Continuous Filament Knit Aramids for Extremity Ballistic Protection

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ABSTRACT

Ballistic tests are performed on a continuous filament knitted aramid (CFKA) to determine the protective capabilities. CFKAs are candidates for implementation into garments that protect extremities, such as arms, legs, and the neck, from debris and other projectiles. These garments are expected to be designed at lower areal densities than conventional torso body armors, and have more demanding comfort requirements to accommodate flexible body joints. These unique requirements have prompted exploration of non-traditional armor materials such as knits and felts. The V_{50} performance of a CFKA is compared to a woven aramid and commercial-off-the-shelf materials including: silk, polyester, Army Combat Uniform nylon-cotton blend fabric, staple yarn aramids, and aramid felts. Ballistic tests involve impacting each target multiple times with 0.22 caliber glass spheres in a pre-determined shot pattern. All targets are backed with ballistic gelatin and maximum likelihood estimation is used to calculate V_{50} values. Target areal densities range from approximately 200 g/m^2 to 1200 g/m^2. The results show that non-traditional materials like knits and felts can play an important role in extremity protection, and that unique design approaches are required for this emerging application area. Furthermore, the CFKA material appears to provide a unique combination of comfort and ballistic performance that may be well-suited to extremity protection applications.

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INTRODUCTION

In early 2010, warfighters in Afghanistan experienced an increasing number of attacks from improvised explosive devices (IEDs) [1]. An IED detonation causes injury through blast overpressure and acceleration of fragments, including soil debris. IED attacks tend to cause significant injuries to the extremities [2-4]. To defend against pelvic injuries, the Joint IED Defeat Organization (JIEDDO) funded rapid procurement of a two-tier system designed by Cooneen Watts and Stone Ltd (CWS). The first level of protection consists of multi-layered, silk boxer briefs. This protective undergarment (PUG) is intended to defend against accelerated soil debris. The second part of the system is an optional apron of ballistic material that the user can wrap over the pants as deemed necessary. This outergarment armor is engineered to protect against larger projectiles and fragments. Since procurement of the CWS pelvic protection system, there has been a strong desire to enhance the PUG and extend that level of protection to the extremities.

The requirements of extremity armor differ from traditional torso protection materials. Torso body armor is normally made from an engineered ceramic, multiple layers of woven aramid, or some combination of the two. Since the chest is inflexible, the stiffness of these armors is not problematic. Conversely, a significant amount of movement occurs at the pelvis and extremities; making traditional torso armor impractical as it would impede movement. Armor that covers the legs, arms, and neck must offer adequate protection without sacrificing comfort.

To meet comfort requirements, candidate materials for extremity protection need to be flexible and implemented at low areal densities. Given these requirements, knitted fabrics are an attractive option. Most commercial knits are formed from "staple" yarns that are constructed by entangling short filaments of material, generally via a spinning process. Natural yarns, such as cotton and wool, can only be produced in staple form because their fibers are inherently short. Synthetic yarn, for example aramid, is composed of long, continuous filaments instead of short fibers. However, when used in commodity goods, synthetic yarns are often processed into staple form.

For manufacturers of synthetic commodity goods there are several advantages to using synthetic staple yarns. First, they are cheaper to produce because several smaller denier staple yarns can be drawn down from a single, large continuous filament yarn. Second, staple yarns are easier to knit due to their flexibility [5]. Finally, discontinuous yarns have a softer feel against the skin. The disadvantage to using staple yarns is that they are weaker than their continuous filament counterparts [6-9]. This limitation is of little concern in applications where mechanical strength and penetration resistance are not a critical concern.

The goal of this study is to evaluate the ballistic performance of potential extremity protection materials. Several different materials are studied including: a series of commercially available fabrics, woven aramid, developmental felts, and a novel continuous filament knit aramid (CFKA). Fabric areal densities are between 200 g/m^2 and 1200 g/m^2. The projectile used in the tests is a 6mm diameter, glass sphere. During ballistics tests, targets are wrapped around a synthetic gelatin cylinder to create realistic loading conditions. A V_{50} ballistic limit is determined for each fabric and compared on a per weight basis.

