Journal of Fiber Bioengineering and Informatics 18:1 (2025) 41–55
Cite as: R. Zhang et al.
doi:10.3993/jfbim03192

Elastic High-Performance Covered Yarn: Fabrication, Characterization and Application

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Abstract

To increase the protective capacity of yarns while maintaining human wearing comfort, pure UHMWPE filament and Spandex were combined to fabricate an elastic high-performance covered yarn. The various wrapping process parameters were adjusted to prepare this single-lay-covered yarn with a perfect wrapping status, which also can achieve the balance of strength and elasticity. It was discovered that the wrapping process seriously affected the covered yarn's performance, and the new single-lay covered yarn showed desirable high strength and super elasticity. The strength of covered yarns shows three types of trend with the twist added, including first steep (300 t/m ∼ 400 t/m), then gentle (500 t/m ∼ 600 t/m) and last drastic (700 t/m ∼ 800 t/m). The covered yarn twisted at 700 t/m shows the optimal coverage morphology, excellent elasticity, and high strength. Finally, an elastic cut-resistant fabric is practically knitted by this fabricated elastic cut-resistant composite yarn, and it presents good flexibility and protection with Level 2 cut resistance under standard testing. The fabricated elastic high-performance covered yarn is an ideal material for producing highly elastic protective textiles and is applied to manufacture high-quality flexible protective equipment.

Keywords: Elastic; High-performance; Covered Yarn; UHMWPE; Spandex

1 Introduction

Textiles for personal protection are vital to human survival and consistently play a significant part in social evolution [1]. Researching appropriate protective fabrics is essential since personal activities carry the potential of injury from knives and blunt objects, whether one is a soldier in wartime or a civilian in peacetime. High-performance yarns are a fundamental element of protective fabrics, and their research is important in both theory and practice [2]. Protective

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Mar. 2025

fabrics are usually made of high-performance fibres due to their special functionality [3], including ultra-high molecular weight polyethene (UHMWPE), Kevlar, POB, glass fibre and carbon fibre. These fibres improve the fabric's resistance against cutting, stabbing, tearing, chopping, and sharp objects. For instance, the US patent "criminology" discusses using glass fibre as an effective material for cut resistance, providing excellent protection against sharp objects like knives and cones [4]. Tuba Alpyildiz designed a two-sided knitted fabric structure that utilises Kevlar 1414 fibre-covered yarns, significantly enhancing the fabric's cut resistance compared to the conventional weft-knitted fabric [5].

These strong fibres are not flawless, though. The short service life of Kevlar is caused by its ultra-low UV resistance [6]. Glass fibre has limited wear resistance and is fragile. Furthermore, it has been observed that PBO fibre may experience a drastic decrease in strength when exposed to water or continuous light sources [7]. The UHMWPE will melt when temperatures rise above 130 °C [8]. On the other hand, Kim et al. discovered that contact area and pressure should be considered when designing stab-resistant vests to enhance the wearer's comfort [9]. However, most protective fabrics lack elasticity, making them inappropriate for clothing and activities alone. Conversely, Spandex is a highly elastic chemical with an excellent elongation of 400% to 700% and a rebound rate of 95% to 99%. It is typically utilised in highly elastic, cosy clothing with a tight fit, such as sportswear and tights, and can withstand repeated stretching [10]. Based on the properties of high strength and elastic yarns, Huang created a fabric using UHMWPE as the sheath yarn to provide cut resistance and the Nylon/Spandex as the core to provide elasticity. Consequently, the glove possesses both elasticity and cut-resistant [11]. Nevertheless, UHMWPE's applicability is so broad that its capabilities do not align with what the general public wants. Otherwise, no single-ply covered yarn currently available offers the reported technology. Achieving a balance between high elasticity and strength for yarns is a considerable challenge.

An innovative solution was applied to solve this problem, which uses a core-sheath structure with UHMWPE as the sheath yarn wrapped around the Spandex. A single-ply cover and a high-strength yarn fineness of less than 100D have been effectively developed for a covered yarn. It has a high strength and flexibility tolerance. The wrapping effect can be changed by altering the process parameters, which can balance strength and elasticity for various conditions. The covered yarn has more remarkable performance qualities due to this technique. Furthermore, three knitted fabrics with French Terry structure have been fabricated using one of the covered yarns, which simultaneously exhibits remarkable elastic and cut resistance. Covered yarn, in the meantime, makes it possible to fabricate the ideal protective garments that combine high elasticity with superior protection.

2 Experiment

2.1 Materials

Spandex (70D, 105D) was supplied by Yantai Tayho Advanced Materials Co., Ltd (Shandong, China), and the pure UHMWPE filaments (50D, 75D, 100D) were provided by Zhejiang Jiayun New Materials Co., Ltd (Zhejiang, China).

2.2 Preparation of Covered Yarns

Spandex and pure UHMWPE filaments were chosen as raw materials. The Direct-Twist machine (Model: C6/D6, Manufacturer: AGTEKS, Turkey) created thirteen distinct types of covered yarns with five types of twist (300 $\sim$ 800 t/m). Table 1 displays the wrapping process parameters for these covered yarns, in which Spandex was used as the core yarn and UHMWPE as the sheath yarn. These two fibres were curled and twisted through the entrance roller, and the covered yarn was then drawn and stretched until it reached the receiver. The ideal structure of a covered yarn and the manufacturing process is depicted in Fig. 1.

