Md. Zayedul Hasan,[1, 2] Rochak Rathour,[1] Apurba Das,[1] Ramasamy Alagirusamy,[1] Nandan Kumar[3]
[1] Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi Hauz Khas, 110016 New Delhi, India
[2] Department of Textile Engineering, Mawlana Bhashani Science and Technology University, Santosh, 1902 Tangail, Bangladesh
[3] High Performance Textiles Pvt. Ltd., Panipat, Haryana, India

# Design and Development of Comfortable Cut-Protective Workwear: A Review

*Oblikovanje in razvoj udobnih delovnih oblačil za protiurezno zaščito: pregled*

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Corresponding author/*Korespondenčni avtor:*
**Md. Zayedul Hasan**
E-mail: zayedul.hasanmbstu@gmail.com
ORCID iD: 0009-0002-5055-475X

## Abstract

The challenge of developing cut-protective clothing that ensures wearer safety and comfort remains complex in protective textile engineering. Traditional designs often compromise comfort for mechanical protection, leading to decreased wearer compliance and productivity. This review critically examines the interplay between comfort and cut resistance in the designing of protective apparel for industrial workers. Recent advancements in fibre science, yarn engineering and fabric architecture are highlighted for optimizing performance. This review begins by analysing the prevalence and causes of occupational cut injuries to establish functional requirements for protective clothing. It then explores how fibre type, yarn configuration and fabric structure impact cut resistance and comfort. Standardized test methods for evaluating cut resistance are discussed to provide context for material performance. Additionally, the review outlines garment design strategies that incorporate ergonomic principles to enhance mobility, reduce heat stress and improve user acceptability. It concludes with an outlook on emerging technologies such as smart textiles and 3D body scanning that could revolutionize future cut-protective workwear design.
Keywords: protective clothing, textile structure, clothing design, cut hazard, ergonomic comfort

## *Izvleček*

*Razvijanje zaščitnih oblačil proti urezninam, ki hkrati zagotavljajo varnost in udobje uporabnika, ostaja kompleksen izziv v načrtovanju in izdelavi zaščitnih tekstilij. Pri tradicionalno oblikovanih zaščitnih oblačilih je udobje pogosto žrtvovano v prid mehanske zaščite, to pa vodi v zmanjšano upoštevanje varnostnih ukrepov ter nižjo učinkovitost uporabnikov. Članek kritično analizira medsebojno povezavo med udobjem in odpornostjo proti urezu pri oblikovanju zaščitnih oblačil za industrijske delavce. Poseben poudarek je na najnovejših dosežkih na področju znanosti o vlaknih, tehnologiji prediva ter zgradbi tkanin, ki prispevajo k optimizaciji zmogljivosti oblačil. Študija se začne z analizo pogostosti in vzrokov delovnih poškodb zaradi ureza, da se določijo funkcionalne zahteve za zaščitna oblačila. Sledi raziskava vpliva vrste vlaken, konfiguracije prediva*

*in strukture tkanin na odpornost proti urezu ter udobje. Obravnavane so standardizirane metode testiranja odpornosti proti urezu, ki omogočajo oceno zmogljivosti materialov. Prispevek opisuje tudi strategije oblikovanja oblačil, ki vključujejo ergonomska načela za izboljšanje mobilnosti, zmanjšanje toplotnega stresa in povečanje sprejemljivosti med uporabniki. Povzetek se zaključi z vpogledom v nastajajoče tehnologije, kot so pametne tekstilije in 3D skeniranje telesa, ki bi lahko v prihodnje močno vplivale na oblikovanje delovnih oblačil za protiurezno zaščito.*
*Ključne besede: zaščitna oblačila, struktura tekstilij, oblikovanje oblačil, nevarnost ureza, ergonomsko udobje*

## 1 Introduction

Design plays a crucial role in gaining approval from observers and potential customers for popular daily apparel. Humans respond to visual information, including clothing and other everyday items. Clothing serves the fundamental purposes of modesty and safety, with beauty becoming increasingly important. The protective clothing market is shifting its focus towards emphasizing safety as its primary purpose, with protective textiles being developed to safeguard workers from a range of hazards. However, the performance of protective textiles may be limited by the need to meet safety standards [1, 2]. Occupational safety is a global concern, with millions of workers facing risks in various industries. The International Labour Organization (ILO) reports over 317 million work-related injuries annually, leading to more than 320,000 fatalities and significant human and economic costs [3]. The protective gear, such as stab-proof suits, cut-resistant aprons and gloves, is intended to minimize the chances of injury and offer protection from different dangers. It is important for individuals working in high-risk environments to wear appropriate protective gear to minimize the potential for harm [4–6]. These advancements are designed to improve the human body's ability to withstand or completely avoid injuries caused by sharp objects and other dangerous impacts [7, 8]. However, traditional protective options such as leather clothing, wire mesh steel, and steel gloves have faced various challenges, such as discomfort, reduced flexibility and inadequate protection [9]. Safety in the workplace is a top priority in industries such construction, manufacturing and logistics, where employees face risks from tools, machinery and materials. Cut-resistant workwear is essential for preventing injuries, protecting workers and meeting safety standards. Although current protective clothing offers good safety features, it often overlooks the importance of comfort, ergonomics and ease of wear. This can make it difficult for workers to follow safety protocols and stay productive [10]. Wearing larger and denser cut-protective suits can raise the energy expenditure of activities by 20% [11, 12]. This can lead to significant stress on the body when working, particularly in humid environments, resulting in cognitive impairment, discomfort, fatigue, reduced operational efficiency and potential harm [13]. The regulation of human body temperature relies on heat transport within the body and between the human body and its environment [14, 15]. When the body's heat regulation mechanisms are overwhelmed and heat accumulates, the core temperature can rise dangerously resulting in heat stress, which poses a significant risk to health and performance in various industrial settings [16]. Factors such as ambient temperature, physical activity levels and clothing choices play a crucial role in the development of heat stress-related illnesses [17]. Understanding these factors and their underlying principles is essential for assessing the risk of heat stress. The importance of wearer health is increasingly recognized in the use of cut-resistant gear [18–23]. To address this, companies must focus on developing more comfortable and breathable protective workwear that can be worn in all types of weather conditions. Additionally, training programmes should be implemented to raise awareness about the importance of wearing protective gear and the potential risks of not doing so. By prioritizing employee safety and comfort, companies can create a safer work environment and reduce the risk of workplace accidents [24]. The process of creating cut-protective workwear is based on and tailored to the specific requirements of the user. These requirements are influenced by the user's work environment and the tasks they undertake, aiming to enhance both comfort and performance. Cut-protective workwear is an essential part of personal protective equipment (PPE) in various industries such as manufacturing, construction, healthcare and emergency services, where workers are exposed to risks from sharp tools, machinery or hazardous materials. While there have been significant improvements in enhancing the protective features of such clothing, the importance of comfort is often overlooked. Workers are more likely to wear protective gear consistently if it allows them to work without hindrance, discomfort or fatigue. Balancing comfort and protection is a complex challenge that involves integrating material science, ergonomic design and user-centred innovation. Protective clothing must meet strict safety standards for cut resistance while also providing breathability, flexibility and a proper fit. As the focus on worker well-being grows, there is rising demand for workwear that focuses on safety and comfort. This review aims to explore current advancements, challenges and research gaps in designing comfortable cut-protective workwear. It discusses the latest materials, design principles and technologies used to improve functionality and user experience. Additionally, it sheds light on the changing needs of industries and workers, offering insights into future directions for innovation in this field.

