IED-threat protective knits based on UHMWPE-Dyneema® fibres: A systematic review

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Abstract. Secondary fragment wounds of high-energy blasts are one of the major causes of injury in modern warfare. An increase in wounding based on explosively accelerated fragments is seen among police officers, Law Enforcement, as well as First Responders. If applied, current ballistic Personal Protective Equipment (PPE) protects the vital organs of the torso's core and the head against gun-shot impacts, while the destructive blast forces of Improvised Explosive Devices (IEDs) simultaneously affect the unprotected body regions with potentially life threatening end results. This study provides a systematic overview on the research and development for knitted textile solutions made of UHMWPE fibres, branded as Dyneema®, to address this identified gap in personal protection. The resulting fragment protective knits are developed to serve the need for armouring against secondary fragmentation wounding. For those, systematic applied knit forming elements the loop, tuck, and float enable the fabric to respond to various fragment types in the most optimum way. The balanced knit structures level the geometric deformation response, identified as crucial for an optimized penetration resistance behaviour. Protective performance is achieved through various configurations while also addressing the added considerations of environmental exposure as well as the micro-climate of the human body in activity and rest. Knitted textiles are therefore developed to protect, while also providing comfort, identified as a being mission critical. Burden reduction is key for the wearer. The typical stretch characteristics of the knits give the protective textiles flexibility and drapability supporting the overall comfort while enabling integration into PPE systems at current unprotected areas. The specific yarn selection, knit patterns, and finishing processes result in knits providing the lowest possible burden on the wearer. Low weight, flexibility, moisture-, heat stress- and hygiene-management, create next-to-skin comfort without compromising mobility of the wearer. Fabric durability and launderability enable easy product maintenance.

1. BACKGROUND

One of the main threats faced in today's conflicts are Improvised Explosive Devices (IEDs). Besides the affected international military and peacekeeping missions, small IEDs are utilized in violent demonstrations causing accelerated fragmentation wounds to the local forces such as police officers and first responders. Though most vital body parts are covered by current ballistic protection systems, still about 70% of the body remains ballistically unprotected providing an extensive surface for serious detonation wounding, Figure 1 [1]–[3]. Resulting secondary injuries are characterized by high-energy fragmentation wounds containing a wide range of retained foreign materials within the body as the studies of Centeno *et al.* [4] show. However, only limited clothing system exist that addresses potential soft tissue wounding caused by IED weaponized soil and environmental debris, despite the fact that these fragments can cause traumatic amputation and/ or excessive injury leading to physical disabilities, long-term health care, and fatalities [4]–[6]. Consequently, protection against IED detonation threats is one key element for active personnel on combat missions to operate safely in an IED Environment.

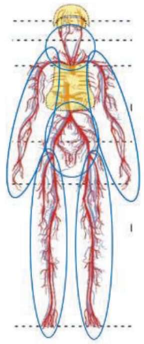

Figure 1: Fielded systems only cover vital organs (yellow) [3], while most of the human body remains unprotected (circled in blue)

In response to the identified protection gap, knitted textile structures are developed with the aim to broaden the protected area of the body for PPE clothing systems, complementary to the current ballistic body armour. The resulting knit constructions are made of high strength, low density, and high modulus Dyneema® yarn types. The knits respond to accelerated micro- to meso-mass fragments (referring to dirt, dust, debris up to 1.1 g fragment masses) holistically in the best possible way. At the same time, they provide high comfort for the wearer. Consistent performance properties under varied conditions have governed the development process as the textile solution will be integrated into PPE systems used in different environments under diverse mission activities. In order to effectively mitigate the ballistic fragmentation while enabling full mobility and comfort, DSM Protective Materials has studied the fragment impact into ductile knitted textile structures by the means of FEM modeling and supporting the results by empirical experiments leading to optimized textile fabric construction parameters, as e.g. introduced in the studies of Hazzard *et al.* [7].

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Most protective materials for soft armour are either UD type of materials, or woven constructions. Here, we demonstrate the performance of knitted structures made with Dyneema® fibre from the ballistics, but also in terms of comfort, and ability to integrate into PPE system solutions providing fragmentation protection to close the protection gap.