EXPERIMENTAL

Materials

Fabrics tested range from commercial textiles to developmental armor materials. Table I presents details about each fabric. Figures 1 and 2 show micrographs of the materials at magnifications of 10× and 250× respectively.

This study includes tests on five commercial textiles that are normally used in non-ballistic applications. Army Combat Uniform (ACU) material is a woven product constructed from blended staple nylon and cotton yarns. ACU fabric is representative of the material used in current U.S. Army pants. The silk is a jersey style knit that is very similar to the material used in first-generation PUGs. Silk is classified as a staple yarn product; however, its filament lengths are longer than typical natural fibers. Light and heavy knitted Kevlar (referred to as "Light KK" and "Heavy KK", respectively) are both staple yarn products. These types of aramids are used in commodity goods such as gloves and sports apparel. Polyester represents a typical lightweight, stretchable, synthetic commercial comfort fabric. Like silk, nominally polyester is a continuous filament knit but with a moderate population of fiber ends.

K706 is a woven, ballistic fabric made from 600d KM2 Kevlar yarns. The yarns in this material are continuous filament, with few fiber ends. K706 is used for a variety of protection applications and is representative of the armor currently used in the Army outer tactical vest (OTV).

CFKA is a prototype knit made from continuous filament, 600d KM2 Kevlar yarns. The fabric was knitted at the Natick Soldier Research, Development, and Engineering Center (NSRDEC) in Natick, Massachusetts. Tubes of CFKA 7 cm in diameter were produced on a Lawson Hemphill Fiber Analysis Knitter Sampler (FAK-S). This machinery is intended for small knitting runs, not commercial scale production. The tubes were cut to create approximately 20 cm wide strips that could be used for ballistic tests. Figure 3 compares images of Light KK and CFKA. The high population of fiber ends is clearly visible in the staple yarn product.

Felts are an emerging class of fabrics that could be implemented into future protection systems. HED felt is a developmental material made from ultra-high molecular weight polyethylene (UHMWPE). The UK Ministry of Defense, Defence Science and Technology Laboratory provided HED. ArmorFelt is a commercially produced felt. It is composed of felted aramid and UHMWPE filaments. TexTech is a commercial felt-woven hybrid. It contains both felted and woven aramid. The bulk material is held together with needle punched staple aramid yarns. TexTech fabric is notably heavier than the other materials tested.

TABLE I. CANDIDATE MATERIALS EVALUATED FOR EXTREMITY PROTECTION

Sample name	Description	Part number	Source	Areal density (g/m^2)
ACU	"Improved Defender M" Fire Resistant ACU fabric	-	Tencate (Almelo, Netherlands)	220
K706	woven 600d KM2 Kevlar	Style 706	JPS Composites (Anderson, SC)	180
Silk	knitted Jersey silk	-	NY Fashion Center (New York City, NY)	165
Light KK	"light" knitted staple Kevlar	145KV30	Green Mountain Knitting (Milton, VT)	225
Heavy KK	"heavy" knitted staple Kevlar	437KV17	Green Mountain Knitting (Milton, VT)	328
Polyester	knitted polyester	-	Jo-Ann Fabrics (Bel Air, MD)	96
CFKA	continuous fiber knitted KM2 600d Kevlar	-	NSRDEC (Natick, MA)	200
HED	hydroentangled Dyneema felt	-	UK Ministry of Defense	200
ArmorFelt	Armorfelt, hybrid aramid/PE felt	-	Kennon Covers Inc. (Sheridan, WY)	250
TexTech	hybrid felt / woven fabric	9010	TexTech Industries (Portland, ME)	844