## 2 Cut and slash incidents in the workplaces

Preventing cuts is vital for workplace safety. Every year, numerous work-related accidents occur globally that could be prevented using proper protective equipment. Cuts and scratches are common injuries that can easily be prevented. Although statistics may differ, cuts and scratches are consistently listed as the second or third most common workplace accidents. These injuries account for approximately 30% of all industrial accidents, with hands and thumbs involved in about 70% of these cases. This has led to the development of protective gloves and sleeves [25]. Cutting hazards are prevalent in various industries. Incidents of cuts and wounds occur at a rate of 8.1 per 10,000 workers. Despite wearing cut-resistant gloves, an employee at an automobile production factory's pressing workshop sustained a thumb injury when a stainless-steel sheet slipped from his grip. While workstations may vary, the risks associated with cuts remain consistent. In industries where glass sheets are handled, hand and arm injuries are common during carrying and moving tasks. Forestry workers using chainsaws often require full-body protection, with minimal emphasis on hand protection. Electronics assembly and handling also pose cut risks to workers. Workers in food-processing plants and busy kitchen environments are at high risk of cut injuries due to the use of sharp equipment. Glass containers can crack or burst due to defects, necessitating the use of cut-resistant gloves when handling them. Textile factory operators face cutting hazards from vibrating threads in spinning processes. Hockey players risk neck cuts from extremely sharp skate blades, with some opting to forego neck guards despite the potential for injury. Workers must be aware of and take precautions against these cutting hazards to prevent injuries[26].

### 2.1 Fundamental requirements of cut-protective workwear

The term cut-resistant refers to a material's ability to withstand cuts, as tested by standardized methods while the term cut-protective encompasses all aspects of protection against cuts, not just cut resistance. It is important to use these terms accurately when selecting safety gear to ensure realistic expectations for workplace safety. Cut-resistant focuses on a material's ability to resist cuts, while cut-protective considers overall protection against cuts. Cut-resistant reduces the risk of cuts but does not guarantee absolute prevention, while cut-protective includes all protective features. Cut-resistant is rated by standards such as EN 388, ANSI/ISEA 105 and ISO 13997, while cut-protective may reference cut resistance as one component of protection.

Cut-protective clothing prioritizes practical functionality, thermal comfort and human movement to create a safe and comfortable micro-environment for the wearer. This clothing system acts as a barrier to protect the human body from potential hazards. In essence, cut-protective apparel serves three main purposes: protecting the user from cut and slash risks, providing psychological relaxation through sensual and thermal comfort, and enabling human movement during various activities. High-performance textiles composed of fibres, yarns, fabrics and composite components made from inorganic and functional organic polymers exhibit exceptional properties and qualities. UHMWPE provides exceptional cut resistance but has poor heat resistance, with a maximum continuous use temperature typically below 100 °C and a melting point of around 150 °C. For applications requiring both high cut and high heat resistance, aramid fibres such as Kevlar are the better choice, as they maintain their properties at temperatures exceeding 200 °C and do not melt. These fibres are commonly used in cut-protective clothing structures. Textile materials used in cut-protective clothing possess key mechanical attributes such as tensile strength, modulus, abrasion resistance, puncture resistance, flame resistance, thermal and electrical insulation properties, heat resistance, chemical resistance, liquid absorption and dispersion properties, and protection against high levels of radiation. These properties are integrated into a single protective gear system to ensure adequate protection and comfort in different weather conditions [27].

## 3 Material selection for cut-protective workwear

### 3.1 Selection of fibre

Functional clothing, such as activewear, innerwear and protective workwear, utilizes a variety of natural and synthetic fibres with distinct properties. The choice between natural and synthetic fibre depends on the intended level of physical activity. Natural fibres are hydrophilic and suitable for low activity levels, while synthetic fibres are hydrophobic and preferred for high activity levels. Hydrophilic fibres quickly absorb moisture due to their higher surface energy, while hydrophobic fibres resist moisture absorption due to their lower surface energy [28]. The cut-resistance functionality and comfort of clothing are greatly influenced by the characteristics of the chosen fibre components [29]. It is crucial to carefully choose fibre components with various anti-cutting capabilities for different operating conditions. Workers in conventional factories were provided with protective clothes made from cut-resistant textiles, which mostly consisted of natural fibres and synthetic fibres such as cotton, hemp, polyester and spandex. Cut-resistant clothing composed of conventional natural fibre content has poor safeguarding properties due to inadequate mechanical and outdoor resistance, which restricts their utilization in various safety gear industries. However, due to their high utilization rate, lightweight, versatility and low cost, they are still a frequently used protective material in factory manufacturing situations [30–32]. Natural fibres exhibit the strength and stiffness typical of most fibres, have a low specific gravity and demonstrate improved elasticity and extensibility.

When integrated into protective textiles, it improves wearer comfort and offers greater strength and durability than natural fibres. Furthermore, it is affordable and incredibly cost-efficient. While natural fibres and synthetic fibres offer numerous benefits, they also possess significant drawbacks. For instance, cotton fabrics exhibit limited elasticity, are prone to shrinking and distorting after washing, and lack resistance to acid. Similarly, hemp fabrics have a coarse texture and tend to develop burrs when in direct contact with the body, resulting in a less smooth and comfortable experience. The truncated fibres generated during the processing and shaping of synthetic fibres have detrimental effects on the skin and respiratory system of personnel. In addition, conventional cut-resistant fibre materials lack effective protection and fail to meet the safety criteria for people's work activities. To enhance the competitiveness of both natural and synthetic fibres, it is crucial to modify and enhance their value in usage [33, 34]. Conventional fibres such as cotton, polyester, nylon and wool are being blended with HPPE or aramid to develop cut-resistant materials. High-performance fibre has progressively displaced conventional fibre components for cut-resistant clothes due to its superior mechanical strength, excellent heat retention and anti-abrasion properties. Currently, aramid 1414, ultra-high molecular weight polyethylene fibre, p-benzoxazole polyester fibre, glass fibre, metal fibre and other high-performance fibres are commonly employed as barrier components in factory manufacturing workflows for cut-protective clothing. Using physical and chemical techniques, some researchers have enhanced the cutting capability of fibres or yarns. For example, Jeffrey CM employed a lab-scale wet spinning experimental approach to generate aramid copolymer fibres used in cut prevention [35]. Table 1 provides an overview of the characteristics of the major high-performance fibres used in cut-resistant textiles.