Table 1: Process parameters of covered yarns

Sample ID	Sheath yarn (D)	Core yarn (D)	Curl rate (m/min)	Pre-drawing multiplier	Twist (t/m)
1#	100	105	20.00	3.8	300
2#	100	105	20.00	3.8	400
3#	100	105	20.00	3.8	500
4#	100	105	20.00	3.8	600
5#	100	105	20.00	3.8	700
6#	100	105	20.00	3.8	800
7#	75	70	20.00	3.61	600
8#	75	70	20.00	3.61	700
9#	75	70	20.00	3.61	800
10#	100	70	20.00	3.61	600
11#	100	70	20.00	3.61	700
12#	100	70	20.00	3.61	800
13#	75	105	20.00	3.8	600

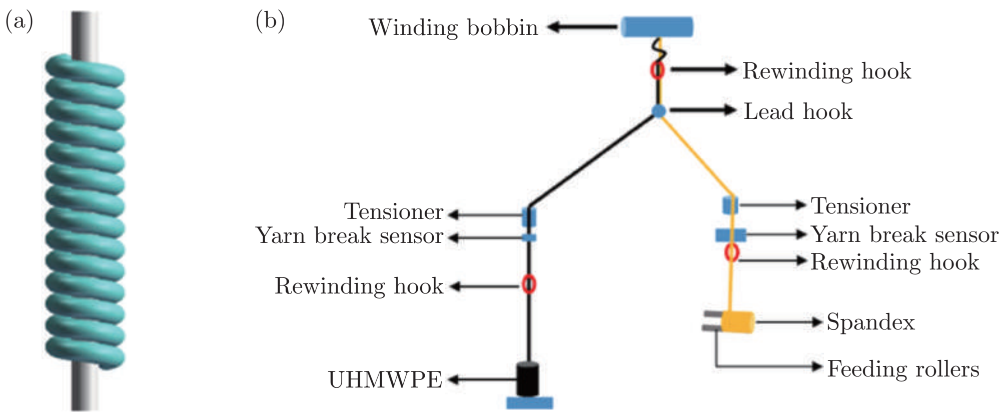

Fig. 1: Schematic diagram of (a) the ideal structure of a covered yarn and (b) the production process of covered yarn

2.3 Fabrication of Knitted Fabrics

Three types of knitted fabrics with a French Terry structure were fabricated using a circular knitting machine (gauge: 34 inches, 12 needles; manufacturer: Fujian Taifan Industrial Co., Ltd., China). The details are provided in Table 2. The face yarn was a Nylon/Spandex composite yarn consisting of 40D Nylon and 70D Spandex. The link yarn and ground yarn were formed by UHMWPE/Spandex composite yarn, incorporating 75D UHMWPE filament yarn and 105D Spandex.

Table 2: Information on knitted fabric

Fabric ID	Face yarn (%)	Link yarn (%)		Ground yarn (%)	
		UHMWPE	Spandex	UHMWPE	Spandex
A1	30.09	30.26	11.74	21.30	8.79
A2	31.96	32.11	10.21	19.53	6.18
A3	27.83	34.57	10.30	18.50	6.55

2.4 Test Performance of UHMWPE

Yarn Linear Density

According to the standard GB/T4743-2009 "Textiles - Determination of Yarn Linear Density by the Winding Method," the actual fineness of UHMWPE continuous filament is determined using the weighing method.

Mechanical Properties

According to the "High-Strength Fiber Yarn Tensile Property Test Method," the mechanical properties of UHMWPE are measured using the universal strength tester(Model: Instron 5966, Manufacturer: INSRON, US).

Morphology of UHMWPE

Fix a 1.0 cm length of UHMWPE filament onto the sample stage with conductive adhesive tape, then sputter coat with gold for scanning electron microscopy (SEM) observation of the surface.

Diameter of UHMWPE

The SEM images captured are analysed using Image Pro to measure the diameter of a single filament 100 times. The results are then statistically processed using Origin software to create a distribution graph and to calculate the average diameter (unit: μm).

2.5 Test Performance of Covered Yarns

Morphology of Covered Yarns

The electron optical microscope tested the covered yarns (Model: V5200, Manufacturer: KEYENCE, China) optical profiler. Choose a straight but not elongated sample, then observe the exposure core yarn and the coverage of the sheath yarn.

Tensile fracture

The test used the universal tensile testing machine (Model: Instron 5966, Manufacturer: INSTRON, US). Test the mechanical properties of pure UHMWPE filament and covered yarn based on the GB/T 19975-2005 "Test Method of Tensile Properties for High Tenacity Filament Yarn" and the GB/T3916-2013 "Determination of breaking strength and elongation at break of single textile covered yarn (CRE method)", respectively.

Elasticity

According to FZ/T 50007-2012, "Testing method for the elasticity of spandex filament yarns" [12], the elastic recovery rate and plastic deformation rate of the covered yarn should be measured using the universal strength tester (Model: Instron 5966, Manufacturer: INSTRON, US).

2.6 Characterization of Knitted Fabrics

Thickness

According to GB/T 3820-1997, "Determination of the thickness of textiles and textile products standard," a thickness meter(model FS-60DS; manufacturer: Daiei Kagaku Seiki Mfg. Co.,Ltd., Japan) is used to obtain the value of fabric thickness.