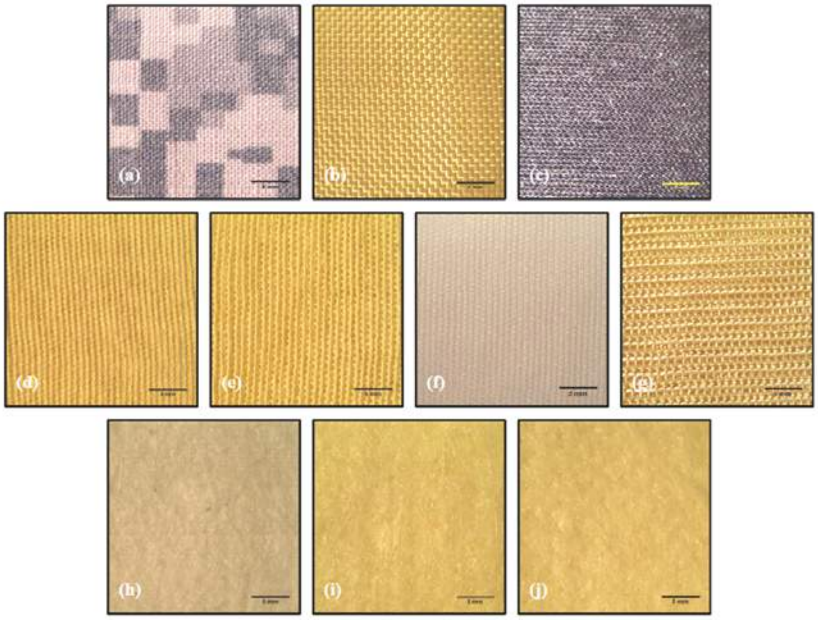


Figure 1. Photographs of evaluated fabrics at 10× magnification. Scale bars at 5mm. (a) ACU, (b) K706, (c) Silk, (d) Light KK, (e) Heavy KK, (f) Polyester, (g) CFKA, (h) HED, (i) ArmorFelt, and (j) TexTech.

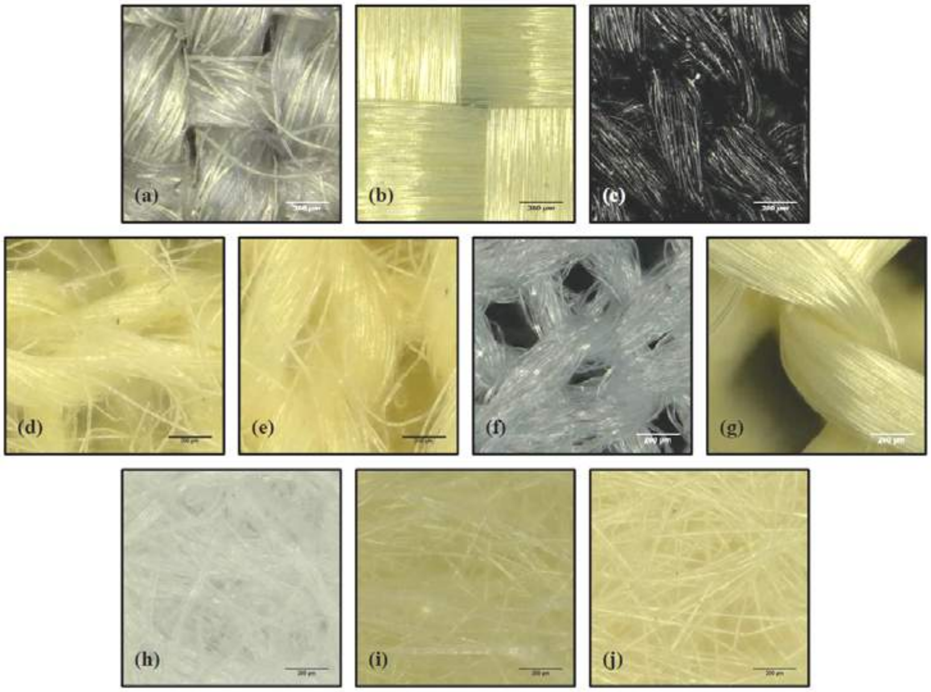
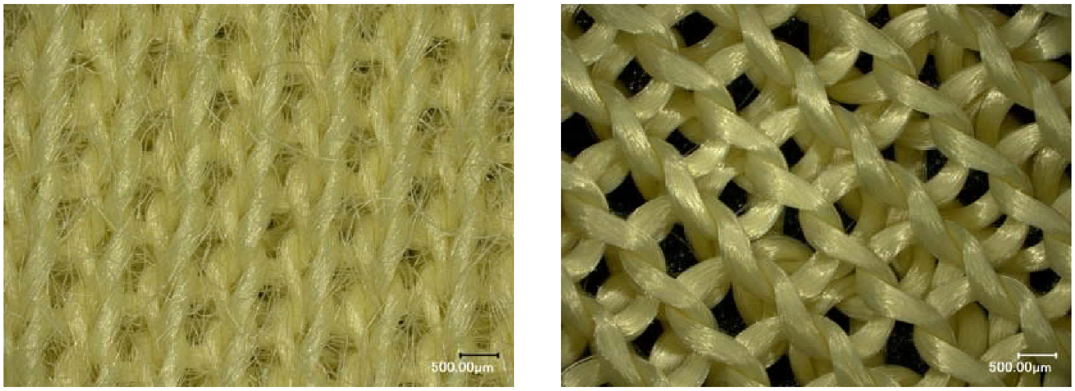