*Table 1: Overview of properties of major high-performance fibre [36].*

| Fibre | Diameter (μm) | Strain (%) | Density (g/cm$^3$) | Tensile stress (GPa) | Modulus of elasticity (GPa) |
|---|---|---|---|---|---|
| Para aramid | 13.0 | 3.3 | 1.44 | 3.31 | 94 |
| UHMWPE | 18.8 | 3.6 | 0.98 | 2.62 | 88 |
| PBO | 12.3 | 3.5 | 1.54 | 5.80 | 180 |
| Aromatic polyester | 23.5 | 3.3 | 1.41 | 3.20 | 75 |
| Glass | 5.5-9.3 | 5.5 | 2.48 | 4.80 | 85 |

DSM introduced Dyneema Diamond Technology in 2006 to improve its unique properties. This technology combines HPPE (high-performance polyethylene) filled with a micro-sized, cut-resistant inorganic filler to create a composite material [37]. The fibre produced using Dyneema Diamond Technology, as shown in Figure 1, has a distinct morphology. By incorporating an inorganic filler, this technology significantly boosts the cut resistance of the fibre compared to traditional HPPE fibre. According to DSM's data, Dyneema Diamond Technology offers a 200% increase in cut resistance over standard Dyneema fibre [38]. The addition of extraneous material complicates the process of fibre spinning. Superdrawing is essential for achieving a significantly elevated level of alignment and crystalline structure, allowing for the exceptional stiffness and strength of HPPE fibre. However, the addition of inorganic filler substantially increases the difficulty of superdrawing and has a significant impact on spinnability. The fibre's strength decreased by over 50% [39].

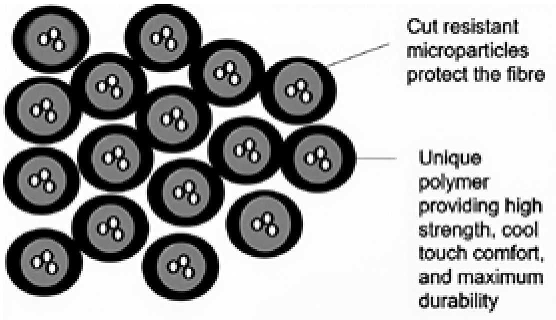


*Figure 1: Microscopic composition of a fibre utilizing the Dyneema Diamond Technology*

Indeed, the utilization of hard filler to enhance cut resistance in thermoplastic fibre is not a novel concept. In the 1990s, Hoechst Celanese submitted patent applications for the utilization of inorganic fillers or fibres to enhance the cut resistance of fibres [40‒47]. The patents explicitly describe the use of tungsten and aluminium oxide, which resulted in an improvement in cut resistance of over 300% according to a certain cut-testing method. The addition of alumina to para-aramid fibre to increase cut resistance was also revealed in another patent [48]. The cut resistance was increased by 15% with 0.5% by weight of alumina in the fibre, without compromising tenacity.

### 3.1.1 Function of fibre structure

Fibres of different cross-sectional shapes are being used in functional clothing due to their ability to transfer heat, moisture and liquids through fabrics effectively. The inclusion of non-circular fibre profiles increases the fibre's shape factor. This, in turn, affects the capillary gaps between fibres, the spaces between yarns, the density of packing, the specific surface area and, ultimately, the thermo-physiological properties of fabrics [49,50]. Fibres that have a higher specific surface area exhibit excellent moisture absorption and release properties. The presence of micro grooves on the surface of the fibre increases its ability to absorb liquid by capillary action. This allows moisture to be drawn in and then spread out over the surface of the fibre, facilitating its dissipation [51]. Various fibres and their cross-sections are frequently utilized in functional clothing. Hollow fibres and fibres with varying sizes of grooves are commonly used in activewear, sportswear and clothing that is worn next to the skin to achieve favourable thermal insulation characteristics. Hollow fibres have a significant trapped air volume, leading to enhanced thermal insulation properties in fabrics or garments made of these fibres. Thermolite fabrics with improved thermal insulation and wicking properties are produced using hollow core fibres with twisted or convoluted surfaces [52]. The formation of irregular capillaries occurs when cotton fibres are embedded within the yarn, inhibiting fluid flow due to the flat, lima bean-shaped cross-section and ribbon-like appearance of the cotton fibre [53]. Introducing voids in the fibre core can enhance wicking and heat resistance. Welkey is a type of fibre that has a hollow core and a body with numerous tiny pores. The thermal resistance of fibres increases due to an increased amount of air gaps inside them. The capillary action, resulting from the formation of microscopic pores in the fibre body, enables sweat to be wicked away from the skin. Coolmax is a type of polyester fibre that has been altered and improved by Dupont. The fibre has a double scallop shape with four channels, providing 20% more surface area compared to regular polyester fibre. This results in improved wicking, moisture vapor permeability and water spreading over a larger area in the fabric [54‒56]. Karaca et al. conducted a study comparing the thermal comfort properties of fabrics made from polyester fibres with different cross-sectional shapes. They observed that fabrics made from hollow fibres had low thermal insulation, air permeability, and water vapor permeability. On the other hand, fabrics made from trilobal polyester fibres had higher air and water vapour permeability and lower thermal conductivity compared to fabrics made from round fibres [57]. According to Behera and Singh, the physical properties and tactile characteristics of polyester multifilament yarn fabric were modified when the form of the filaments was changed [58].

*Table 2: Role of fibre parameters on different attributes of clothing*

| Fibre parameter | Performance attributes | Aesthetic attributes | Tactile attributes | Wearing comfort attributes |
|---|---|---|---|---|
| Strength, fineness, cross-sectional shape, maturity | Tensile strength, tear strength, bursting strength, abrasion resistance, crease resistance | Surface texture, lustre, fancy effect, handle, drape | Compression, friction, shear, bending rigidity | Stretchiness, lightness, slip-ability, reduction in clinging, prickliness |

Varshney et al. conducted a study on the impact of polyester profile on the physiological characteristics of polyester fabrics. They found that noncircular fibres increased the volume of the fabric, resulting in a higher mass flow rate and greater resistance to heat flow [59]. Wang et al. compared monofilament yarns with a circular cross-section to those with a five leaf cross-section. They found that, at the same twist level, the fibres with a five leaf cross-section formed five beads along the length of the fibre and had a greater number of capillaries in the yarn than conventional yarns made with circular cross-section fibres. The wicking height of five leaf yarns was found to be greater than that of ordinary yarns [60]. The role of fibre parameters is also summarized in Table 2.

## 3.2 Selection of yarn

The selection of yarn is closely linked to the desired characteristics of the fabric. The choice of compound yarns is crucial in producing pleasant cut-protective fabric. Compound yarns are formed by intertwining many types of fibres or yarns, merging the advantageous characteristics of each constituent. This leads designers to produce cut-protective clothing with higher performance characteristics, including strength, flexibility and abrasion resistance, which are critical for cut prevention, by intelligently selecting the types of fibres and arranging them in the compound yarn. Compound yarn is generally prepared by using core spun and wrap spun processes. The staple spun yarn spinning technique yields core spun yarn [61]. In the spinning process, the core is introduced into the roving, which is then twisted around the core. Over time, the primary thread gradually forms a protective covering that encases the central part. The core can be made of either spun yarn or filament yarn in practice. However, in practice, the core is typically made of filament yarn, such as steel, glass, spandex or the monofilament of organic fibre-like polyester. The sheath must still be made of staple spun yarn. Typically, a sheath composed of staple spun yarn adequately conceals the core, making it difficult to perceive from the outside. Wrap yarn is alternatively referred to as spin-covered yarn. The process involves the continual wrapping or twisting of yarn around a core yarn, which can be either a monofilament or multifilament yarn, or a staple spun yarn. Wrap spinning uses a hollow spindle to make this sort of yarn [62–69].