Fabric density

The density of the fabric was evaluated by the electronic balance(model BSA224S; manufacturer Sartorius AG, Germany) in accordance with standard GB/T 4660-2008, "Determination of mass per unit length and area of textiles standard."

Elasticity

A universal strength tester(model: Instron 5966; manufacturer: INSTRON, US) was used to examine fabric elasticity according to FZT 70006-2004 [13], the test method for knitted fabrics' tensile elastic recovery rate.

Cut-resistance

Using a glove cut-resistance test machine(model: SGJ6000A; manufacturer: Zhejiang Sangong Instrument Co., Ltd., China) to evaluate the cut-resistance index of the fabrics according to the

GB 34541-2009 Hand protection: protective gloves for preventing mechanical hazards standard [14].

3 Results and Discussion

3.1 Performance of UHMWPE

Table 3 shows the breaking strength, initial modulus, and breaking elongation rate of UHMWPE continuous filament, which were calculated based on a load-displacement curve and the actual fineness. A higher tensile breaking strength indicates that the UHMWPE continuous filament can withstand greater external tensile forces per unit fineness, leading to a higher breaking elongation rate.

Table 3: Tensile break properties of UHMWPE continuous filament

UHMWPE	Fracture strength		Initial modulus		Break elongation	
Specification (D)	Average (cn/dtex)	CV (%)	Average (cn/dtex)	CV (%)	Average (%)	CV (%)
50	31.95	12.50	1311.44	5.78	2.87	12.51
75	34.35	10.10	1328.01	6.00	3.10	10.13
100	33.99	10.25	1336.19	5.24	3.21	12.27

The morphology of UHMWPE continuous filament is shown in Fig. 2. The images reveal that the surface of these fibres exhibits lateral non-uniform micro-cracks and longitudinally subtle strip-like grooves. As the linear density increases, the lateral cracks become more evident. This arises from the production of UHMWPE. Ultra-drawing is an effective method to obtain high strength high modulus polyethylene fibres, although this disrupts the fibre's surface and leaves grooves and lateral cracks on the fibre surface [15].

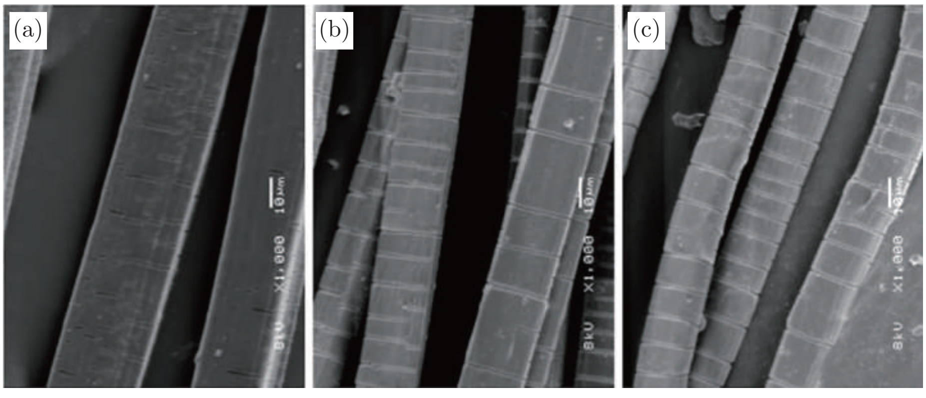

Fig. 2: SEM × 1000 images of UHMWPE filaments (a) 50D, (b) 75D, (c) 100D

The diameter of individual filaments in UHMWPE continuous filaments was measured using SEM imagery and software (Image Pro), with results presented in Table 4. The data show that increasing the linear density of these fibres decreases the filament diameter. Figure 3 illustrates the distribution of 100-diameter measurements, indicating a more concentrated diameter distribution with increased linear density. This consistent filament diameter minimises weak points and ensures a more even distribution of external forces during stretching than non-uniform diameters, enhancing tensile resistance. Therefore, 75D and 100D UHMWPE are preferred over 50D fibres due to their superior mechanical properties.

Table 4: Monofilament diameter of UHMWPE filaments

Linear density	Filament diameter (μm)	CV (%)
50D	28.65	4.36
75D	21.94	6.22
100D	17.36	5.25

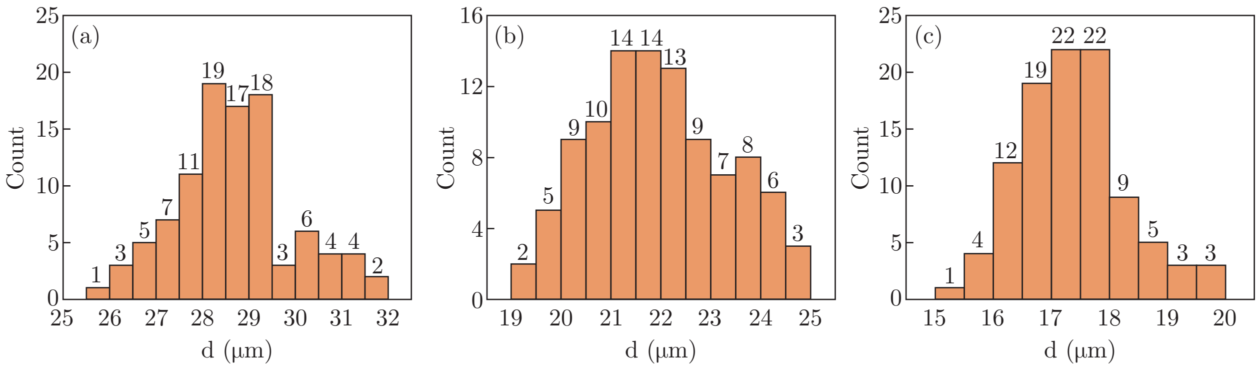

Fig. 3: Distribution of single fibre diameter for UHMWPE measured over 100 times: (a) 50D, (b) 75D, (c) 100D

