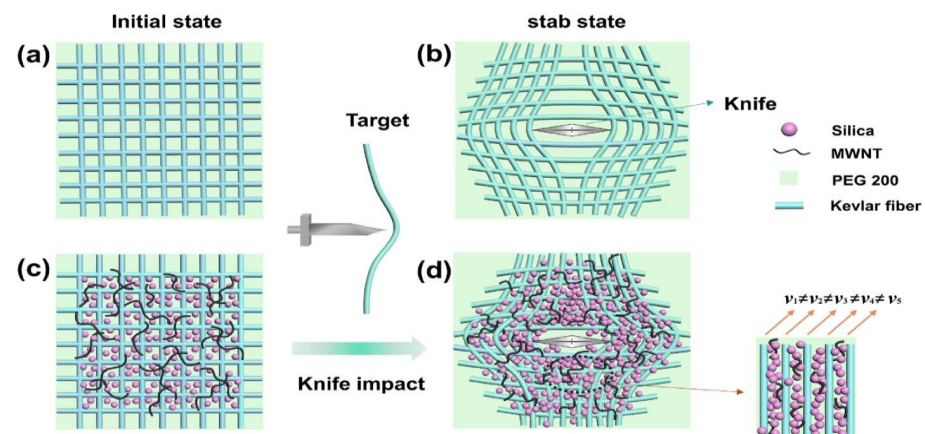


Figure 10. The stab resistance mechanism of (a,b) Neat Kevlar and (c,d) STF/Kevlar fabrics under the impact of the knife. Reprinted with permission [111]. Copyright under open access publication (CC BY/4.0).

Depending on the types of chemicals, the treatment of textiles improves the compressive resistance and increases the force required to pull out the yarn. The nanocomposite hydrogel treatment of the Kevlar woven fabrics improves the compressive resistance and yarn pull-out force [112]. This result shows that the Kevlar woven fabrics' stab resistance performance will improve through metal treatments using an aluminum and copper bond coat. The result revealed that the use of a copper bond coat enhanced the stab resistance by 10% compared with the aluminum bond coat. The tensile strength test also indicate that the structure of the fabric has been preserved, and no damage to its fibers was observed after the tensile test [113]. Other research also examined the capacity of fibrilized aramid fabric to improve stab protection against a spike by performing drop tower testing on treated targets from a fixed height with varying drop masses [114]. The fibrilization treatment on the fabric does not significantly alter the areal density, thickness, or flexibility of the aramid fabric. As a result, the same number of plies was used for untreated and treated fabric targets to ensure a fair comparison. The drop height was set at 0.35 m, while the total drop mass ranged from 1.407 kg (unloaded carriage) to 1.907 kg. The Depth of Penetration along with the impact load for each drop mass can be seen in Figure 11.

Based on the investigation, the penetration depth and impact load increase with drop mass for both untreated and treated fabrics. However, treated aramid fabrics offer superior stab resistance, preventing puncture at 1.407 kg and reducing penetration depth by 230% while increasing impact force by 110% at higher masses. The study was further examined using the failure modes of untreated and treated aramid fabrics post-stabbing to greatly understand the role of the fibrilization treatment in the stab resistance reinforcement mech-

anism as shown in Figure 12. Moreover, experimental results on fibrilized aramid fabrics (Figure 12) highlight that while surface treatments increase inter-yarn friction and improve resistance to spike penetration, they may not prevent damage entirely when exposed to sharp-edged knives. The treatment enhances resistance by limiting yarn displacement and increasing energy absorption; yet, some degree of fiber rupture remains inevitable depending on impact conditions. Therefore, based on the result, untreated aramid fabrics exhibit significant puncture damage post-stabbing, while treated fabrics show enhanced stab resistance due to fibrilization treatment. This treatment increases inter-yarn friction, restricting fiber mobility and preventing spike penetration, unlike untreated fabrics that fail via intra- and inter-yarn slippage.

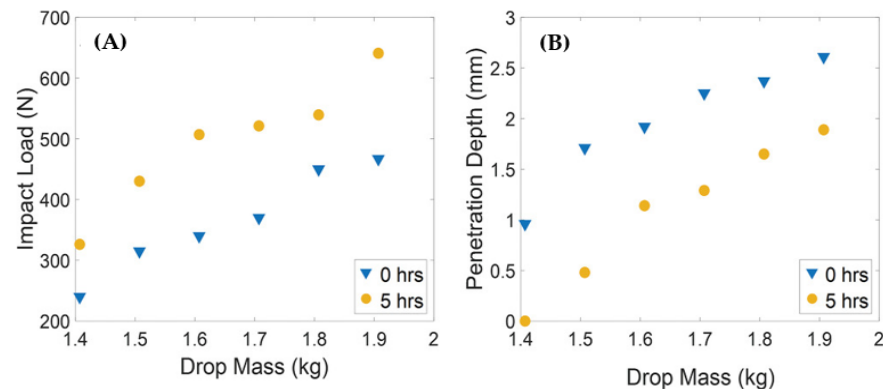


Figure 11. Quasi-static stab testing: (A) Penetration depths of untreated and treated aramid fabric targets against spike impactor for different drop masses. (B) Impact loads of untreated and treated aramid fabric targets against spike impactor for different drop masses. Reprinted with permission [114]. Copyright under open access publication (CC BY/4.0).

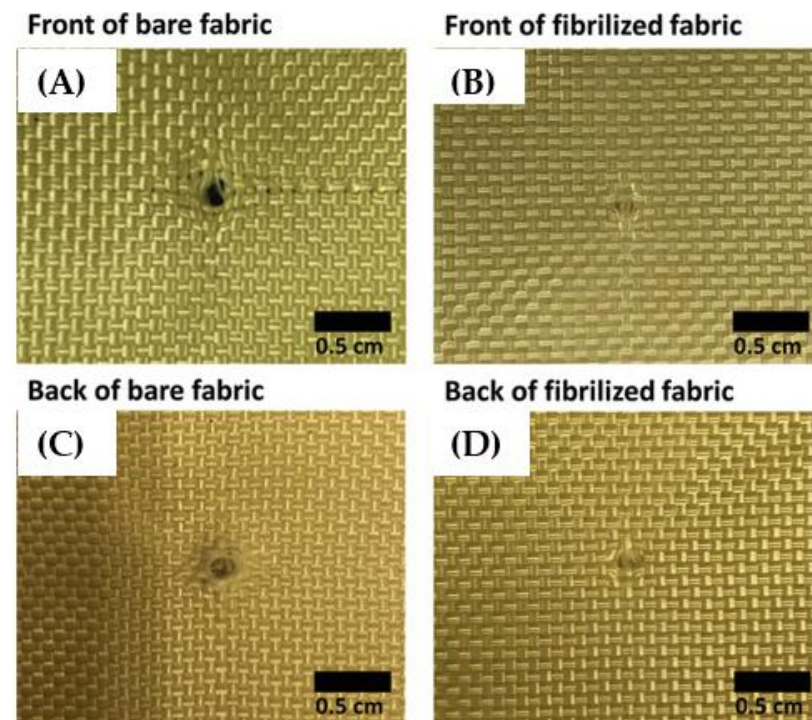


Figure 12. Comparison between untreated aramid fabrics and treated aramid fabrics after testing against spike impactor: (A,B) damage to the front of untreated and treated aramid targets at a drop mass of 1.807 kg, respectively; (C,D) damage to the back of untreated and treated aramid targets at a drop mass of 1.807 kg, respectively. Reprinted with permission [114]. Copyright under open access publication (CC BY/4.0).