The core is often located in the inner layer of the yarn and gives special bulk qualities such as remarkable strength (e.g. polyester or nylon filament) or high flexibility (e.g. rubber or spandex). To eliminate fibre separation or core sliding, the sheath or yarn wrap should have a solid hold on the core. It should also insulate the main filament from outside influences. This is especially critical if the core filament is elastomeric (e.g. rubber or spandex), as these filaments can disintegrate when exposed to a variety of chemicals or UV radiation. Furthermore, the wrap that comes into touch with the user should have comfort features including softness, flexibility and porosity. The wrap yarn can be either spun or filament. Two wrap yarns may be used in some circumstances, with one twisted in the opposite direction to the other, resulting in unique appearance effects and an appropriate equilibrium towards unwanted yarn sneering. The combination of various fibre types in compound yarns enables the attainment of desired performance levels while simultaneously reducing weight. Compound yarns are frequently preferred due to their enhanced comfort and safety protection to meet the requirements of mobility and agility in cut-protective gear for industrial or sports use.

#### 3.2.1 Influence of yarn structural properties

The characteristics of fabrics are influenced by several yarn variables, such as yarn twist, yarn count, yarn spinning system and yarn types. Modifications in any of these characteristics ultimately result in alterations to the yarn's structure which, in turn, is influenced by the geometry of the fibres. The arrangement of fibres in yarn determines the heat and moisture transport characteristics of fabrics. The versatile nature of yarn structure allows for capillary flow, which can result in lateral tension that impacts the size of capillaries as the liquid rises. The disruption of the continuity, length and orientation of the capillaries is caused by variations in the packing density inside the yarn structure. The variation in pore size, shape and orientation has an impact on how liquid enters the structure of the yarn and, consequently, its ability to retain liquid. The role of yarn parameters and yarn type on the different attributes is presented in Tables 3 and 4.

*Table 3: Role of yarn type on the structural and expected properties*

| Yarn type | Structural attributes | Expected features |
|---|---|---|
| Spun yarn | - hairy surface<br>- random fibre arrangement<br>- variability in count and diameter<br>- presence of imperfections | - textured or "spun" appearance<br>- soft and warm hand feel<br>- greater bulkiness than combed yarn |
| Bulk yarn | - high volume<br>- low fibre packing density | - lofty and soft texture<br>- textured appearance<br>- hairy surface similar to spun yarn |
| Stretch yarn | - filament core with staple fibre sheath | - high stretchability<br>- enhanced comfort and fit |
| Filament yarn | - maximum fibre alignment<br>- high uniformity<br>- dense filament packing | - lustrous and smooth appearance<br>- high sheen<br>- soft handle<br>- low bulk and covering power<br>- limited potential for intimate fibre blending |
| Textured yarn | - combines features of both spun and filament yarns<br>- high degree of fibre disorder (crimps, loops, coils)<br>- uniform yarn count and diameter<br>- low fibre packing density<br>- increased surface area and air entrapment | - highly textured and voluminous appearance<br>- enhanced bulk and softness<br>- improved covering power and opacity<br>- good elasticity and stretch<br>- effective thermal insulation<br>- moisture-wicking with low moisture retention<br>- improved comfort and flexibility<br>- resistance to wrinkling and creasing |

Ozguney et al. explored the impact of yarn fineness on the comfort qualities of garments created from it. They observed that the bending stiffness and compression of textiles made from increased linear density yarns are greater than those made using reduced linear density yarns [70]. An increase in yarn coarseness improves all of the fabric's low-stress mechanical properties. Raj and Sreenivasan's studies on various cotton textiles reported that increasing yarn count, twist and giving a thinner construction enhances the fabric's air permeability [71]. Ozdil and fellow researchers evaluated the influence of twist number and yarn count on the performance of rib cotton textiles. Their research reveals that when linear density declines, so do yarn diameter and fabric thickness. These standard yields decreased heat

*Table 4: Role of yarn structural parameters on the different attributes of clothing*

| Yarn structural parameter | Performance attributes | Aesthetic attributes | Tactile attributes | Wearing comfort attributes |
|---|---|---|---|---|
| Yarn count | Tensile strength, tear strength, bursting strength, abrasion resistance | Surface texture, lustre | Handle, drape | Lightness, stretchiness |
| Yarn twist | Tensile strength, crease resistance, abrasion resistance | Surface texture, fancy effects | Compression, bending rigidity | Slip-ability, reduction in clinging |
| Yarn hairiness | Abrasion resistance, pilling tendency | Surface texture, dullness | Prickliness, handle | Air permeability, reduction in clinging |
| Yarn evenness | Uniformity in strength, reduced weak spots | Smoothness, visual uniformity | Consistent handle | Consistent comfort, reduced irritation |
| Yarn blending ratio | Balance of mechanical properties, durability | Colour effects, lustre variation | Handle, drape | Moisture management, thermal regulation |
| Yarn bending rigidity | Crease resistance, dimensional stability | Drape, form retention | Bending rigidity, handle | Flexibility, ease of movement |
| Packing co-efficient | Tensile strength, abrasion resistance, bursting strength | Bulk, opacity | Compression, surface feel | Thermal insulation, reduction in clinging |

insulation and thermal conductivity while increasing water vapor permeation. As a result, textiles made of finer yarns have a warmth sensation and reduced heat absorption. Water vapor permeability and thermal absorptivity rise as the twist number of the yarns increases, resulting in decreased thermal resistance and a cooler sensation. They also demonstrated that combed cotton yarn knitted textiles had greater thermal conductivity, thermal absorptivity and water vapor permeability than carded cotton yarn knitted clothing. As a result, combed yarn textiles are more comfortable than carded yarn fabrics [72]. Aliouche and Viallier investigated the hairiness qualities of yarns. They demonstrated the importance of hairy appearance on tactile sensations such as roughness on the exterior, fabric compression and handling [73]. There has been various research on the wicking characteristics of yarns and textiles as an essential criterion [74-79]. Wicking is a need for clothing permeability. Asayesh and Maroufi investigated the effect of yarn rotation on the wicking ability of cotton interlaced weft knitted fabric. A higher yarn twist number in such fabrics results in reduced wicking ability [80]. Wickwire et al. discovered that while slack clothing reduces the efficiency of transporting moisture and perspiration away from the skin, it may improve the wearer's comfort, regardless of its ability to wick moisture away [81].