3.2 Morphology of Covered Yarns

The wrapping status is essential to balance the elasticity and strength of a covered yarn. A perfect wrapping of sheath yarn around the core yarn will result in a uniform and smooth surface, which can reduce the defects of later fabricated textiles. Three yarn combinations were wrapped in varying twists to investigate the impact of yarn fineness and a covering twist on wrapping. Figure 4 illustrates the morphology of these combinations(UHMWPE (75D) / Spandex (70D), UHMWPE (100D) / Spandex (70D) and UHMWPE (100D) / Spandex (105D) at the twist ranging from 600 t/m to 800 t/m.

The morphologies for three combinations of the covered yarns are all improved as the twist increases because the sheath yarn winds around the core yarn at more turns. Uneven wrapping of the sheath yarn around the core yarn occurs at the twist of 600 t/m, which is unfavourable for bearing and elasticity. On the other hand, with a twist of 800 t/m, the core yarn is tightly locked by the sheath yarn, restricting the stretching space of the elastic Spandex and impeding yarn elasticity. Interestingly, the coverage of badly formed covered yarn is greatly improved at the twist of 700t/m, and the sheath yarn is equally distributed around the core. Furthermore, the coverage effect of Fig. 4(b) is more regular than that of Fig. 4(a) at the same twist rate, especially at the low twist level. This is because the coarser sheath yarn can provide better coverage than

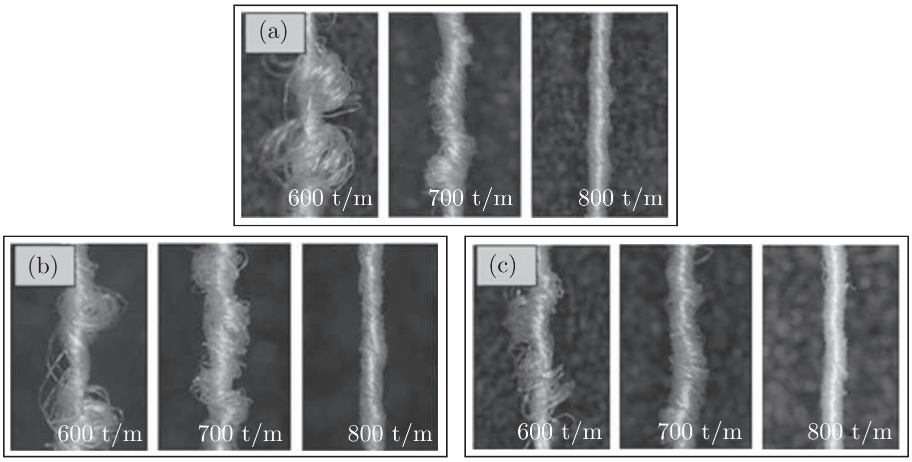

Fig. 4: Morphology of covered yarns (100x) with different core/sheath combinations under twist from 600 t/m to 800 t/m. (a) UHMWPE (75D) / Spandex (70D); (b) UHMWPE (100D) / Spandex (70D); (c) UHMWPE (100D) / Spandex (105D)

a fine one. Additionally, it is reasonable that a coarser core yarn benefits from an even coverage of sheath yarn, as the coarser core yarn has better elasticity, as seen in the comparison between Fig. 4(b) and Fig. 4(c). Therefore, the yarn fineness and twist level of the core and sheath yarn have a great influence on the morphology of the coverage, and the UHMWPE (100D) / Spandex (105D) covered yarn at the twist of 700 t/m offers an even morphology, which is suitable for the fabrication of elastic protective textiles.

3.3 Tensile Fracture of Covered Yarns

The strength of yarn is vital for the protection of fabricated textiles, and the higher strength of yarn always presents more difficulties in being destroyed. The tensile load-displacement curves of pure UHMWPE filaments (75D and 100D) are shown in Fig. 5(a). The variation of the load is positively correlated with that of displacement, and the 75D and 100D pure UHMWPE filaments are 29.75 N and 37.76 N, respectively, with the breaking strength of 35.74 cN/dtex and 34.02 cN/dtex individually. Since pure UHMWPE filament comprises dozens of monofilaments, these monofilaments share the force when the external force is applied. So it is reasonable that the external force which the fibre withstanding enhances with the increase of the fineness of the fibre. A sudden drop-off is observed when the filament is broken, as the pure UHMWPE filament is stretched to the limit and can no longer resist the applied force. Since a coarser UHMWPE filament usually has less monofilament uniformity than finer ones, they are more prone to breaking at weaker points. This explains why the 100D UHMWPE filament has a lower breaking strength than the 75D UHMWPE filament.