2. METHODICAL APPROACH ON FRAGMENT PROTECTIVE KNIT DEVELOPMENT

The stress strain behaviour of knitted textiles is one of the key-parameters in response to the forces of impacting fragments. Once the fragment contacts the target structure, it delivers kinetic energy which dissipates as momentum transfer as well as mechanical work to the textile. In response, the knit follows the characteristic stress strain behaviour of ductile materials, driven by the knit architecture. Generally, the load leads to change in length (Δl) of the fabric system allowing elastic and plastic deformation, absorbing the impact energy through mechanical work and momentum transfer. Single jersey knits are the most basic knit construction and have been applied previously for investigations of ballistic protective performances in comparison to other textile structures on a weight basis [7]–[9]. However, modifications of the knit architecture enable the fabric structure to respond to the impacting fragment in an optimized way. Considering the three main pattern forming elements loop, tuck, and float (missed stitch) **Figure 2**, the dynamics of the structural response can be tailored.

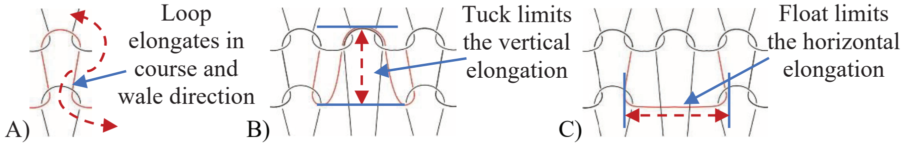

Figure 2: Image of A) Loop; B) Tuck; C) Float (‘missed stitch’)

In knits, each loop shapes along a 360-degree path (Figure 2 A) that enables high stretch of the structure in comparison to woven constructions where the warp and weft yarns interlaced at right angles limiting the natural extension. The loop course allow vertical and horizontal elongation (Figure 2A), while tucks set the boundary to the stretch in the wale (vertically) (Figure 2B), and floats in the course direction (horizontally) (Figure 2C). The fabric stretch is further steered with the loop height on the needle-bed and fabric pull-down within the manufacturing process that helps to determine the fabric density [10], [11]. By arranging the structural elements within the knit pattern, stiffness and elongation become controlled elements in the plane while the structural density and flexibility are balanced. The applied yarn type, thickness, and its surface structure further influence the characteristics. The present development process took advantage of these features to steer the physical properties in response to the impact forces of accelerated fragments.

Empirical ballistic studies:
Knit constructions have been developed varying in yarn type and knit pattern arrangement. To investigate the influence of the individual construction parameters, the V_{50} of the textiles have been determined according to STANAG 2920, with a 40 x 40 cm specimen size of which the edges were ducktaped for handling before framing, (Figure 3). 8- and 16-plot shooting patterns are shot with the RCC 0.13 g (2 grain) and 1.1g (17 grain) FSP creating empirical data sets. High-speed camera images show the structural behaviour in the process of collision allowing to draw further conclusions on the impact behaviour and knit structural response.

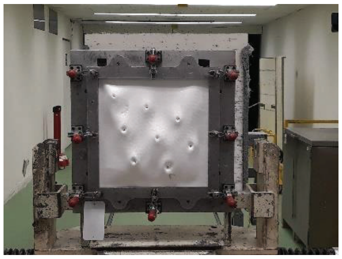

Figure 3: Image of 40 x 40 cm framed knit specimen in V_{50} testing with the 1.1 g FSP against air.

Test process:
Once the accelerated fragment is in contact with the target, the strain waves spread radially outward from the impact location along its surface. The elongation and tensile toughness of the knit fabric control the dynamics in response to the impacting fragment. During impact, compression initially occurs within the protective material at the impact point as momentum is transferred to the knit. The impacting forces spread longitudinal and perpendicular to the structure’s axes. Stress-strain waves move through the

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system producing shear and tensile forces. The energetic forces spread at the speed of sound engaging a larger area of the knit.

Figure 4 shows the fragment impact process into a knit structure with its physical reaction and dynamics to the penetration force of a 1.1g FSP tested against air, captured with the highspeed-camera.