Figure 2. Micrographs of evaluated fabrics at 250× magnification. Scale bars at 200µm. (a) ACU, (b) K706, (c) Silk. (d) Light KK, (e) Heavy KK, (f) Polyester, (g) CFKA, (h) HED, (i) ArmorFelt, and (j) TexTech



(a) (b)

Figure 3.Micrographs of (a) Light KK and (b) CFKA

Ballistic Testing

Extremity protection garments will likely be worn close to the skin, similar to the PUG. To replicate these boundary conditions, targets were impacted while wrapped around a synthetic gelatin cylinder. The cylinders were cast at 15.2 cm in diameter and 30.5 cm in height, in order to roughly replicate the geometry of the human thigh. The gelatin is based on a physically associated polymer mixed with a low volatility non-aqueous solvent. It was developed at the U.S. Army Research Laboratory (ARL) to satisfy the calibration standards for 20% ordnance gelatin. This synthetic gelatin does not require refrigeration and has a significantly longer shelf life than natural gelatins.

Nominal target dimensions were 46.5 cm × 30.5 cm (L × W). Velcro strips were sewn to the edges of each target to secure it to the gelatin cylinder. The target dimensions were chosen to ensure that the fabric was slightly taut during testing.

A helium driven, smooth bore gas gun with a length of 114 cm and a 5.982 mm bore was used to fire the projectiles. Projectile velocities were measured using two light chronographs manufactured by Shooting Chrony Inc. (Amherst, New York). The impact speed reported is the average of the two chronograph velocities. The projectile used for ballistic testing was a spherical, glass BB with a nominal diameter and weight of 6 mm and 0.28g. Blast arena tests show that the silica BB accurately replicates the size and weight of a gravel particle. Projectiles were purchased from BB Bastard (bbbastard.com).

Each ballistic test consists of nine shots. Impacts were positioned in a pre-determined, staggered pattern on the target. V_{50} values are calculated using maximum likelihood estimation [10, 11]. An impact that caused the BB to embed in the gel is defined as a penetration.

RESULTS

Table II and Fig. 4 present the results from ballistic testing. In Fig. 4, dashed lines provide a guide-to-the-eye, interpolating the overall performance of the fabrics. Micrographs of failure zones are presented in Fig. 5, all are taken from the lowest velocity, penetrating impact for each target.

TABLE II: Results from V_{50} testing

Material			**Number of plies** 1	2	3	4	6	8
ACU	Areal density	(gsm)	-	440	-	-	-	-
	V_{50}	(m/s)	-	205	-	-	-	-
K706	Areal density	(gsm)	-	360	-	-	1080	-
	V_{50}	(m/s)	-	290	-	-	460	-
Silk	Areal density	(gsm)	-	330	-	660	-	-
	V_{50}	(m/s)	-	190	-	233	-	-
Light KK	Areal density	(gsm)	-	450	-	-	-	-
	V_{50}	(m/s)	-	213	-	-	-	-
Heavy KK	Areal density	(gsm)	328	656	-	-	-	-
	V_{50}	(m/s)	191	240	-	-	-	-
Polyester	Areal density	(gsm)	-	-	-	384	-	768
	V_{50}	(m/s)	-	-	-	197	-	230
CFKA	Areal density	(gsm)	-	400	-	-	-	-
	V_{50}	(m/s)	-	270	-	-	-	-
HED	Areal density	(gsm)	200	400	600	-	-	-
	V_{50}	(m/s)	298	367	403	-	-	-
ArmorFelt	Areal density	(gsm)	250	500	-	-	-	-
	V_{50}	(m/s)	327	410	-	-	-	-
TexTech	Areal density	(gsm)	844	-	-	-	-	-
	V_{50}	(m/s)	414	-	-	-	-	-