The breaking strength properties of UHMWPE filament (100D) and Spandex (105D) covered yarns with a twist ranging from 300 t/m to 800 t/m (sample 1# to 6#) are shown in Fig. 5(b). A notable decrease in breaking strength is observed in the covered yarns, decreasing from 22.94 cN/dtex to 14.09 cN/dtex along with the twist increases. Compared to the pure UHMWPE filament (100D), whose breaking strength is 34.02 cN/dtex, the decline in strength after wrapping is justifiable. Firstly, the fineness of the covered yarn inevitably increases after wrapping. Break strength refers to the tensile force per unit of fibre, i.e., the ratio of the fibre's breaking strength.

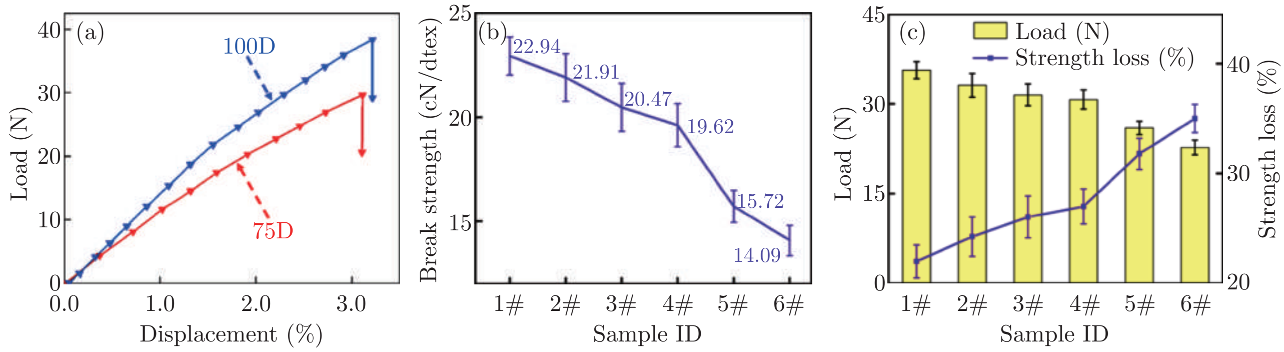

Fig. 5: The tensile fracture of pure UHMWPE filament and covered yarns. (a) 75D and 100D UHMWPE load-displacement curves; (b) Break strength of covered yarns; (c) Load and strength loss of covered yarns

Due to the rapid growth in yarn fineness after wrapping, while the yarn's ability to withstand the strength grows slowly, the ratio of strength to fibre diminishes, which leads to a decrease in breaking strength. Secondly, the UHMWPE filament sheath yarn is converted from wrapping to twisting. The twist of the filament leads to the loss of strength, and the decline increases with the twist number.

As previously mentioned, the load of the covered yarn was proportional to the breaking strength, and this strength loss gradually increased (Fig. 5(c)) with the twist growth. This data is derived from the author's previous research [16]. The primary reason for the decrease in strength is the reduction in the load the yarn can support. The increase in twist makes the strength of covered yarns show three types of decreasing trend, including initial steep (low-twist zone, 300 t/m $\sim$ 400 t/m), then gentle (medium-twist zone, 500 t/m $\sim$ 600 t/m) and final drastic (high-twist zone, 700 t/m $\sim$ 800 t/m). In the medium-twist zone, the sheath yarn is uniformly distributed around the core yarn, resulting in a balanced force distribution in each direction during stretching. However, in both the low-twist and high-twist zones, the strength loss is more pronounced compared to the medium-twist zone. This is due to the overall uniformity of the force applied during stretching in these zones. As a result, the wrapping status's unevenness weakens the yarns. The strength loss in the low-twist zone is slower than the high-twist zone. This is because the lower twist number causes the originally loose monofilaments to be held together and increases the integrity of the tensile force. In contrast, in the high-twist zone, the fibres are highly twisted, and shear force works on the monofilaments, which reduces their strength.

However, the covered yarn maintains its ability to withstand significant forces. The 100D pure UHMWPE filament and sample 5# covered yarn (UHMWPE (100D) / Spandex (105D) twisted at 700 t/m) exhibit respective performances of 37.76 N and 30.86 N.

During stretching, the force is applied along the twist direction of the covered yarn, while breakage occurs due to the axial component of the tensile force in the vertical direction. As illustrated in Fig. 6, the sheath yarn twists across different zones, where the angle α between the filament path and the axial direction determines force distribution. The axial force component F results when the yarn is subjected to a tensile force F. As the twist increases, F' gradually decreases as the filament path steepens and the angle α increases. Consequently, the breaking strength decreases with increasing twists. For optimal performance, the twist of 100D UHMWPE continuous filament covering 105D spandex filament should ideally be controlled at approximately 700 t/m, ensuring a balance between achieving a uniform and continuous appearance and minimising excessive tensile loss. Although the wrapping process contributes to the inevitable decrease of the maximum loading force, the covered yarn achieves a desirable balance between morphology and strength, making it an ideal yarn for preparing flexible protective textiles.