### 3.3 Selection of woven fabric

The selection of weave patterns impacts the fabric's flexibility and drape. It is crucial to acknowledge that the selection of weave structure is contingent upon the particular demands of the application. Although satin weave has benefits in terms of comfort and cut protection, different weave structures may be better suited for situations where criteria such as durability, rigidity or breathability are the main considerations listed in Table 5. Weaves with more aperture, such as plain weave or leno weave, exhibit increased flexibility and improved drape ability, thus boosting wearer comfort through unrestricted mobility. The satin design was selected due to its tight structure with fewer interlaces compared to other weaves such as plain or twill weave. This tightness improves the fabric's resistance to cuts by minimizing the areas where a blade can penetrate. The satin weave produces a silky, shiny surface that feels smooth and cozy against the skin. This is especially advantageous for cut-protective fabric when worn close to the body since it reduces irritation and pain after extended periods. Cut resistance changes in fabrics depending on the cutting angle of the blade, cutting speed and the fabric surface roughness. With an increase in yarn linear density, a woven fabric's surface roughness and frictional resistance increase [82]. The amount of frictional force generated also depends on the surface roughness of the fabric. Ajayi. J. O. and Elder. H. M in their research found that the surface roughness and frictional resistance of a woven fabric increase with an increase in the yarn's linear density. This was due to the increased yarn crown height which caused the mechanical interlocking of crowns during any movement [83]. In addition to meeting the demands for cut resistance, composite materials and hybrid architectures are frequently used. Cut-resistant clothing employs combination cord threads that include stainless steel filaments as the core and other high-performance fibres as the sheath to offer versatility and cut protection [84]. The conventional protective clothing for chainsaw employees comprises trousers and chaps that typically have an exterior material made of nylon, polyester or denim, and inner inserts made of layers of ballistic nylon or high-tenacity polyester fabric, while higher-quality apparel comprises layers of aramid fabric such as Kevlar® or ultra-high molecular weight polyethylene (UHMWPE) such as Dyneema. The cut-resistant safeguards offer minimal protection to the user and are intended to block the chainsaw driving sprocket, preventing the cutting blade from slashing through the trousers [85].

*Table 5: Role of weave structure on general attributes of clothing*

| Weave type | Interlacing pattern | General character |
|---|---|---|
| Plain | - each warp yarn interlaces with each weft yarn in an alternate sequence<br>- no distinctive design; can use contrasting colours | - maximum number of interlacements per unit area (balanced or unbalanced)<br>- tends to wrinkle the most<br>- may feel sleazy if sett is low<br>- least absorbent among basic weaves<br>- simple, firm and durable structure |
| Twill | - warp or weft yarns float over two or more yarns in a regular progression to either to the right (z) or left (s) | - characteristic diagonal lines (s or z twill)<br>- fewer interlacements than plain weave<br>- wrinkles less than plain weave<br>- strong, firm texture<br>- enhanced tear strength<br>- can be woven at higher setts (densities) |
| Satin | - warp or weft yarns float over four or more yarns in a staggered progression, creating a smooth surface | - very few interlacements; long floats<br>- flat, smooth, and highly lustrous surface<br>- maximum drapability<br>- high sett possible<br>- prone to slippage and snagging due to long floats<br>- luxurious appearance and feel |

### 3.3.1 Role of fabric structural parameters

The thermo-physiological properties of clothing are affected by the structural factors and general characteristics of fabrics. Factors such as fabric structure, thickness, cover factor, aerial density, bulk density, fabric porosity and finishing treatments affect the heat and moisture management capabilities of fabrics, ultimately defining their comfort properties. Woven fabrics are commonly used in outerwear, active wear, workwear and athletic attire. The level of air trapped inside different fabric structures varies due to differences in porosity, with knitted fabrics generally trapping more air than woven fabrics. Thermal insulation in fabrics is achieved through the presence of fibres, creating air pockets that restrict air circulation and act as a barrier against heat loss through radiation [86]. Fabric with multiple spaces for stagnant air, such as pile or napped fabric constructions, exhibits enhanced thermal insulation properties. However, as the bulk density of the fabric increases, thermal insulation decreases, as heat can pass through more easily. Approximately 70% of a fabric's volume consists of trapped air, with fibre making up the remaining 30%. The characteristics of air primarily influence the transfer of heat through textile materials. Fabrics with fibres and strands brought to the surface, such as pile or napped fabric structures, provide enhanced thermal insulation [87, 88]. Differences in the amount of water carried by fabrics derive from variations in their fundamental material structure. The arrangement of fibres in yarn affects structural variances, impacting the roughness factor (cos $\theta$) of the yarn and the size and continuity of capillaries. A haphazard distribution of fibres results in a greater contact angle, while a strong alignment of fibres leads to a lower contact angle, facilitating faster water movement in yarns and textiles. Sledzinska et al. conducted a study on the comfort attributes of work attire for employees with locomotor disabilities. They emphasized that overall comfort, including the design and choice of materials, is crucial for handicapped individuals. The test results indicated that twill 2/1 S fabrics with a surface mass of 243 g/m$^2$, 204 g/m$^2$ and 175 g/m$^2$ were the most viable options for developing work attire for impaired employees [89]. Limeneh et al. conducted a study to examine the impact of different weave structures, specifically plain, twill and satin, on the comfort properties of fabrics. The researchers found that satin woven fabrics had the highest levels of water vapour permeability, water absorption rate and air permeability. Twill woven fabrics ranked second in these properties, while plain woven fabrics ranked third. Nevertheless, the heat resistance of plain-woven fabrics was found to be the highest, while the stiffness was the lowest for satin woven materials [90]. Tahvildar et al. examined the visual and tactile characteristics of worsted fabrics made with four different weave structures (plain, twill 2/1, twill 2/2 and hopsack 2/2) and four sets of yarns produced using different yarn-spinning methods (solo, siro, single-ply ring and two-ply ring). According to their suggestion, the fabric's open structure and the movement of threads within it enhanced its capacity to recover from creases, increased flexibility and improved air and water vapour permeability. However, the fabric's resistance to abrasion and pilling decreased. In addition, the researchers determined that the comfort and appearance characteristics of fabrics made from yarns spun using different spinning processes may be significantly influenced by the level of compactness and the position of fibres within the yarn structure [91]. The impact of fabric parameters on the different attributes of clothing is summarized in Table 6.

*Table 6: The role of fabric parameters on the different attributes of clothing*

| Fabric parameter | Performance attributes | Aesthetic attributes | Tactile attributes | Wearing comfort attributes |
|---|---|---|---|---|
| Thread density, fabric thickness, weave type cover factor, bulk density, areal weight, | Tensile strength, tear strength, bursting strength, abrasion resistance, resistance | Surface texture, lustre, fancy effect, handle, drape | Compression, friction, shear, bending, rigidity | Stretchiness, lightness, slip-ability, reduction in clinging, prickliness |

# 4 Standard methods for cut protection performance

The referenced articles identify three cut test standards, with each evaluation technique usings a distinct testing apparatus. The specimen is placed on the specimen holder and under the blade in all but one of the three cases. Additionally, there are some similarities and differences between the ASTM and ISO procedures but these two, along with the EN 388, have fundamentally different tools and testing methods.

## 4.1 EN 388 (Europe): Protective gloves against mechanical risks

The EN evaluation method determines a material's cut resistance by measuring its response to the cutting action of a rotating circular blade. During testing, the specimen is placed under a load of 5 N, which is applied to the blade with minimal tension, as illustrated in Figure 2. The rotary blade used has a diameter of 45 mm, while the sample holder is a straight container measuring 90 mm in width and features five holes, each 5 mm wide, along its base. To ensure the accuracy and consistency of the blade, a standard cotton fabric is tested as a reference, both before and after the evaluation of each specimen [92]. The protective performance of the material is then quantified using the 'I' index, as detailed in Table 7.