3. Exogenous Parameters in Stab Resistance of Textiles and Composite Materials

The performance of a textile against sharp object penetration is strongly influenced by the intrinsic properties of the material itself but also by exogenous parameters, which include the stabbing methods and condition, nature of the external force, geometry of threat, and environmental factors. Knowing those external influences is important to design effective materials that can face real challenges. Some of the most important exogenous parameters involve the type and shape of the penetrating object, the angle of incidence, speed and energy of impact, and temperature and humidity. For example, a narrow, pointed object like a needle focuses its stress on a small area, while broader or more blunt objects distribute force over larger surfaces. The angle of incidence is a relevant factor concerning the resistance of the textile structure, as an oblique incidence generates a loss of resistance when compared with an incidence in a perpendicular position. The speed and energy released by the force have an influence on performance, and the velocity of impacts also allows for an increase in the probability of penetration in all high-performance textiles. Other factors, such as high temperatures, may soften some of the textile materials, which will make them less resistant to punctures, while the rise in humidity can alter some mechanical properties of fibers, mainly in natural textiles. Considering such external factors puts researchers in a better position to understand the interaction of the threat with the textile structure and thus design optimized materials that can withstand application-specific requirements. This section discusses in detail the effects of the different exogenous parameters on stabbing response and performance of the final stab resistance of protective materials.

3.1. Stabbing Methods and Conditions

Stab testing techniques are categorized based on impactor characteristics and varying energy levels. According to stabbing impact energy, several standards, including the National Institute of Justice (NIJ0105.00), Home Office Scientific Development Branch standard (HOSDB), PSDB, ASTM, and European standards, identify other protection levels. The armor panel's stab resistance capabilities are assessed by quasi-static and dynamic testing. In general, stabbing is a dynamic impact event. The foundation of dynamic test methods lies in air cannon tests and drop mass impact test rigs. The drop mass test rig, which is proposed by NIJ standard 0115.00 (Stab resistance of personal body armor), has been used by most researchers. This standard has been created to replicate the biomechanics of stabbing attacks regarding impactor mass, velocity, and damping properties. It is frequently used globally to describe how well body armor resists stabs and punctures. Quasi-static testing is carried out at a very low strain rate compared to dynamic tests. Dynamic impact tests better reflect actual stab and spike attack events, which occur at a higher strain rate [115,116].

3.1.1. PSDB Standard

The UK Home Offices follow the PSDB standard test widely used by police agencies in the country. Thereafter, the PSDB and NIJ developed NIJ standard 0115.00. The test procedure is often referred to as the KR42 standard. A small group of volunteers stabbed a high-density foam block, recording the knife's penetration into the block and its terminal velocity. The test was then performed with the knife launched at the same speed using an air cannon. The knife missile's mass was changed to get the same penetration into the target. The air-cannon device approach uses two distinct types of knives (a little pocketknife and a large Bowie knife). The dimensions and shape of these blades vary. One of the two knives is chosen for the test, and it is launched from the air cannon at the target, which

is a conditioned Plastilina block while being held in sabots. The total projectile weight is 0.4 kg, and optical methods are used to estimate its muzzle velocity. Once the knife strikes the target, the penetration is calculated from the depression in the Plastilina clay. The penetration is displayed as a function of impact energy, and the impact energy is adjusted within the range of 20–65 J. In addition to the air cannon test, the armor is subjected to a manual, angled attack. The hand test aims to assess the armor in a real-time situation, which is made up of distinct plates [117–119].

3.1.2. National Institute of Justice (NIJ) Standard

The United Kingdom Police Scientific Development Branch (PSDB) test methodology was the basis for the NIJ standard [120]. To simulate the characteristics of a stabbing attack, this protocol employs single-pointed and double-edged weapons, as seen in Figure 13.

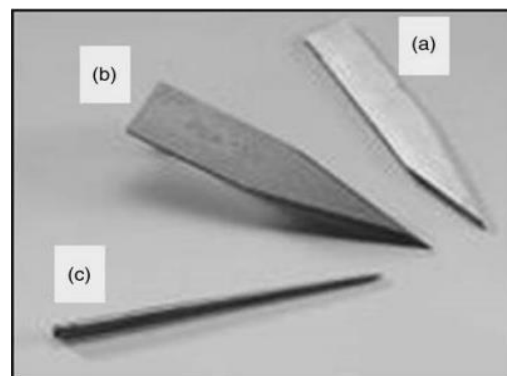


Figure 13. Various stab knives, (a) P1 knife; (b) P2 knife; and (c) spike for stab and spike protection testing based on National Institute of Justice (NIJ) 0115.00 standard.

The test involves mounting each weapon separately on a damped two-part drop mass that drops freely from a predetermined height onto unclamped textiles layered on top of a backing material to determine the protection level, as listed in Table 1. The following elements should be present in dynamic test assemblies created using the drop mass impact test rig method per the standard: a drop assembly for conducting the stab and spike test; a drop mass that descends freely in the presence of gravity; and the test knife's inability to spin around its vertical axis while in free fall; the drop mass and knife assembly's combined weight must be counted during the calculation of total impact energy.

Table 1. Displays the striking energy for the protective level of stab resistance (National Institute of Justice, norm 0115.00).

Protection Class		Protection Class E1 with a Maximum Penetration of 7 mm	Protection Class E2 with a Max. Penetration of 20 mm
Protection level	Threat level	Strike energy E1 (J)	Overset strike Energy E2 (J)
1	Low	24 ± 0.50	36 ± 0.60
2	Medium	33 ± 0.60	50 ± 0.70
3	High	43 ± 0.60	65 ± 0.80

In most drop mass experiments, the armor material is supported by a flesh simulant, and the weapon of choice (e.g., drop mass with a knife) is used to determine the stab energy. The knife's kinetic energy, or the force of slashing, is measured by its drop mass and velocity. A drop mass of around 2 kg is used in several test standards for the instrumented knife test.

Instead of changing the mass, one may alter the drop height to achieve a range of impact energy. Generally, an energy range appropriate for the study of stab protection may be produced using a drop mass of 2 kg and a drop height of 0.5–3 m. The drop mass's velocity at the point of contact should be measured as part of the dynamic test. Various devices can be used to detect the velocity before impact, including photoelectric light screens, light/laser sensor diodes, light arrays, and high-speed cameras. The apparatus must be calibrated and capable of measuring velocity to within ± 0.2 m/s [6].

3.1.3. Home Office Scientific Development Branch Standard (HOSDB)

The second recommended approach, an alternative to the NIJ standard, is produced by the UK's Home Office Scientific Development Branch (HOSDB). The operational idea of both standards is quite similar. The HOSDB standard is also extensively used, although it has a different approach to outcome evaluation. Part 3 of the HOSDB Body Armour Standards for UK Police (2007) provides comprehensive details on the kinds of weapons (knives and spikes), test settings, and backup ensembles to be used with body armor. The standard recommends choosing police clothes according to danger levels as listed in Table 2 [116,121]. KR1 and KR1 + SP1: At a 24 J energy level, the lowest protection level was evaluated. This level of testing should ensure that the armor is appropriate for overt and covert usage in low-risk patrolling environments and that wear-ability concerns are resolved. KR2 & KR2 + SP2: 33 J energy level was used to assess the medium protection level. The armor must be wearable and appropriate for overt and covert use at this testing stage. KR3 and KR3 + SP3: The maximum protection level was tested at an energy level of 43 J. The armor should only be worn for a few minutes in high-risk scenarios.

Table 2. Protection level, energy level, and maximum penetration depth as per the HOSDB standards.