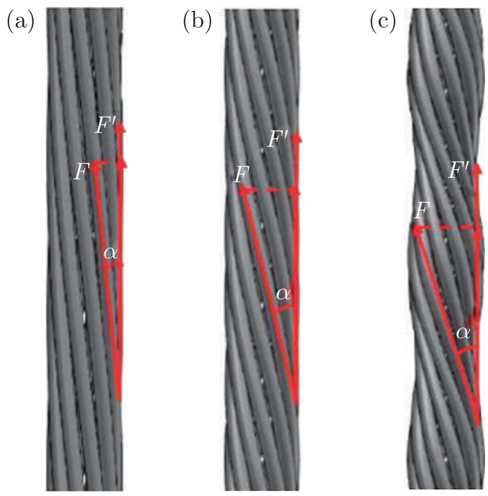

Fig. 6: UHMWPE twisting diagram. (a) Low twist zone; (b) Medium twist zone; (c) High twist zone

3.4 Analysis of the Tensile Curve

Fig. 7(b) shows the tensile load-displacement curve for the UHMWPE/spandex elastic-covered yarn, a composite yarn combines the mechanical properties of UHMWPE continuous filaments and spandex filaments, resulting in a tensile curve divided into low-tension and high-tension regions. Compared to the curve of pure UHMWPE continuous filaments (Fig. 7(a)), the primary distinction lies in a roughly 2.0% increase in breaking elongation rate in the low-tension region. This enhancement is attributed to the rigidity and limited elasticity of pure UHMWPE continuous filaments, which restrict stretchability. However, in the UHMWPE/spandex elastic-covered yarn, UHMWPE continuous filaments are wrapped around the spandex filament with a high twist, introducing slack during stretching and thus contributing to the increased breaking elongation rate.

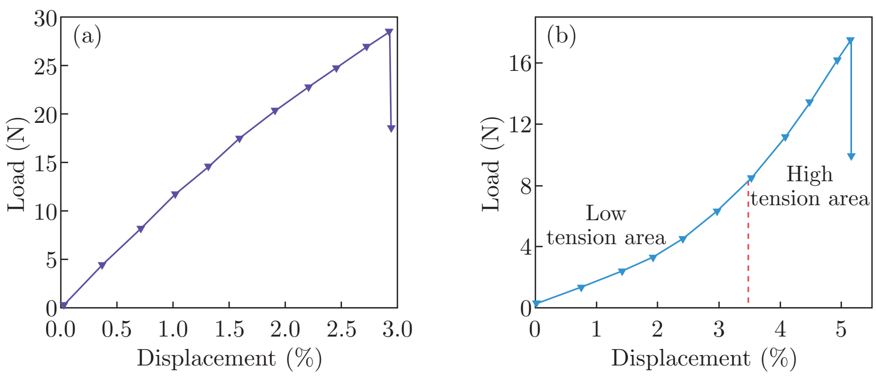

Fig. 7: Tensile load-displacement curves. (a) Pure UHMWPE continuous filament, (b) UHMWPE/ Spandex elastic covered yarn

According to the slope of the load-displacement curve, it is evident that the composite yarn exhibits greater elasticity in the low-tension area and enhances strength in the high-tension area.

In the low-tension area, the tensile load-displacement curve rises roughly in a parabolic shape. In contrast, in the high-tension area, it rises linearly, resembling the tensile curve of UHMWPE continuous filaments. During stretching, the core spandex yarn extends while the sheath yarn is relaxed and curls into loops due to the twisting action. During low-tension stretching, the spandex filament primarily bears the load, causing the UHMWPE continuous filaments to gradually move closer to the centre. As external force increases, the sheath yarn tightly wraps around the core yarn in a spiral, transitioning to the high-tension area. In this phase, the sheath yarn has no room for relative slippage, and the UHMWPE sustain higher tensile forces until the yarn approaches its maximum stretch capacity. In conclusion, the UHMWPE/spandex elastic covered effectively integrates the elasticity of spandex with the tensile strength of UHMWPE, balancing these properties to meet the demands for high elasticity and stretch resistance.

3.5 Elasticity Performance of Covered Yarns

The covered yarn exhibits remarkable stretchability compared to pure UHMWPE filament without any elasticity. Fig. 8(a)-(c) illustrates the stretching process of the sample 5# covered yarn. In the unstretched, relaxed state, the sheath yarn surrounds the core yarn in a spring-like structure. As stretching occurs, the sheath yarn rotates and gradually approaches the core yarn. When the external force reaches a critical value, and the stretching process ends, the sheath yarn tightly wraps around the core yarn and locks it in place. There is no space for the sheath yarn to slide at the full stretching status, despite the core yarn's potential for further stretching. To illustrate in detail the effect of different core yarn fibres on the elasticity of covered yarn, the elasticity of sample 5# (100D sheath yarn / 105D core yarn) and sample 11# (100D sheath yarn / 70D core yarn), both at a twist of 700 t/m were compared. As shown in Fig.8(d), the 105D Spandex presents a higher elasticity than the 70D as a core yarn. Sample 5# boasts a high elastic recovery (92.72%) and low plastic deformation (7.29%). While the elastic recovery and plastic deformation of sample 11# covered yarn are 89.09% and 10.91%, respectively. Overall, the high elasticity of the covered yarn can meet the comfort requirement for protective fabric preparation.