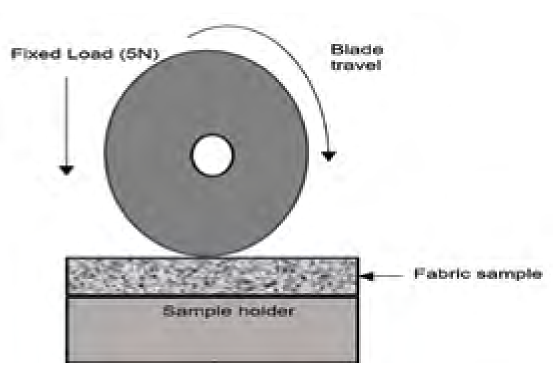


*Figure 2: EN 388 (Europe) Coupe cut test*

*Table 7: Performance grading of cut protection clothing [93]*

| Cut protection level | Index "I" |
|---|---|
| Level 1 | 1.2 |
| Level 2 | 2.5 |
| Level 3 | 5.0 |
| Level 4 | 10.0 |
| Level 5 | 20.0 |

## 4.2 ASTM F1790 (USA): Standard test method for measuring cut resistance of materials used in protective clothing

The assessment is based on determining the force necessary to cut through the specimen after the square blade has traversed 20 mm, the current standard test distance in either direction. During testing, the rectangular blade moves at a constant speed of 150 mm/min in a single direction [94]. As shown in Figure 3, the upper section of the specimen holder is designed with a curved surface having a 38 mm radius. This curvature helps prevent misalignment between the sample surface and the blade. Cut resistance is calculated by analysing the relationship between applied load and displacement, as represented in the load-displacement curve [95].

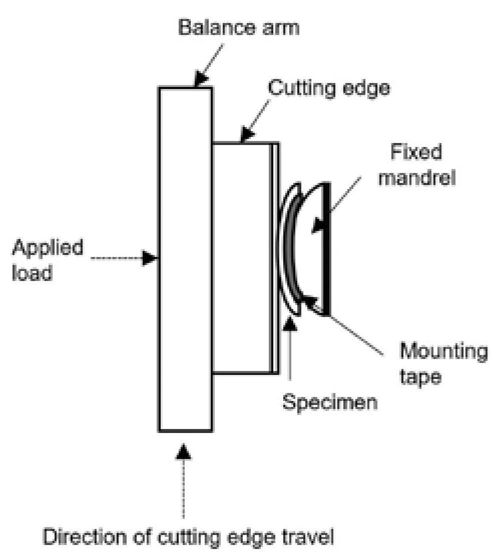


*Figure 3: ASTM F1790-05 CPPT cut test*

### 4.3 ISO 13997 (international): Protective clothing — Mechanical properties — Determination of resistance to cutting by sharp objects

Both ASTM F1790 and ISO 13997 standards use straight blades and angled specimen holders to evaluate cut resistance following similar testing principles. The cut-testing apparatus is illustrated below. During the test, the blade moves horizontally across the specimen at a controlled speed, while the primary measurement is the force required to achieve a cut [96]. This value serves as the key indicator of cut resistance, as shown in Figure 4. The standards also define different performance categories or regions, which are detailed in Table 8.

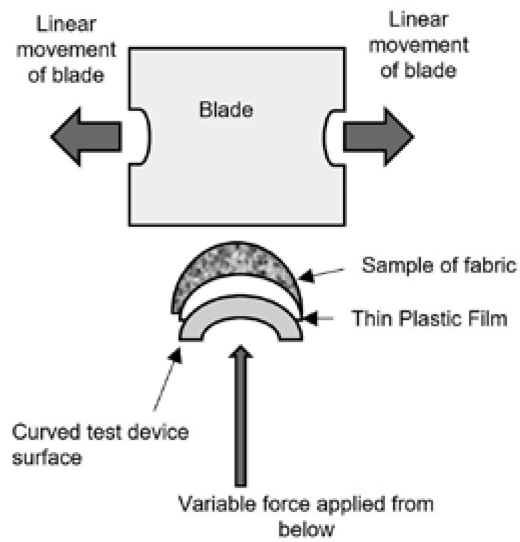


*Figure 4: ISO 13997 (international) TDM cut test*

*Table 8: Different locations of ISO13997 and ASTM F1790 [97]*

| S. no. | ISO13997 | ASTMF1790 |
|---|---|---|
| 1. | Constant normal force | The normal force is a variable that depends on the coefficient of friction of the materials. |
| 2. | Consistent blade speed | Blade speed remains same. |
| 3. | Calculate cut resistance for a 20mm blade displacement. | The cut resistance is determined by measuring the movement of the blade at a distance of 25 mm. |
| 4. | Installation procedure: the sample is positioned on double-sided adhesive tape, ensuring direct contact with the conductive substance. | Installation process: the sample is affixed to double-sided tape. The blade must penetrate the sample material and the double phase tape to make contact with the conductive material. |
| 5. | The process for correcting blade sharpness is as follows: the value of C is equal to 20 / I, where I represents the cutting stroke on neoprene at a force of 5N. | The process for correcting blade sharpness is as follows: the value of C is equal to 25 /I, where I represents the cutting stroke on neoprene at a force of 400 grams. |

### 4.4 ISO 13998 (international): Protective clothing - Aprons, trousers and vests protecting against cuts and stabs caused by hand knives

Figure 5 depicts the apparatus used for impact cut resistance testing. In this setup, the test specimen is repeatedly struck by a standard knife blade mounted within a guided falling block. Upon release, the block drops freely, allowing the blade to penetrate the sample positioned beneath it. The blade is fixed in the block so that it extends 40 mm below the holder. Additionally, the centre of gravity of the block-and-blade assembly is situated 65 mm above the blade tip. The combined mass of the block and blade is 1,000 grams [98].

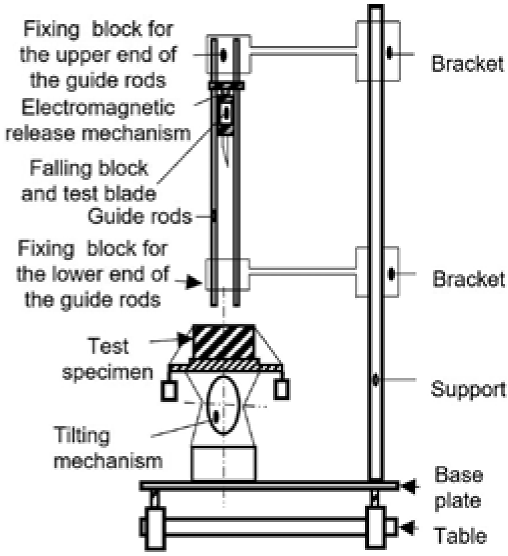


*Figure 5: Schematic diagram of ISO13998 impact cut test*

### 4.5 ISO 13999-3 (international): Protective clothing—gloves and arm guards designed to protect against cuts and stabs caused by hand knives—Part 3: Impact cut test for fabric, leather and other materials

This evaluation standard is designed solely for testing and is not intended to serve as a performance specification. The testing procedure closely follows the methodology outlined in ISO 13998. Figure 6 shows the apparatus used for knife impact penetration testing. The primary distinction lies in how the test specimen or glove is supported. In this method, the specimen is placed on a horizontal arm that terminates in a circular anvil with a central hole, through which the knife blade passes after free-falling. In contrast, the ISO 13998 method positions the specimen on an inclined plastic mass. The circular anvil in this setup features a convex top surface to support the specimen and a central rectangular slot that allows the blade to penetrate during testing [99].