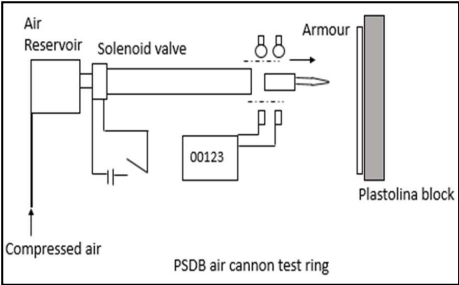
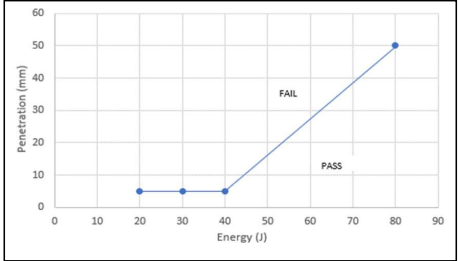
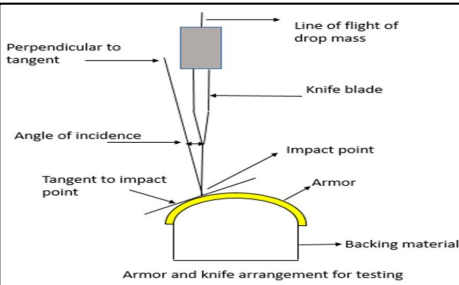
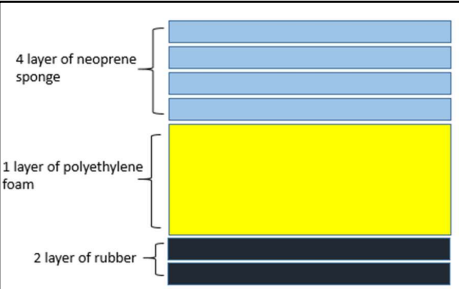
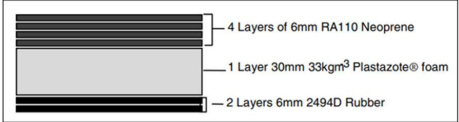
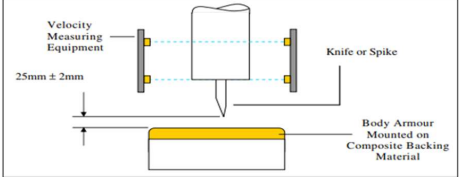
Protection Levels	Energy Level E1 (J)	Maximum Penetration at E1 (mm)	Energy Level E2 (J)	Maximum Penetration at E2 (mm)
KR1	24	7	36	20 *
KR1 + SP1		KR1 = 7, SP1 = 0 *		KR1 = 20, SP1 = N/A
KR2	33	7	50	20*
KR2 + SP2		KR2 = 7, SP2 = 0 *	KR2 = 50, SP2 = N/A	KR2 = 20 *, SP2 = N/A
KR3	43	7	65	20*
KR3 + SP3		KR3 = 7, SP3 = 0 *	KR3 = 65, SP3 = N/A	KR3 = 20 *, SP3 = N/A

* One penetration not exceeding 30 mm is permissible at E2 knife testing and one penetration (no depth limit) is permissible for spike testing. N/A—Not applicable, KR-Knife resistance, SP-Spike resistance.

Table 3 shows the summary of the common standard methods described above. It includes the standard test methods, testing setup, and pass/fail criteria of the stab resistance armor. Apart from the stab resistance pass/fail criteria, the calibration of the composite backing materials is an equally important factor to measure the true performance of any stab resistance armor panels. In general, two types of composite backing materials are reported, which are either made of foam or Plastilina® No 1. The foam-based composite backing material is calibrated by using 63.5 mm diameter steel sphere having the weight of $1.043 \text{ kg} \pm 5 \text{ g}$. The calibration drop shall consist of a free fall of the sphere onto the backing material. To achieve this, the pack should be placed on a solid concrete floor. Three drops shall be completed, and the arithmetic mean height of rebound achieved from

three drops shall be $425\text{ mm} \pm 75\text{ mm}$. In the other case, Plastilina[®] No 1 is used as backing material, and the calibration drop shall consist of a free fall of the same sphere as described above onto the clay. A minimum of three drops shall be completed, and the mean depth of depression shall be $15\text{ mm} \pm 1.5\text{ mm}$, measured from the top edges of the clay box.

Table 3. Commonly used test standards for stab and puncture resistance material assessment.

Standard	The Setup Used for the Test	Pass/Fail Criteria															
(Method 1) PSDB air-cannon test rig	 PSDB air cannon test ring <table border="1"><caption>Penetration vs Energy Data</caption><thead><tr><th>Energy (J)</th><th>Penetration (mm)</th><th>Result</th></tr></thead><tbody><tr><td>20</td><td>5</td><td>PASS</td></tr><tr><td>30</td><td>5</td><td>PASS</td></tr><tr><td>40</td><td>5</td><td>PASS</td></tr><tr><td>80</td><td>50</td><td>FAIL</td></tr></tbody></table>	Energy (J)	Penetration (mm)	Result	20	5	PASS	30	5	PASS	40	5	PASS	80	50	FAIL	On the left, a visual representation of the maximum permitted penetration for a pass or fail is displayed (energy penetration).
Energy (J)	Penetration (mm)	Result															
20	5	PASS															
30	5	PASS															
40	5	PASS															
80	50	FAIL															
(Method 2) NIJ 0115.00	 Armor and knife arrangement for testing 	E1 strike energies: at impact angles of incidence of 0° and 45° , the armor should not permit penetration of a knife blade or spike larger than 7 mm. E2 strike energies: at a 0° angle of incidence, the body armor cannot permit the penetration of a knife blade or spike longer than 20 mm. The armor fails the stab resistance drop test if a hit with energy less than E1 results in more than 7 mm of penetration.															
(Method 3) HOSDB Body Armour Standards for UK Police-part 3	 	At different knife alignments, a maximum of 7 mm of knife penetration into the backing material is permitted. It is not allowed for the spike to penetrate.															

3.1.4. Quasi-Static Methods

In contrast to dynamic testing, quasi-static testing involves a substantially lower traverse speed of the blade mechanism. In quasi-static testing, the test equipment moves at a significantly reduced speed, such as 1 cm/min, but in dynamic testing, the test assembly travels in guided rails with very little friction. Quasi-static tests are often performed using a tensile tester based on a constant rate of elongation (CRE) or constant rate of loading (CRL). Rigidly fixed to the upper jaw of the testing apparatus is the test knife or test spike, and the load cell measures the penetration force through the fabric specimen. Before performing the dynamic tests, the quasi-static test techniques can be utilized as a reference when an initial evaluation is required. It is possible, though, that the outcomes of the quasi-static testing will not transfer over to the dynamic tests [32]. For both stab and puncture examination, quasi-static testing has been the focus of several studies. Shin et al., for instance, moved a knife blade through a yarn made of polyethylene, aramid, and Zylon held at both ends at an even rate of 0.25 m/s. The load-deflection relationship was determined by measuring the energy needed to cut through the yarn. Russell et al. used a flat-faced puncture probe to examine the puncture resistance of nonwoven textiles made from spun-lacing high-modulus polyethylene (HMPE) fiber. The impact resistance of the fabric, particularly the ballistic resistance, was examined, and the effects of web stacking and applied water jet pressure were examined. Because the fabric density increases as the water jet pressure increases, it was found that the puncture resistance increases as well. All laboratories equipped with simple tensile testing apparatus or load sensors may perform the quasi-static test procedures, which take less time to complete. When there is no option for dynamic testing, they are recommended. However, because the processes of puncture and stab at various velocities change, the quasi-static test findings could not correlate well with the dynamic test. Therefore, preventing a direct connection between the findings from the quasi-static tests and the dynamic testing may be possible. Furthermore, depending on the test's specific parameters, the outcomes of dynamic tests might differ from one location to another. Even when a comparable test standard or technique is employed, variable results may still occur depending on the kind of knife, Plastilina grade, sample edge clamping, and test circumstances. Body armor producers mainly test their goods or armor materials by the particular test criteria listed in Table 3 [122–125].