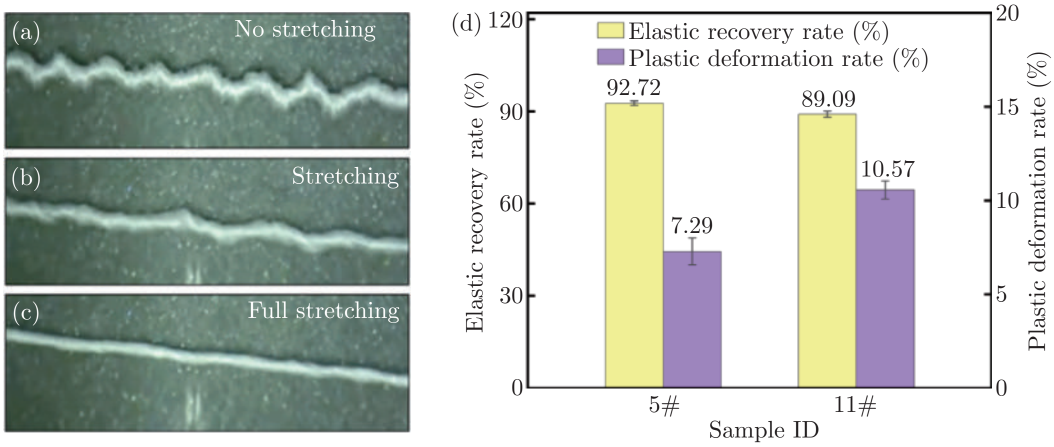

Fig. 8: (a)-(c) Schematic diagram of wrapping yarn with no stretching, stretching and full stretching; (d) The elastic recovery rate and plastic deformation rate of sample 5# and sample 11# covered yarn

3.6 Performance of Knitted Fabric

The break strength of UHMWPE/Spandex composite yarn slightly changes with the use of different sheath yarns (50D, 75D and 100D). This allows for the selection of optimal fineness based on the fabric requirements. Considering the better breathability and comfort performance of the fabric without significantly sacrificing strength, a finer 75D UHMWPE filament fibre was composited with 105D Spandex to fabricate three types of knitted fabrics, detailed in Table 2. These fabrics are knitted with French Terry structured, consisting face, link and ground yarns in varying UHMWPE proportions. Due to the inherently significant elasticity of the knitted fabric, it presents the ideal structure of high elasticity cut-resistant fabric. Specifically, the face yarn is a Nylon/spandex composite, which enables dyeing and printing on the fabric surface due to the presence of Nylon. Both link yarn and ground yarn contribute to the fabric's cut resistance and augment its elasticity beyond the inherent elasticity of the knitted fabric structure. Fig. 9 depicts the knitted structure and the fabric's front and back views.

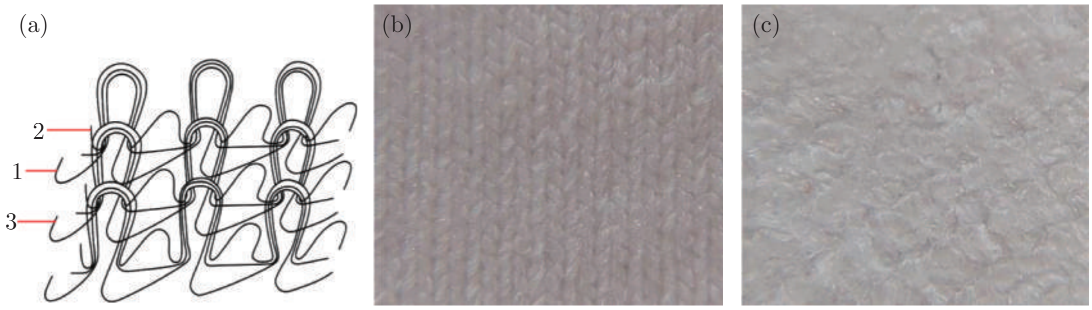

Fig. 9: (a) French Terry structure (1 ground yarn, 2 face yarn, 3 link yarn); (b) Front view and (c) Back view of the knitted fabric

Table 5 presents the thickness and density of the three fabrics. The fabrics exhibit slight differences in thickness, with all values close to 1.10mm. However, the fabric density noticeably decreases with the increase of the UHMWPE percentage.

Table 5: The thickness and density of three knitted fabric

Fabric ID	Thickness (mm)	CV (%)	Fabric density (g/m^2)	CV (%)
A1	1.11	2.18	399.72	1.73
A2	1.05	0.85	384.43	2.53
A3	1.13	3.42	382.39	2.34

3.7 Elasticity of Knitted Fabrics

The elasticity of knitted fabrics is combined with the inherent elasticity of covered yarn and the structure of fabrics. The elastic recovery rate and plastic deformation rate were measured for the warp and weft directions at a fixed elongation of 50%, as shown in Fig. 10(a) and (b). After three stretching cycles, the elastic recovery rate in the warp direction fluctuates around 83.19% to 84.75%. Fabric A2 exhibits the highest plastic deformation rate of 8.40%, attributed to the permanent damage caused by stretching. In the weft direction, the three fabrics exhibit parallel trends compared to the warp direction, with the order from highest to lowest being A1 > A3 > A2. The plastic deformation rate is lower than that in the warp direction. Notably, A2 exhibits a higher plastic deformation rate and a lower recovery rate after several stretches in both directions, suggesting A1 and A3 are proper for creating high elasticity and cut-resistance knitted fabrics.