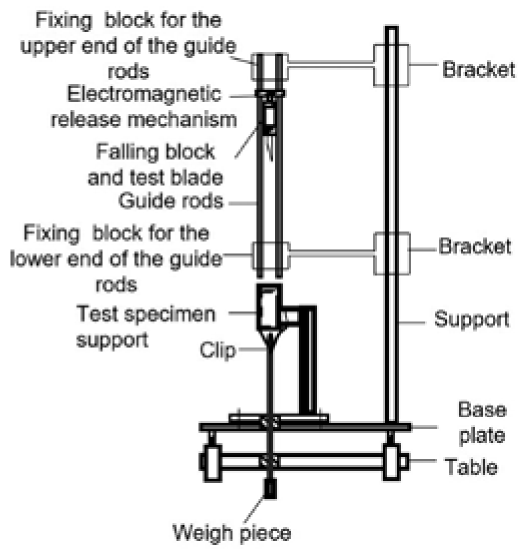


*Figure 6: Schematic diagram of ISO13999-3 impact cut test*

## 5 Trends regarding the growth of cut-protective workwear

The market for cut-protective workwear is experiencing robust growth, driven by several key trends related to safety regulations, technological advancements, evolving end-user demands and sustainability initiatives. Governments and regulatory bodies worldwide are enforcing more stringent safety standards, especially in high-risk industries. This has led to the increased adoption of cut-protective workwear to minimize workplace injuries and ensure compliance. Innovations in materials and manufacturing processes are leading to the development of lighter, more comfortable and more durable cut-resistant garments. New fibres such as ultra-high molecular weight polyethylene (UHMWPE), aramids and engineered blends provide higher cut resistance without sacrificing dexterity or comfort. A lighter weight often provides the user with more comfort and dexterity, while greater cut resistance offers more protection. These two factors are often conflicting. Less material results in a lighter weight, which usually means reduced cut resistance. To address this challenge, innovative solutions must be developed. For example, in an extreme scenario, a very thin medical latex glove could offer strong cut resistance, providing surgeons with more protection compared to conventional latex gloves without cut-protective function. There is a growing demand for workwear that offers protection against multiple hazards such as cuts, abrasions, impacts, chemicals and cold, while maintaining comfort and flexibility. High-visibility features are also increasingly integrated to enhance safety in low-light or high-traffic environments [100].

# 6 Designing of comfortable cut-protective workwear

People's daily lives cannot function without clothing, which also shapes how they view themselves. It can foster a well-being-promoting transdisciplinary functional approach. The development of pleasant and appealing goods that can benefit us in many parts of our everyday lives may be aided by good aesthetic and technological design, which is fuelled by relevant end-user research. With the addition of intelligent features, technological advancements are leveraged to improve the functionality of protective garment systems. Functional cut-protective clothing gives the wearer access to unique features, such as help with monitoring and assessing possible risks that the user may encounter, which conventional protective equipment could not. An integrated approach for the development of functional protective textiles is shown in Figure 7.

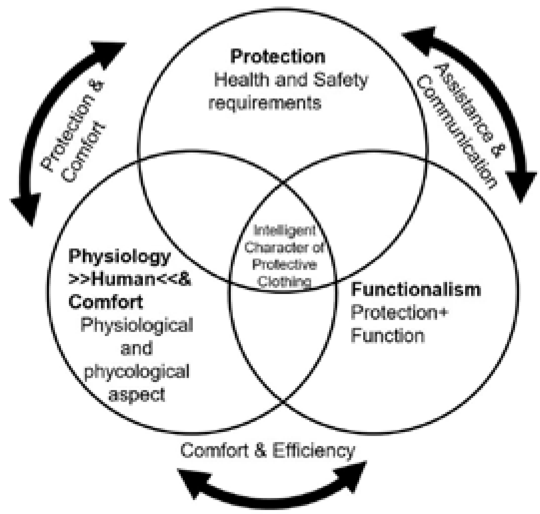


*Figure 7: Integrated approach to functional protective textile [101]*

## 6.1 Initiation of design process

The design process entails a sequence of methodical stages that must be adhered to before the actual production of the product. Dastoor conceptualized the process of manually designing [102]. The synthesis of a fabric structure involves a step-by-step process that starts with the main design goal and progresses through many sub tasks in a top-down manner. The designer selects the type of fibre for interlacing yarns, considering factors such as cost and physical properties, based on the limitations of the property. The specified tensile strength of the cloth thereafter determines the yarn count. The precise modification of yarn characteristics is achieved by changing the twist of the yarn, followed by adjusting the density of the yarn in terms of the number of ends and picks per inch. The choice of fabric weave is determined by factors such as tearing strength, thickness, fluid permeability, etc. Hearle states that in a conventional process, the current design is altered by incorporating expert opinions regarding fabric samples and/or consumer feedback about a fabric or product [103]. The incorporation of macro-mechanics, which examines the relationship between fabric performance and fabric properties, and micro-mechanics, which explores the connection between fabric construction and fibre, yarn and fabric properties, has become an integral component of contemporary design procedures. Matsuo introduced the concept of FASE (Fibre Assembly Structural Engineering) as a method for creating textile products. FASE is a type of knowledge system that focuses on configuration, structure and phenomenology [104]. According to the author's perspective, the design process should begin by acknowledging requirements and then proceed with the sequential steps.

### 6.2 Steps in designing comfortable cut-protective workwear

Functional clothing is primarily constructed from technological textile materials. However, it is crucial to combine high-tech materials with similarly cutting-edge procedures and techniques for garment design and production to fully utilize the unique functions that they provide. Improved cutting, stitching and connecting techniques are required to handle and transform novel materials into performance clothing systems. Each of these phases influences the final appearance, fit, comfort and functionality of a piece of clothing [106].

### 6.3 Measurement of body dimensions and sizing

The initial stage in clothing design is generally to create body measurements of the desired end users. The conventional size chart cannot be used in designing cut-protective clothing since it depends on traditional anthropometry. Data provide measures that show size but provide no information on the complicated human body shape incurvature or postures. Ergonomic block creation necessitates the collection of 3D anthropometric data in a variety of realistic poses. 3D body scanners may be used to acquire form, size and posture data from the population in both static and dynamic modes. Ergonomic measurements, such as range of motion, must also be gathered and considered while developing. Human motion analysis systems are used to understand the changing body shape of clothing during specific activities.

### 6.4 Pattern engineering

Pattern creation is a multi-step process based on a trial-and-error method. To obtain the proper fit and performance, the 3D-2D-3D procedure necessitates a significant amount of tweaking, modification or fitting. Cut-protective clothing should be created based on an approach that precisely reflects the shape of human beings, regardless of whether in a stable manner or an energetic form during labour and movement. As a result, the traditional pattern technique that relies on basic front/back/sleeve panels is limiting. Ergonomic clothing design shapes must correspond to the user's size and posture while matching the 3D shape and function of the individual's body [107–110]. Therefore, cut-protective clothing designs are developed in 3D, for example on the body directly. Furthermore, cut-protective workwear would require the "zoning" of patterns, such as using spacer fabric for thermal insulation or durability against impacts in the upper body region, etc. To allow for the use of multiple components in a block, pattern blocks are constructed in new ways. Patterns must be designed for ergonomic purposes based on body movement to provide greater mobility and reach areas that experience strain during strenuous activities (crotch, underarm, knee and elbow). It is essential to develop articulated knee and elbow designs. Pattern formations are produced directly from a three-dimensional image of a moving body, responding to external properties as required. Flattening these selected 3D areas results in 2D patterns. Fabric mechanical characteristics can be considered in the 3D pattern, and a coloured simulation of the deformation stresses and strains may be visible while the garment is being worn.