3.1.5. Backing Materials for Stab and Spike Tests

Different kinds of backing materials have been detailed in many of the test standards. During testing, the back face deformation (BFD) in the backing material determines the pass/fail standards. Different kinds of backing materials have been detailed in many of the test standards. During the testing, the back face deformation (BFD) in the backing material determines the pass/fail standards. On the rear side of the striking material, BFD characterizes the impact of a projectile or drop mass assembly. The NIJ establishes 44 mm as the maximum amount of permitted distortion in its standards. Stab and puncture tests frequently use backing materials to mimic a human body's reaction. In addition to being helpful information for evaluating the effectiveness of protective equipment, the findings of testing with backing materials can also be beneficial in forensic investigations of stab-wound-related crimes [62,126,127]. Numerous supporting materials, varying in stiffness, viscosity, and combination, are available for stab and spike testing, including pork, gelatin, multilayer foam, and Roma Plastilina No. 1. The stab and puncture resistance are influenced by the backing material's stiffness or viscosity. More resistance to penetration will be offered by stiffer materials, which will result in a lower measured trauma. The relative humidity and ambient temperature affect the viscosity of the backing material; however, these factors can be reduced with appropriate preparation before use. Both alone

and in conjunction with other materials, materials like Roma Plastilina No.1, a kind of clay used in ballistic and stab tests to simulate human flesh, are employed. Usually, a rigid container or wooden box with an open-top surface is filled with clay, making sure there are no air spaces between the clay and the container walls. For some Plastilina, the clay must be conditioned at a specific temperature for at least eight hours. The drop test is carried out once the sample has been positioned as needed. After being released, the drop mass descends in a precise direction onto the cloth. Measurement tools like a profiler, a clean metal rod, or a ruler should be used to determine the stress inflicted on the Plastilina during the stab test. The depth of the impression may be measured with a ruler and can be described as the “total trauma” by inserting the profiler or metal rod into the depression the knife left after the test. Before conducting further experiments, the Plastilina must be reconsidered and reshaped. For every sample, it is imperative to perform several measurements and provide the average value and standard deviation (SD) [6,128]. The impact energy is absorbed and dispersed inside the structure based on the kind of armor and backing material when the knife installed in the drop mass assembly contacts the test specimen positioned over a backing material. The Depth of Penetration is reduced when the backing material easily releases energy. For instance, the impactor can penetrate deeper into softer and more pliable backing materials due to their softness in testing. As a result, the impactor has greater penetration depth. However, the penetration depth would be minimal if the backing material was inflexible and non-deformable. This results in a decreased penetration depth because the backing material’s hardness prevents the penetrator from entering the structure. As per the NIJ 0115.00 standard, the proposed numerous layers, as shown in Figure 14, include four layers of thick neoprene (5.8 mm), a single layer of closed-cell polyethylene foam (31 mm, 33 kg/m³), and two layers of thick natural rubber (6.4 mm).

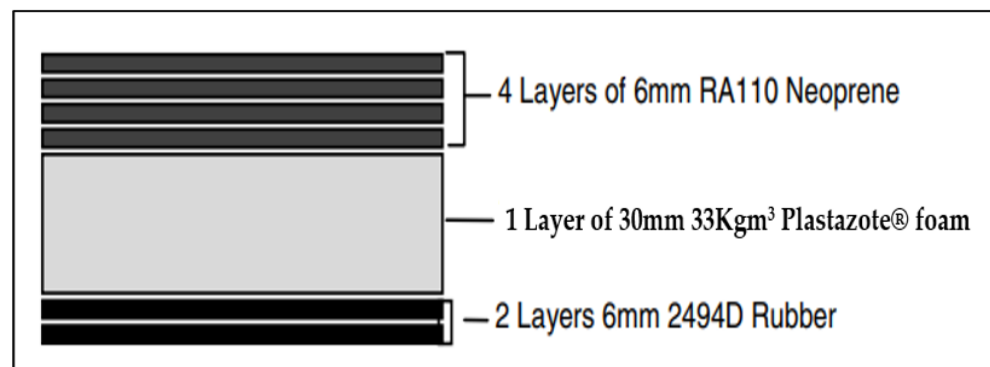


Figure 14. Composite backing material based on the National Institute of Justice (NIJ) 0115.00 standard.

Comparably, the HOSDB Body Armour Standard (Part 3) backing material for stab testing consists of a composite (Figure 15) made up of (i) four layers of neoprene (6 mm thick; RA110), (ii) one layer of Plastazote (30 mm thick; 33 kg/m³), and (iii) two layers of rubber (6 mm thick; 2494D).

In general, optimizations of stab-resistant textile materials must be selected and designed according to an integrated strategy considering both internal (fiber composition, yarn structure, weave architecture, and finishing treatments) and external (environmental conditions, aging effects, and expected types of threats) parameters. For instance, high-performance fibers such as aramid and ultra-high-molecular-weight polyethylene (UHMWPE), typically embedded in composite systems, currently provide the optimum performance under various stabbing conditions due to their high tensile strength, energy absorption capacity, and inherent cut resistance. These polymer-based textiles, however, are susceptible to degradation from exposure to harsh environmental conditions. High

temperatures can plasticize UHMWPE and lose mechanical integrity, compromising its penetration resistance, and prolonged exposure to UV radiation can lead to embrittlement as well as fiber degradation, particularly in aramid-based fabrics [129]. Furthermore, the performance of traditional woven and nonwoven stab-resistant fabrics may be enhanced by utilizing advanced structural engineering methods, including multi-material hybrids, 3D-structured textiles, multi-layered or interlocked textile structures, and impact-responsive materials. These arrangements allow for improved energy dissipation, load distribution, and penetration depth minimization and are therefore promising candidates for future protective textiles [88]. Hybridization with smart textiles such as shear-thickening fluids (STFs) and auxetic structures gives an additional impetus to stab resistance by dynamically adapting to impact loads and adding further strength at high-strain levels. Innovation in future stab-resistant fabrics will persist in emphasizing durability improvement, flexibility, and multi-threat protection while challenging environmental and material limitations by advancing hybrid and adaptive materials [130–133].

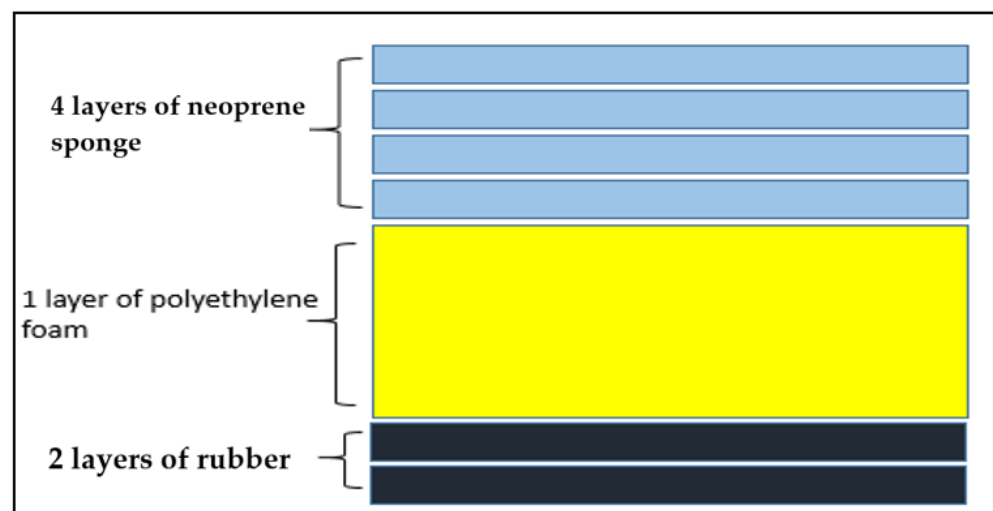


Figure 15. Composite backing material based on the Home Office Scientific Development Branch (HOSDB) standard.

3.2. Effects of Impact Velocity, Energy, and Angle of Incidence

This section will discuss the influences of stab blade velocity, weight, impact energy, and angle of the stabbing materials on the stab response, as well as the performance of the final stab materials.

3.2.1. Effects of Impact Velocity and Energy

An impacting projectile energy loss determines the energy-absorbing characteristics of textile structures made of high-modulus and high-strength fibers. It also depends on the coating of shear-thickening fluids, polymers, shear-stiffening gel, and boron carbide, etc. [134,135]. The coating of polymeric materials enhances the coefficient of friction between the high-performance yarn in the textile structures, leading to higher energy absorption than the neat panels [136]. In the case of smart polymeric materials such as shear thickening fluid and shear stiffening gel, friction and thickening behaviors are also enhanced at a higher shear rate during the impact of the knife and projectile. Both parameters enhance the energy absorption of the textile structures.

The absorbed kinetic energy of the projectile is calculated using the following relationship:

$$E_m = \frac{1}{2} m (v_i^2 - v_e^2), \text{ if } v_i > v_p \quad (4)$$

$$E_m = \frac{1}{2} m v_i^2, \text{ if } v_i < v_p \quad (5)$$

where v_e is the exit velocity (m/s), m is the projectile mass (kg), v_p is the penetration velocity (m/s), and E_m is the energy loss (J).