The elastic recovery rate is generally higher in the weft direction than in the warp direction, which is attributed to the structural characteristics of the loop, as shown in Fig. 10(c). Each loop consists of two loop pillars (**a**, **b**) and one top arc (**c**). During warp stretching, **a** and **b** move warpwise, causing an increase in loop height (**h**) and decreasing loop distance (**d**). The movements of **a** and **b** are relatively slight, so the deformation recovery requires overcoming greater frictional forces. Conversely, the weft stretching shifts **c** weftwise and decreases **h**. This movement causes the yarns in **a** and **b** to stretch to compensate for the loop arc **c**, thereby increasing **d**. This leaves enough space for the fabric to be stretched repeatedly in the weft direction rather than warp.

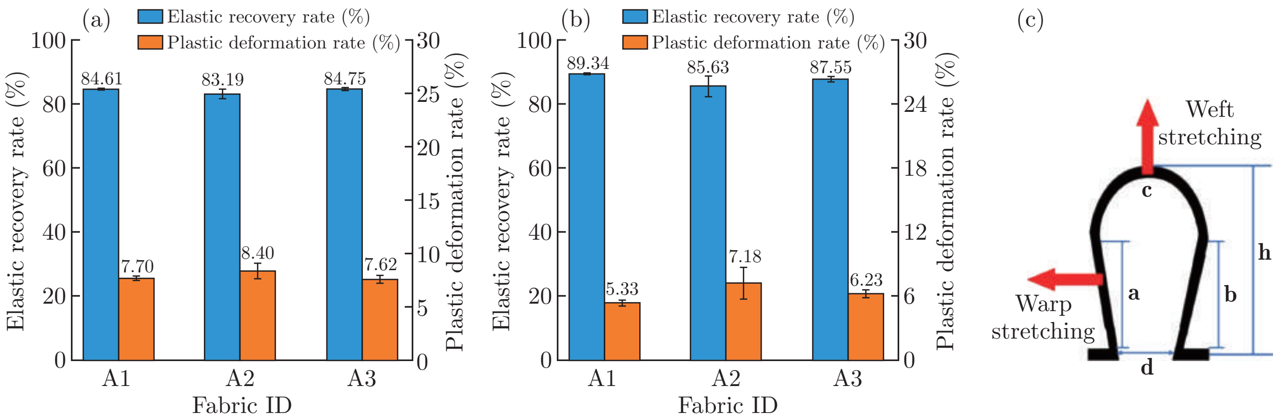

Fig. 10: (a) The elastic recovery rate and plastic deformation rate of the warp direction and (b) weft direction; (c) loop structure

3.8 Cut-resistance of Knitted Fabric

The cut-resistance of fabrics A1-A3 in both the warp and weft directions are presented in Table 6. In the warp direction, the cutting index decreases in the order of A1 > A3 > A2, while the decrease follows the order of A1 > A2 > A3 in the weft direction. Despite similar fabric thickness, A1 exhibits the highest cut resistance in both directions, attributed to its increased density compared to A2 and A3. These findings suggest that fabric density is a pivotal factor influencing cut resistance, and enhancing density can effectively improve this property. Additionally, the cut

Table 6: Cut-resistance of knitted fabrics

Fabric ID	Warp		Weft	
	I	CV (%)	I	CV (%)
A1	4.1	12.19	3.8	15.79
A2	3.3	15.15	3.7	16.21
A3	3.7	13.51	3.3	12.12

resistance is comparable in warp and weft directions, attributed to the advantageous French Terry structure. However, different yarn segments bear the force-loop arc yarns in the warp direction and horizontally arranged loop pillar yarns in the weft direction.

4 Conclusion

A successful single-ply covered yarn was fabricated by wrapping pure UHMWPE filament around Spandex with varying yarn combinations, and the twist parameters significantly influenced the yarn's covering morphology, strength and elasticity. As the twist increased, the strength of the covered yarns exhibited three distinct decreasing trends, including initially steep (low-twist zone, 300 t/m $\sim$ 400 t/m), then gentle (medium-twist zone, 500 t/m $\sim$ 600 t/m) and last drastic (high-twist zone, 700 t/m $\sim$ 800 t/m). The optimal wrapping coverage was achieved at the twist of 700 t/m, presenting an optimal balance between the yarn strength and elasticity. The UHMWPE filament (100D) / Spandex (105D) covered yarn at a 700 t/m twist is 30.86 N. Meanwhile, the covered yarn demonstrated excellent elasticity, with a high elastic recovery rate (92.72%) and a low plastic deformation rate (7.29%). Moreover, the force applied on covered yarn and the textile load-displacement curve were analysed deeply, highlighting its composite mechanical behaviour, characterised by distinct low-tension and high-tension regions. In the end, three types of French Terry structured knitted fabrics were developed. The A1 and A3 demonstrated high elastic recovery and low plastic deformation rates. The knitted fabrics' cut resistance was influenced by fabric density, with A1 exhibiting the strongest cut resistance. Consequently, A1 achieves a balance between cut resistance and elasticity. The successfully fabricated single-ply covered yarn and French Terry structure are ideal for preparing flexible protective textiles.

Acknowledgement

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by a project of the Key Technologies for the Development of High-Performance Clothing for Winter Sports and Training Competitions (2019YFF0302100), and 2023 Erdos Cashmere Industry Revitalization Project (nkykc2023-01).

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