### 6.5 Assembly of clothing components

The process of selecting the design and dimensions of each two-dimensional template that will ultimately be linked to form a 3D shell is known as pattern engineering. After creating these designs, they must be cut, constructed, and linked. They must also be linked with the methods of removing and putting back the clothing (buttons, closures and buckles), as well as any additional components that make up a complete garment assembly. The user's activities, position and working environment, along with the qualities of the materials employed, determine pattern design and link it with assembly processes (sewing, attachment and fusing). Multiple fabric panels with various characteristics must be assembled using advanced handling procedures. Seams that are traditionally sewn can occasionally damage the integrity and functionality of manufactured garments. The cut-protective areas in protective clothing are shown in Figure 8.

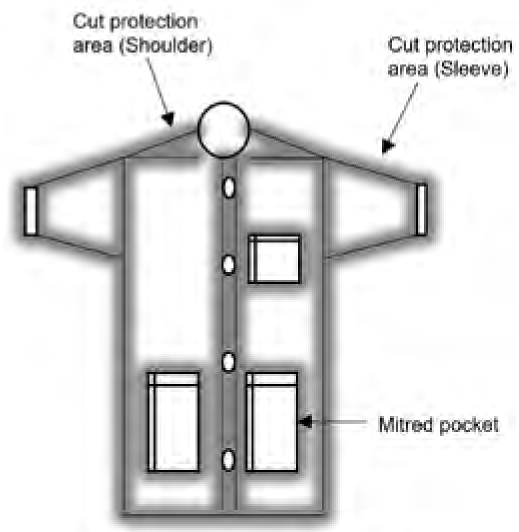


*Figure 8: Cut-protective areas in protective clothing [111]*

These systems are usually constructed using bonded stitches, welding (high frequency, ultrasonic and laser) and bonding with adhesive. A third approach utilized in contoured garments for body contouring and support is 3D moulding. As a result of these changes, new-age clothing appears cleaner, fits better, and is lighter in weight and less bulky.

### 6.6 Role of clothing design on ergonomic wear comfort

Cut-protective clothing requires ergonomic comfort to assist the wearer throughout diverse tasks. The most significant characteristics of ergonomic wear that clothing should meet are the flexibility of mobility, load/strain reduction and physical shape preservation [112, 113]. These are primarily defined by the fit design and pattern structure of the garment, and may be modified by the flexibility or stretchability of the material [114]. Psychological factors demand that the structural properties of clothing correspond to the movement, degree of equality, length of mobility, force and individual joint movement. The majority of the elements that influence this include the shape and fit of the clothes in relation to the body structure and the pressure and abrasion caused by the clothing on the human structure [115]. Providing comfort in clothing for a moving body is a difficult challenge. The number of interconnections between body sizes and shapes, physiological variances, material properties, design choices, environmental challenges and activities is exponential. Clothing has a tremendous impact on worker's comfort and performance in the workplace. In accordance with industrial protection standards, cut-protective workwear is often selected based on functionality and safety [116]. The influence of cut-protective workwear on performance is dependent on the type of task, the required metabolism rate, the surrounding environment and the protective workwear attributes [117]. The ergonomic specifications and characteristics based on the level of relevance for factory workers are as follows: (1) correct fit or size; (2) decrease in heat, as well as improved air circulation through pattern, design and material selection; (3) weight reduction and removal of work-related impediments; and (4) mobility [118]. Many protective workwear standards have been adopted in recent years, and have helped improve the quality of cut-protective workwear and increase worker safety [119]. Cut-protective workwear has significant negative effects, while ergonomic issues often arise with increasing security needs. The main problem is often the additional weight on the body. Furthermore, decreased mobility caused by garment stiffness restricts flexible motion and could increase the risk of falling or becoming entangled in the apparatus. For this reason, cut-protective clothing may worsen rather than improve safety, especially over time. As a result, the user may choose not to wear the necessary protection. Consequently, the shape and material layers of cut-protective workwear need to be carefully chosen to balance protection and comfort, with an emphasis on selecting the lightest and most breathable system that provides enough thermal resistance.

## 7 Future directions

The incorporation of nanotechnology in textiles is leading to the creation of fabrics that offer improved cut resistance, durability and comfort. Nanoparticles can provide features such water repellence, stain resistance, UV protection and antimicrobial properties, all while maintaining the fabric's flexibility and breathability. For instance, graphene and other 2D materials are being studied for their outstanding mechanical and electrical properties, opening new opportunities for lightweight and strong protective clothing [120]. Manufacturing advancements now facilitate highly customizable cut-resistant clothing, allowing users to choose materials, garment types and reinforcement options that suit their specific requirements for comfort and protection. This trend towards personalization is supported by digital technologies such as 3D printing, robotics and advanced textile processing, which also facilitate quick prototyping and scalable production. Customization also extends to fit and ergonomics, focusing on creating garments that cater to various body shapes and movements to enhance comfort and reduce fatigue during extended wear [121]. The future of cut-protection clothing involves integrating wearable sensors that can monitor the wearer's health and the garment's condition seamlessly. Embedded sensors can monitor vital signs, detect exposure to hazards and notify users of any breaches in protection. Graphene-based e-textiles are being developed for their flexibility, washability and potential to accommodate complex sensor arrays [122].

## 8 Conclusion

Cut-protective clothing requires specialized design and engineering approaches distinct from conventional fashion apparel, due to the need for high-performance materials and advanced construction techniques that ensure both safety and comfort. Current innovations, including the use of nanotechnology, smart textiles and adaptive materials, are making garments lighter, more flexible and more durable, and thus directly addressing user needs for comfort and efficiency in demanding environments. The lack of universal standards and the complexity of regulatory compliance remain significant challenges, especially as new technologies and materials are introduced. Ensuring that protective clothing meets both local and international safety standards is critical for effective protection and market acceptance. Garments must be tailored to specific occupational hazards, environmental conditions and user demographics, including considerations for gender and body type, to maximize both protection and usability. Multidisciplinary collaboration among engineers, designers, physiologists, ergonomists and end-users is vital for overcoming challenges in material selection, garment construction and performance evaluation. This review highlights the importance of integrating advanced materials science, user-focused design and regulatory awareness in the development of next-generation cut-protective clothing. Advances in materials, design and technology are transforming cut-protective clothing. However, realizing the full potential of these innovations requires a focused effort on standardization, user-specific solutions and cross-disciplinary collaboration. These steps will ensure that protective garments not only meet the highest safety standards but also deliver comfort, sustainability and practical value across diverse industries.

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***Research data***: The authors have cited the research data in the reference list at the end of article.

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