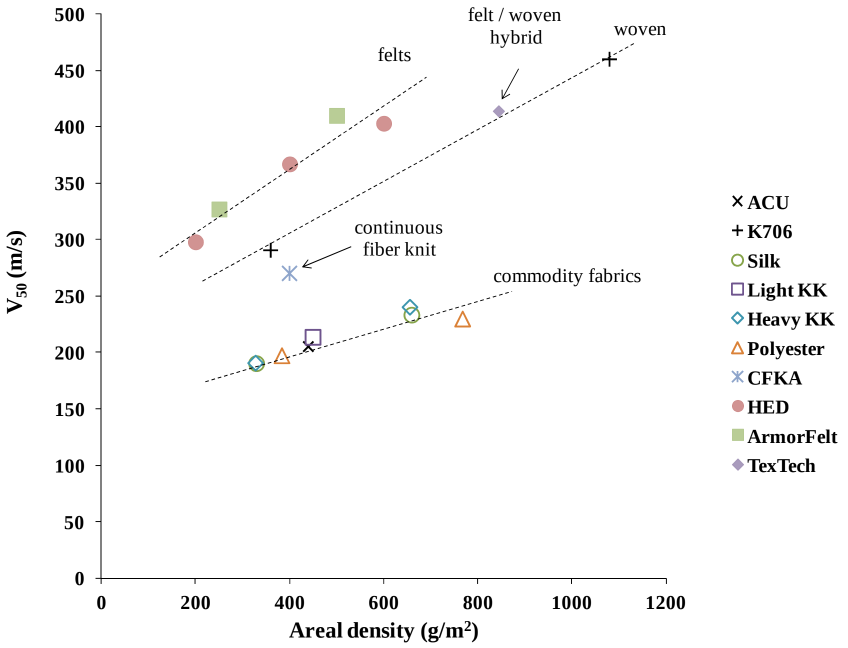


Figure 4. V_{50} as a function of areal density

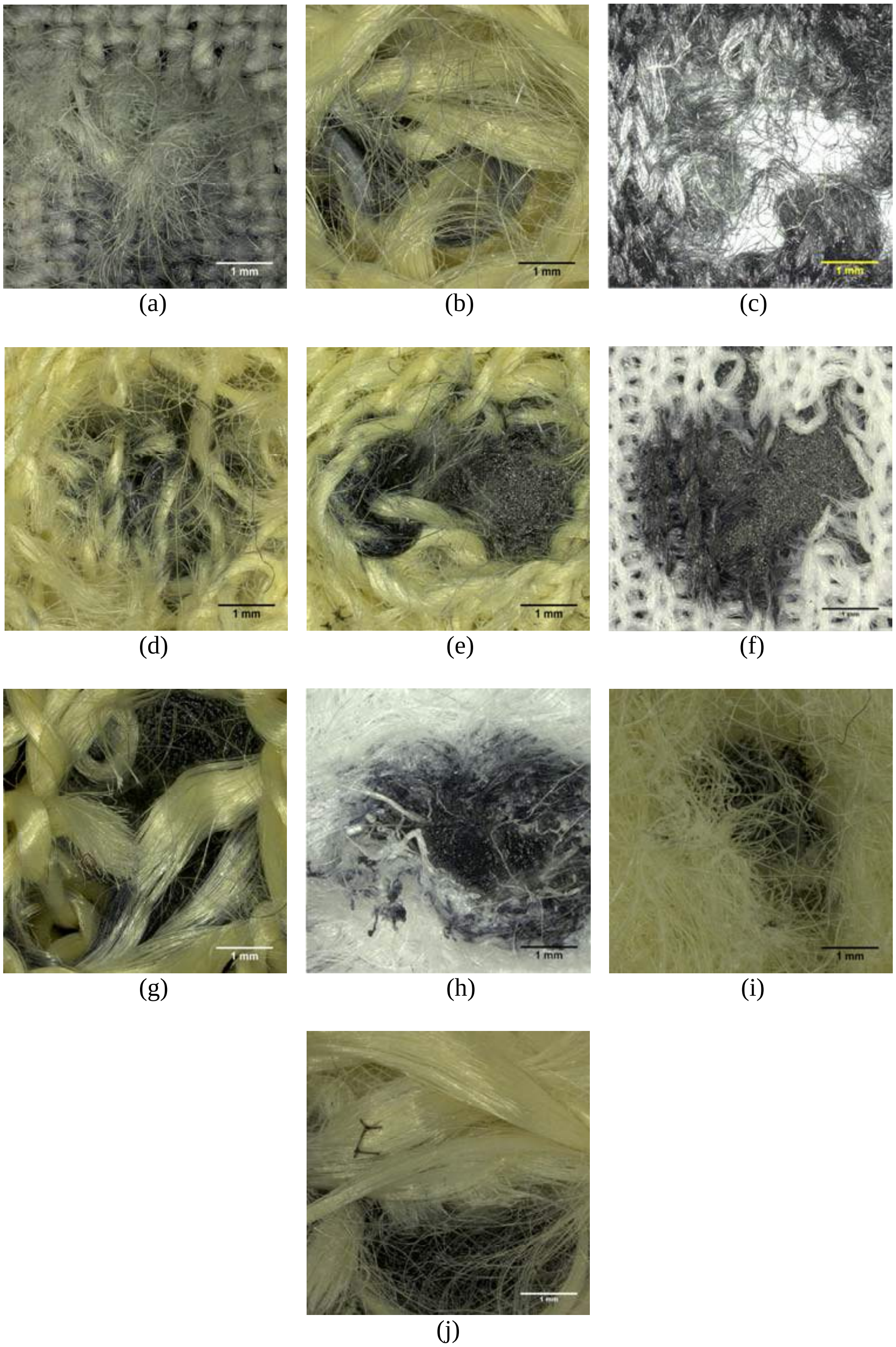


Figure 5.Micrographs of failure regions. (a) ACU, (b) K706, (c) silk, (d) light KK, (e) heavy KK, (f) polyester, (g) CFKA, (h) HED, (i) ArmorFelt, (j) TexTech. (The blackness in the impact region is residual ink from marking the shot location prior to testing.)

The lowest per-weight ballistic performers are the targets composed of silk, knitted staple aramid, knitted polyester, and ACU fabric. We will refer to these fabrics collectively as "commodity fabrics", as they were not originally intended to be used for ballistic protective applications. This group contains a variety of fibers, yet all materials have comparable ballistic responses. ACU, a woven product, does not perform any better than the knits. Similarly, knits with longer filaments (silk and polyester) do not differ ballistically from the staple yarn materials. The data shows that there is no advantage to using staple aramid over other commercial yarns. In all targets, failure appears to be a local event involving only a few yarns. The most important factor determining ballistic behavior appears to be mass path, not fiber type.

Woven K706 performs significantly better than the commercial materials. The increase in ballistic performance is approximately 50%. This result is predictable given that K706 is currently utilized for protection applications. The dominant failure mechanism seems to be yarn pull out and windowing.

The CFKA prototype outperforms the commodity fabrics by roughly 40% and its V_{50} is only 7% below that of K706. Since the CFKA and Light KK are both single jersey knits with similar areal densities, this data suggests that using staple yarn degrades ballistic response. Post-mortem images show that CFKA materials exhibit distinct local yarn failure, while the staple yarn knits show a more distributed failure that could be suggestive of fiber un-tangling instead of true fiber failure.