This relationship offers an easy and valuable method to determine a stab-resistant soft armor vest's ballistic limit. High-speed cameras are used to monitor the exit velocity now that the bullet ultimately enters the vest. The study investigates the effects of impact loads on both soft and stiff vests, analyzing the failure modes of single-fabric and multilayer designs in both in-plane and out-of-plane orientations. Identification of the contribution of each successive fabric layer to the energy absorption process is made to ascertain the interfacial parameters, such as friction and fracture toughness, back face signature, and ballistic limitations. These understandings are essential for creating vests that satisfy specific stab and ballistic protection specifications. Furthermore, it has been noted that the layered fabric vest would split and fail under stab-type loads, such as overarm (10 m/s) or underarm (7 m/s), allowing the blade to pierce through the cloth. This is due to the point of the blade [137].

3.2.2. Effects of Angle of Incidence

Abtew et al. have studied the effect of angles of incidence on stab resistance performance of various types of 2D and 3D fabric structures of aramid fabric at 0° , 22.5° , and 45° angles. It is noticed that as the angle of incidence increases, there is a significant enhancement in the Depth of Trauma (DOT) and Depth of Penetration (DOP), as shown in Figure 16c, which suggests that higher angles of incidence result in greater trauma, indicating a reduced ability to absorb and distribute energy efficiently in the larger area of the armor panel. Figure 16a,b depicts the side view of the impression on the clay at 0° and 45° angles of incident of the knife on the 2D and 3D fabric panels.

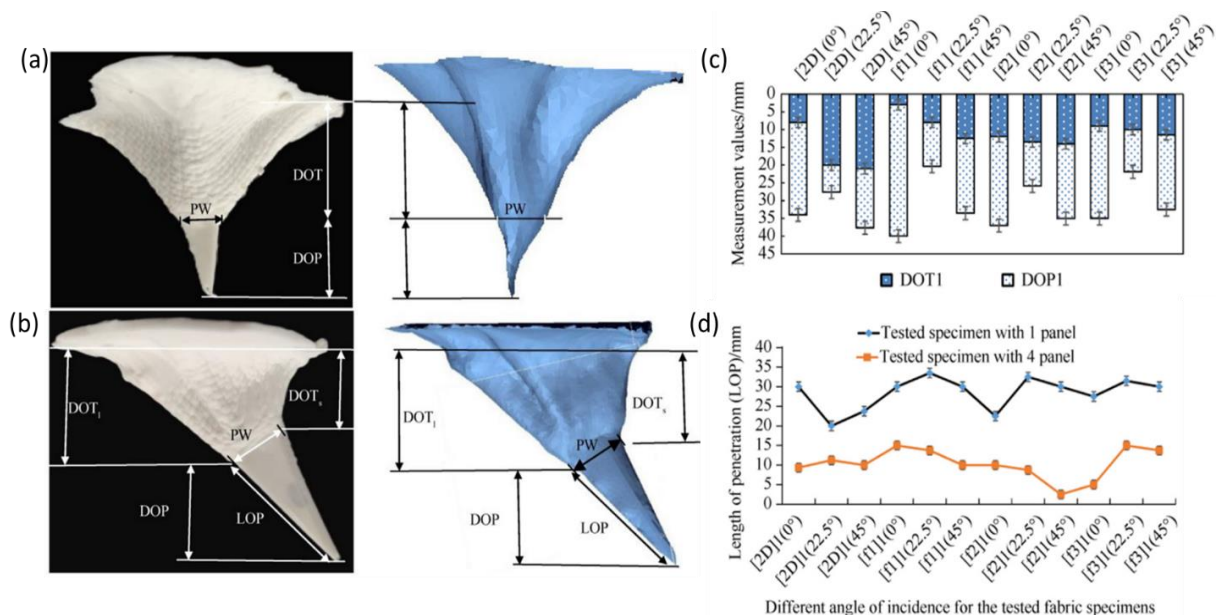


Figure 16. Effect of angle of incidence of knife. (a) Side views of 0° angle of incidence. (b) Side views of 45° angle of incidence. (c) Measurement of Depth of Trauma (DOT) and Depth of Penetration (DOP). (d) Measurement of length of penetration (LOP). Reprinted with permission [19]. Copyright under open access publication (CC BY/4.0).

Figure 16d shows the measurement of length of penetration (LOP). It is observed that LOP values at the backing materials decline as the number of panels increase irrespective of the fabric type used and angle of incidence. Another report showed that the performance

of the materials is also determined by the number of impact incidences in addition to the angle of incidences. If the armor is stabbed repeatedly in a specific area, the resistance of the armor decreases and the fracture width increases [17] so as to allow the knife to penetrate to the soft body.

As shown in Figure 17a,b, the angle of incidence has a significant impact because the hole formed after the impact has a different width, which shows the portion of the knife inside the specimen. Figure 17c-f are an indication that the resistance of the stab vest also depends on the friction resistance of the material to hold the knife and not to pull out simply for repetitive incidence [17]. So, repeated stabs increase the failure of the protective armor, and scientists need to improve the frictional force of the protective material to avoid repeated stabbing on one point of the sample. Another study has also explored how blade angle influences peak force, average force, and work those results from a sharp force impact. Three blade orientations relative to the long axis of the rib were tested (0° , 45° , and 90°), as shown in Figure 18 using 62 porcine side ribs [138].

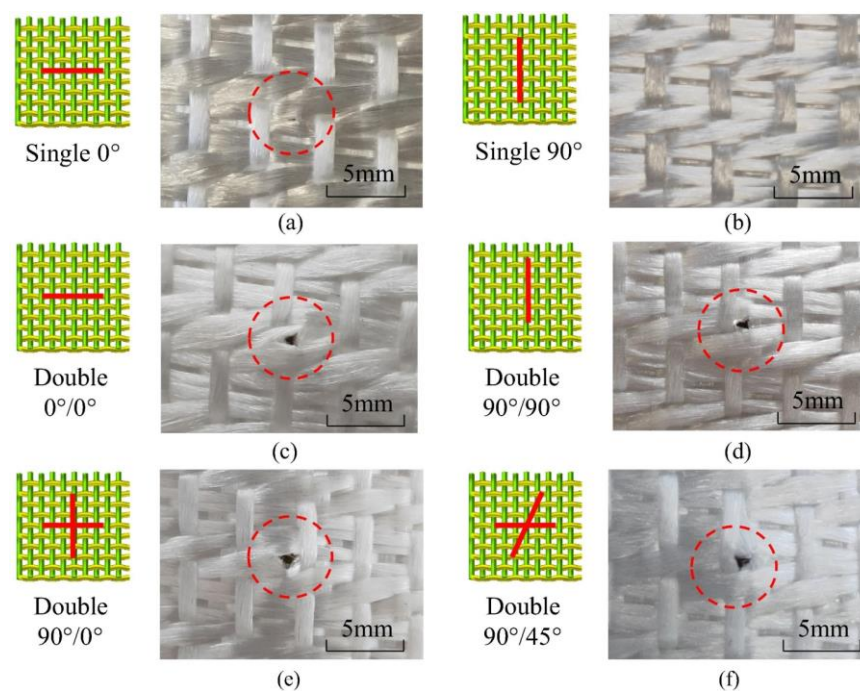


Figure 17. Number of stabs at different angles of incidence, (a) Single 0° , (b) Single 90° , (c) Double $(0^\circ/0^\circ)$, (d) Double $(90^\circ/90^\circ)$, (e) Double $(90^\circ/0^\circ)$ and (f) Double $(90^\circ/45^\circ)$. Reprinted with permission [17]. Copyright under open access publication (CC BY/4.0).



Figure 18. Custom fixture for holding the ribs in one of three orientations [126–133,136–138]. Reprinted with permission [138]. Copyright under open access publication (CC BY/4.0).

For this study, a paring knife (MASTER Chef, Canadian Tire #142-3462-4) was tested, which is 183 mm long $\times$ 17.8 mm wide $\times$ 1.2 mm thick, with a 41° tip angle and a 0.38 mm tip radius. The handle was removed, and the tang was cut, leaving a 138.5 mm length from the knife. The modified knife was set in a blade holder for testing. As shown in Figure 19, the result shows that the highest peak force occurred when the blade was perpendicular (90°), while the lowest was when it was aligned (0°). By contrast, the highest work was needed at an oblique angle of 45° . These results indicate that the orientation of the blade is important in determining the mechanical forces associated with sharp force injuries.

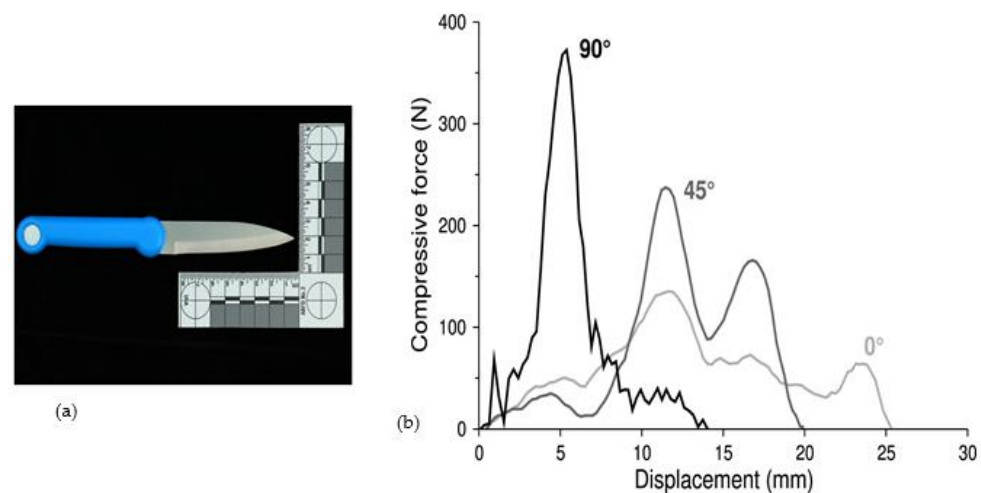


Figure 19. (a) Paring knife used for stabbing tests and (b) one representative force-displacement curve from each of the 90° , 45° , and 0° tests. Reprinted with permission. [138]. Copyright under open access publication (CC BY/4.0).

3.3. Effects of Stabbing Blade Conditions

The performance of armor materials against stabbing threats strongly depends on the conditions of the blade impact against the surface. Factors such as type, shape, sharpness etc. will make a difference in how the material responds to attempted penetration [139]. Unlike ballistic threats, which are high-speed impacts, stabbing threats are very localized and concentrated in force, often taking advantage of weaknesses in fabric structures, seams, or material interfaces [140]. Various stabbing scenarios can result in significantly different performance outcomes for armor materials. For example, a thin, sharp-edged blade may cut through between yarns in a woven fabric, while a blunt or serrated blade may cause more deformation before penetration [141]. Therefore, such conditions have to be well understood in order to design protective solutions that can effectively mitigate such attacks. The following section will discuss those parameters that will help researchers and manufacturers to come up with improved protective structures that can provide improved resistance without sacrificing flexibility, weight, or comfort.

3.3.1. Knife-Making Process

Usually, stainless steel strips are used to make knives. The strip is blanked out, and the knife then runs through a succession of rollers to grind the cutting edge onto the strip's edge. Blade designs for kitchen knives typically come in hollow ground and taper ground. Tapered base knives slope from the blade's keep to its edge. Simple grinding is performed near the tip of hollow-ground blades. Knives that have been hollow or edge ground are more likely to dull after repeated usage. Modern kitchen knives are not always cut from a strip; some are forged from steel alloy. High-strength CrMoV steels are used in the construction of these blades. These blades are made in a process like steel blade knives, but because the material is more challenging, the cutting edge lasts longer on these blades

than on less expensive stainless steel knives. The edges might be coated with substances like tungsten carbide, and the edges might be scalloped, serrated, or plain. These affect the edge's sharpness based on the cutting motion; for instance, bread knives are frequently serrated, providing the blade edge with several sharp cutting points. The knife's shape, when made of blank steel, and the level of sharpening around the tip determine the knife's tip sharpness [139]. The following sections detail the variables affecting tip sharpness.

3.3.2. Shape and Sharpness of the Knife Blade

Currently, no British standards concentrate on the factors that influence a knife's sharpness in terms of tip sharpness and blade geometry. A British Standard Test known as BS EN ISO 8442-5:2004 is used to measure initial sharpness and durability, which implies moving the knife through silica-impregnated cardboard. Because the measurements would change the blade, this procedure is damaging and inappropriate for forensic testing. Furthermore, the cutting motion in the standard takes advantage of the blade's extended edge rather than its tip. When stabbing, the sharpness of the blade's tip matters more than its length since it dictates how much effort is needed to enter the skin at first. There is yet to be an accepted, commonly applied scientific approach for classifying knife sharpness from the point of view of forensic pathology. Traditionally, it is suggested to perform a test using the tip of a finger, characterizing the tip as dull, a little sharp, or very sharp. However, other than this being risky based on safety and health, such types of examination are also undoubtedly subjective. For example, sharp and blunt knife behavior was reported by Hainsworth et al. [127]. It was reported that as the bluntness of the knife increases, the penetration depth reduces. The study captured images via high-speed videography while the pork skin was attacked by a sharp and blunt knife. The pork skin was easily penetrated inside the skin when the knife was sharp. Besides, it was concluded that as the bluntness of the knife increases, the skin shows considerable elastic deformation and more resistance to penetration. From the above study, it is evident that while developing the stab resistance jacket, the sharpness of the testing knife plays a very important role. Another study also reported the method of measuring the sharpness of the knife by using filament and weighing balance, as shown in Figure 20a. Das et al. [131] observed that the knife's performance depends on the number of stabs, as shown in Figure 20b. The force values increased with an increase in the number of stabs in the case of the neat and shear thickening fluid (STF)-treated panels. As the number of stabs and the stab at the STF-treated panels increase, there is a reduction in the knife sharpness.

Another study has also developed and calibrated a handle with an integrated force sensor (Figure 20c) and accelerometer to understand the effects of different shapes on stabbing (Figure 20d) [141]. A volunteer performed 27 medium-intensity stabblings using three blade types on a gelatine tissue simulant, with stabbing velocities recorded via high-speed videography. Results showed a strong linear calibration of the force sensor, with velocities ranging from 2.7 to 5.0 m/s and forces between 54.8 and 129.3 N (Figure 20e). Blunt blades required significantly higher stabbing forces than pointed and serrated blades, while serrated blades also showed higher forces than pointed ones, though not statistically significant (Figure 20f). The findings highlight that blade shape and stabbing velocity influence stabbing force, emphasizing the need for case-specific evaluations in forensic investigations.