Felts have the highest mass-normalized V_{50} values of the materials tested, performing almost two times better than the commodity materials. HED and ArmorFelt have similar responses throughout the range of areal densities studied. Because of the entangled nature of felts, it is difficult to identify specific failure mechanisms. The TexTech felt-woven hybrid does not perform as well as the HED and ArmorFelt. Instead, its behavior more closely follows the overall performance of K706.

DISCUSSION

The two most important performance considerations for groin and extremity armor are the level of protection and comfort. Of the materials discussed here, felts and wovens best satisfy the first requirement. HED, ArmorFelt, TexTech, and K706 all exceed the ballistic performance of the commodity materials such as silk. Providing these levels of protection to the groin and extremities is desirable. However, these four materials may be challenging to integrate into extremity and groin protection due to comfort concerns. Wovens have very little stretch along their principal fiber directions, although some stretch is possible along the bias (45°) orientation. Felts have little stretch in any direction. Extremity garments need to accommodate bending and stretch that happens during movement at joints. Using a non-stretching material for a close-to-skin protective underlayer is therefore unlikely to be feasible in the vicinity of joints. Alternatively, these non-stretching layers could be incorporated into a protective outergarment that sits loosely on the body, with sufficient slack so that joint bending could be accommodated via wrinkling and folding. However, the bulk and thickness of these protective fabrics may inhibit bending and present a considerable comfort burden, including limited range of motion, increased kinesiological work, and the generation of stress concentration points. It should also be noted that tight-fitting protective undergarments require less material area than loose-fitting overgarments, so the overgarment approach includes a considerable weight penalty.

The commodity fabrics tested all performed similarly. This result is somewhat surprising given the variety of fibers tested. In particular, one might expect the Light and Heavy KK to exceed the performance of the other fabrics given the superior fiber strength of Kevlar. Instead, the results indicate that using staple yarns results in a knit that cannot fully utilize the superior mechanical properties inherent to aramids. The significantly higher ballistic performance of CFKA relative to the commercial knits supports this conclusion.

Staple and continuous filament yarns fail differently, which explains the disparity in penetration resistance. A yarn made from continuous filaments can only break when those filaments are loaded to tensile or shear failure. Staple yarn breakage can occur by untangling the filaments rather than loading them to failure. Consequently, discontinuous filament knits are disadvantaged when it comes to resisting penetration.

CFKA almost matches the per-weight performance of the K706, falling approximately 7% short. This similarity in performance is somewhat surprising, given that woven textiles historically have been highly preferred for soft armors [12-14]. We hypothesize that, because of the relatively low energies associated with the present test conditions, the performance penalties normally associated with the high tortuosity of knitted constructions are minimized. The use of a backed test may also influence test results, as knits are likely to stretch considerably before loading. More work is needed to study these factors in detail. However, from a comfort perspective, knits are much more stretchable than wovens or felts and could be used in tight-fitting protective undergarments. Therefore, the CFKA material appears to provide a unique balance of comfort and protection that is superior to conventional woven textiles or commodity knits.

CONCLUSIONS

The results show that, for ballistic conditions simulating explosively launched debris, felts and woven textiles composed of high performance ballistic fibers provide superior protection over commodity wovens and knits. However, a knit constructed of continuous filament high performance ballistic fibers provides much better ballistic performance than the commodity materials. This architecture has high stretch so it is likely to enable construction of highly comfortable near-to-skin protective undergarments.

To fully exploit the advantages of CFKA materials, it is important to optimize construction. The results presented here only cover the performance of a single jersey aramid. It is possible that other stitch patterns will lead to more efficient loading conditions. For example, we hypothesize that knit constructions that lead to more uniform and simultaneous loading of yarns will lead to enhanced performance. Architectures that systematically reduce stretch might allow for further tuning of performance versus comfort. Varying yarn denier and fiber type may also provide avenues for enhanced protection.

It is also important to understand how different knit parameters and constructions influence comfort. Unfortunately, the standard tests for assessing fabric mechanical (flex, stretch, folding) and transport (air and moisture permeability) properties are not sufficient to comprehensively and quantitatively predict garment comfort. Additional research, likely combined with human factors testing, is required to more completely optimize a balance between performance and protection.

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