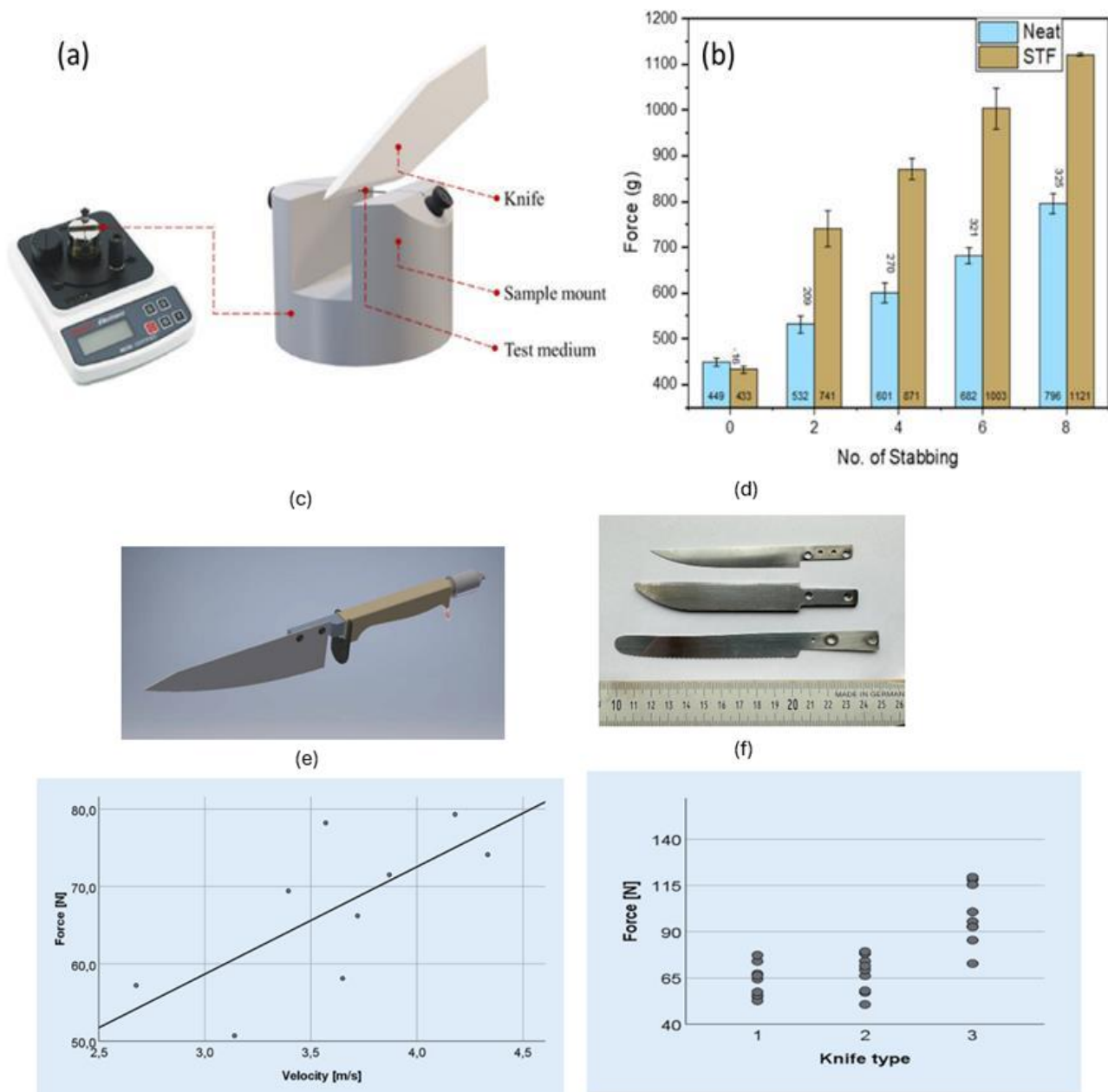


Figure 20. Measurement of knife sharpness before and after the damaging (a) method of measurement. (b) Force values with number of stabs. (c) Measurement device with sensor. (d) Different knife shapes top to bottom (pointed, blunt, and serrated). (e) Linear regression model: Stabbing velocity vs. stabbing force, and (f) the stabbing forces for different knife types in terms of blade shape (1: pointed, 2: serrated, 3: blunt) (Figure 20a,b are reprinted from ref. [131] with permission from Wiley and Figure 20c–e and f are and b reprinted from ref. [142]. with permission from Springer).

3.3.3. Types of Weapons

Domestic knives (kitchen, lock, sheath, pen, and various varieties) are used in most stabbing instances. A lock knife is a knife with a mechanism to lock the blade; a sheath knife is a knife with a fixed blade that fits within a leather sheath; and a pen knife is a compact knife with a blade that folds into the grip. The knife's parts are the guard, hilt, blade, handle, tip, and edge. Awls, screwdrivers, samurai swords, scissors, bayonets, and even shattered glass bottles can be used as additional weaponry. Figure 21 illustrates a few popular weapon types that may be used for slash, pierce, and stabbing attacks. The domestic category, which includes a wide range of blades, is often known as kitchen knives.

These knives usually have high-quality stainless steel blades. The kitchen knives dull with usage if they are not sharpened often enough. Still, they work incredibly well for stabbings. When using a lock knife, the blade may be locked in the extended position to keep it from shutting [139,143].



Figure 21. Various stabbing weapons: (a) lock knife, (b) sheath knife, (c) combat blade, (d–h) kitchen knives, (e) pointed weapon, (g) dagger, (i) awl, and (j) screwdriver. Reprinted with permission [5]. Copyright under open access publication (CC BY/4.0).

Sheath knives are often made with durable blades and well-made hilts and are utilized for outdoor sports. There are various combat knives, including daggers, flicks, butterfly knives, and switchblades. Their primary purpose is stabbing. Miscellaneous knives include utility knives with disposable blades, several kinds of sharp instruments, pen knives, and ceremonial blades. Every knife is made to fulfill the specifications for home or industrial usage or can be used as a weapon. Typically, a knife has a blade and a handle. The handle and the blade designs affect how well a knife works as a tool. The material composition, thickness, angle of the point, and edge sharpness of a blade are some distinguishing characteristics that influence how severe a strike may be. Knives with an acute angle tip are weaker and more prone to damage when used. The angle at which the blade tip is angled and the sharpness of the cutting edges determine how well a knife cuts. The angle between the blade edges determines the degree to which the cut will drive the material apart. In contrast, the sharpness of the edge determines the capacity to perform the first incision. Steel or its alloys, including molybdenum, vanadium, manganese, chromium, or nickel, make up most knives. The toughness of the blades' design ensures that they remain sharp when used. A knife with a high hardness level may be more brittle and hence more prone to breaking. Any of the stabbing weapons mentioned above fall into one of two categories: pointed or edged. As a result, stabbing might be conceptualized as a material cutting or puncturing act. "Edged" weapons have a long, continuous cutting edge and are used to pierce or cut things. Such weapons include knives, swords, tools, and other instruments. A slash is a cutting action in which the knife edge swings to travel parallel to the material surface during an attack. A stabbing is a cutting action in which the knife edge travels primarily in a direction average to the surface of the material being penetrated. Since the force of a stab is focused in a tiny area at the blade's tip and the lengthy cutting-edge acts as a continuous source of injury, stopping stab attacks is far more complex than blocking slash attacks. On the other hand, a knife edge distributes the force of a strike along its cutting edge, continuously inflicting damage across a wider region of the target, making it easier to stop. Awls, ice axes, and ice picks are other pointed weapons with thin rods with sharp tips that can easily penetrate materials. When a material fails under the influence of a sharp

item, the structure's fibers and yarns are displaced, making it possible for the object to pierce and enter its structure. This phenomenon is known as a puncture. Modern materials like ceramics, synthetic sapphire, zirconium dioxide, and rigid plastic can be used as blade materials for stab and slash strikes [140,144,145]. Some research has surveyed the effect of sharp force fatalities and clinical penetrative injuries on the chest and abdomen, as it is the most frequent target location for stab wounds. The location of the cut-type damage recorded during the trial was found to correlate to the location of stab injuries incurred during actual stabbing cases. The research utilized three knives, namely a utility knife, a hunting knife, and a machete knife, to represent weapons commonly encountered in forensic casework and to cover a range of sizes and types, as shown in Figure 22.

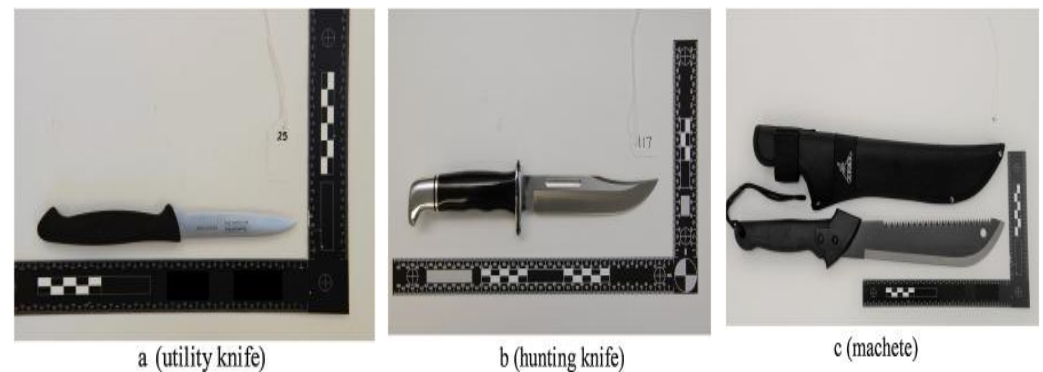


Figure 22. (a–c). Images of weapons used for human participant trials (utility knife, hunting knife, and machete), reprinted from ref. [146] with permission from Elsevier.

The measurements of the different knives are given in Table 4.

Table 4. Measurements of the different knives used in trial [146].

Knife	Total Length (mm)	Blade Length (mm)	Blade Width (mm)	Spine Width (mm)	Weight (g)
Utility	208	90	15	1	29
Hunting	267	137	28	4	224
Machete	473	245	55	2	448

In general, the study indicates that the actions taken depended on the type of weapon. A significant portion of subjects could perform only a limited range of actions, primarily thrusting and hacking, when using smaller utility and hunting knives. In contrast, subjects wielding a machete most effectively utilized slashing and hacking motions, while relatively few employed machete-type instruments for horizontal impact thrusts.

4. Challenges and Future Advancements in Dynamic Stab Resistance of Protective Textiles

Impact-protective textiles have become indispensable in applications ranging from law enforcement and military use to civilian safety gear [147,148]. Despite significant progress in developing stab-resistant materials, challenges persist that hinder the full optimization of these textiles for high-performance applications [2,30]. Addressing these challenges requires targeted research and innovation. This section will explore some of these challenges and suggest some directions for future advancements in the field, supported by current research and emerging trends.

4.1. Challenges in Developing Dynamic Stab Resistance of Textiles

The development of stab-resistant textiles has achieved significant success in enhancing personal safety for both professional and civilian applications. However, several challenges persist in fully optimizing these materials, particularly in balancing protection with other critical performance metrics, including material limitations, complexities in parameters, testing inadequacies, etc. [5,149]. One of the most critical challenges facing stab-resistant textiles is the balance between protection and comfort [150]. While high-modulus fibers, such as aramids and UHMWPE, give very good stab resistance, this is usually at the expense of flexibility and breathability [151]. For instance, puncture- and tear-resistant materials can be heavy and bulky to wear for extended periods in dynamic situations [152,153]. The challenge for researchers and manufacturers will be to strike a balance between robust protective properties and ergonomic comfort. The other challenge would be the involvement of many intrinsic and extrinsic parameters, making material design and testing difficult while complicating the process [8,19,22]. These unpredictable interactions complicate designing materials that consistently perform in diverse scenarios. This further leads to complications in developing any form of standardized performance benchmarks, with significant gaps in understanding their behavior under different conditions [146,154]. Another challenge is the search for and application of the appropriate testing methodologies, machines, and standards for the product [155]. For example, most of the current protocols focus on specific blade types, fixed impact angles, and controlled laboratory conditions, which may not adequately represent the dynamic environments in which protective textiles are used [17–19]. For example, variations in blade sharpness, impact speeds, and environmental factors are hardly ever integrated into standardized testing procedures [156–159]. This lack of inclusivity limits the generalization of test findings to real-field conditions and may render users sensitive under unforeseen circumstances. The other challenge would be understanding and knowing how the materials behave in terms of their stabbing performance due to aging and environmental effects [159]. For instance, stab-resistant textiles lose their performance over time because of environmental exposure and aging [160]. Mechanical properties are degraded by extreme temperatures, humidity, UV radiation, and chemical contaminants, while wear and abrasion further accelerate deterioration [161,162]. However, the limited data about these long-term effects challenge designers in creating protective gear that will be durable and reliable under real-world conditions. Like most performance products, stab-resistant materials are mostly made of synthetic fibers [27]. The demand for eco-friendly solutions is in direct conflict with the reliance on stab-resistant textiles on synthetic fibers and chemical treatments. The materials provide great protection yet bring forth several challenges in terms of sustainability because of poor biodegradability and recyclability. Further work is needed to develop biodegradable polymers, renewable resources, and recyclable materials that balance performance and environmental responsibility.

4.2. Future Advancements and Directions in Stab-Resistant Textiles

The ongoing evolution of stab-resistant textiles requires targeted advancements to address current limitations while meeting future demands. There are some key areas where research and innovation are poised to make transformative impacts. Future advancements in stab-resistant textiles might focus on creating hybrid materials that integrate advanced fibers, nanomaterials, and bio-based composites. For instance, combining carbon nanotubes (CNTs) with shear-thickening fluids (STFs) has shown the potential to enhance both stab resistance and flexibility [163–168]. Bio-based composites, derived from renewable resources, present an eco-friendly alternative that does not compromise performance. These materials can bridge the gap between functionality and sustainability, catering to diverse

applications in protective gear. Advancements in computational modeling and simulation have also emerged as essential tools for understanding the behavior of protective textiles under dynamic stab and ballistic conditions [169–171]. Techniques such as finite element analysis (FEA) and machine learning algorithms enable accurate predictions of material performance across various impact scenarios [172–175]. These approaches not only reduce the dependence on extensive physical testing but also pave the way for virtual design and optimization. As computational power and algorithms improve, these tools will allow for the creation of materials tailored to specific applications, offering a faster and more cost-effective pathway to innovation. The other advancement area will be increasingly realistic and inclusive testing protocols and standards. Future protocols should encompass a broader spectrum of scenarios, including varying blade geometries, impact velocities, and environmental conditions. For example, dual-threat testing that evaluates both stab and ballistic performance can offer a more holistic assessment of protective textiles. Such inclusivity will ensure that laboratory results more accurately reflect real-world conditions, enhancing the reliability of protective materials. The incorporation of smart textiles with embedded sensors and adaptive properties will also represent a promising direction for next-generation stab-resistant gear. Materials capable of stiffening upon impact or altering properties in response to environmental stimuli might provide superior protection and versatility [176,177]. Additionally, integrating electronic components into textiles could enable real-time monitoring of material performance, offering critical insights into wear and durability during use. With growing ecological concerns, innovations in biodegradable polymers, recyclable composites, and energy-efficient production methods will be essential to reduce the environmental footprint of stab-resistant textiles. Besides, as protective textiles are often subjected to harsh environments (including exposure to UV radiation, moisture, and chemical contaminants), which accelerate degradation over time, future research should focus on developing advanced materials, coatings, and treatments to overcome these effects.

5. Conclusions and Recommendations

This review has identified and discussed various intrinsic and extrinsic parameters involved in the stab impact resistance determination of fibrous materials. The key intrinsic factors are fiber type, weave, density of yarn, and chemical treatments that have direct influence on the material properties for energy absorption and penetration resistance. Extrinsic factors such as variation in impact velocity, geometry of the blade, and environmental conditions also influence the stab impact performances of textile materials. This review also discusses several standards and test methods that should simulate the actual situation in order to effectively assess the protection performance of protective textiles against different attacks. The studies show that good stab-resistant material design should be an integrated effort with both intrinsic and extrinsic parameters. All too often, the exclusion of extrinsic parameters, such as the type of blade and impact energy, has resulted in protection gaps under real operations. Optimization of intrinsic properties alone is not sufficient to guarantee consistent performance for various impact conditions. Besides, from the critical review presented in this paper, a number of recommendations are presented that will aid future development in stab-resistant fabrics. For example, besides including the above inherent and extrinsic factors, researchers, engineers, and manufacturers ought to be in a position to come up with materials that will be highly protective but elastic as well as comfortable under different environmental conditions. Further, the integration of hybrid materials, high-performance fibers, nanomaterials, and bio-composites shall be the future of research to develop stab-resistant clothing without compromising their comfort and elasticity for use by law enforcement agencies, armed forces, and civilians. It also needs

to apply advanced computational modeling to support accurate prediction of material behavior under different impact conditions to reduce the necessity for extensive physical testing through computer simulation. Realistic and inclusive testing standards need to be developed to handle a greater range of blades, angles, and velocities, with dual-threat testing for both stabbing and ballistic testing. It is also about using biodegradable and recyclable materials; there also need to be environmentally friendly production and recycling processes. Focusing on these major areas, the field can proceed to engineer multi-functional and sustainable protective material that will enhance personal protection toward a safer and more resilient world.

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