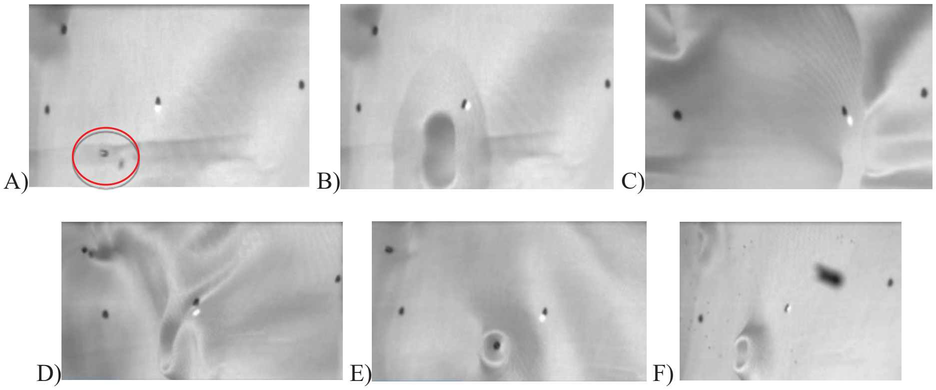

Figure 4: High speed camera sequence of 1.1g FSP impacting a knit structure placed against air. A) the fragment just before impact on the knit, B) once the fragment impacts, in-plane strain wave spreads outwards (light grey ellipse) followed by the (dark) transverse out-of-plane deflection, C) the knit structure elongates further D) at its maximum expansion the structural wave flows back to the centre of impact E, F) finally encapsulating the fragment within the structure.

Within the process of knit structure development general key findings have result:

A) The yarn properties and characteristics govern the fragment stopping process.
B) A loose construction leads to yarn pull out rather than stopping the fragment as well as constructions that offer too limited stretch. Figure 5 shows the yarn pull out in comparison to Figure 6 presenting a balanced stopping behaviour of the knit.
C) The failure criteria of the direction with least stretch in the plain define the resistance of the total construction.
D) The fabric areal density (AD) does not govern the stopping mechanisms alone, Figure 7 and Figure 8**Error! Reference source not found.** show the V_{50} levels of knit constructions on a weight bases, comparing the constructions A and B under impact of 2 grain (0.13 g) RCC and 17 grain (1.1 g) FSP, tested according to STANG 2920 (against air, 16-plot shooting pattern). The results show that the AD is not the leading factor for fragment resistance.

Figure 5: Yarn pull out after fragment impact.

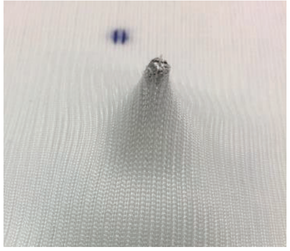

Figure 6: Balanced elongated knit has stopped the fragment.

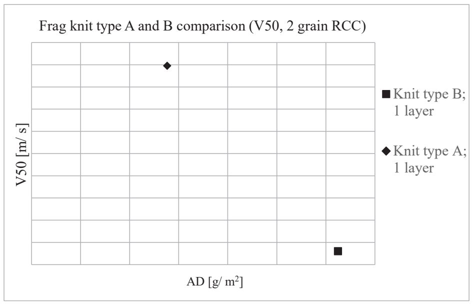

Figure 7: V_{50} (2 grain RCC) comparison of knit type A with B; (N = 5; 3-Sigma)

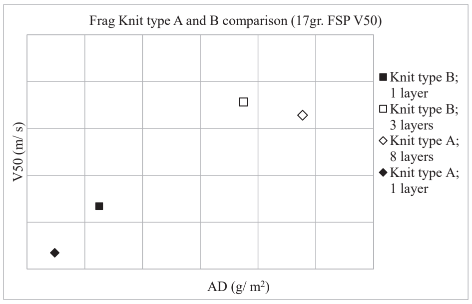

Figure 8: V_{50} (17 grain FSP) comparison of knit type A with B; single layer; multiple layer on a weight basis; (N = 5; 3-Sigma)

E) Higher elongation increases the contact duration with the impacting fragment which in return increases the energy transfer and therewith increases the V_{50} level.
F) The typical stretch characteristics of the knits give the protective textiles flexibility, and drapability supporting the overall garment comfort.

However, the elongation (Δl) of the structure is a critical aspect being considered in the developments, as pencilling of the fabric must be limited in response to tensile toughness of the body's soft tissue. Without limitation, what can occur is that although the fragment will not penetrate it pushes the fabric beyond its original plane of protection and into the protected tissue passing the tensile strength of the underlaying tissue creating penetrations/ injury as demonstrated by Breeze *et al.* [12], [13] within the development studies on related neck-protections. Pencilling and back face signature in clay blocks are shown in Figure 9 for the knit structures.

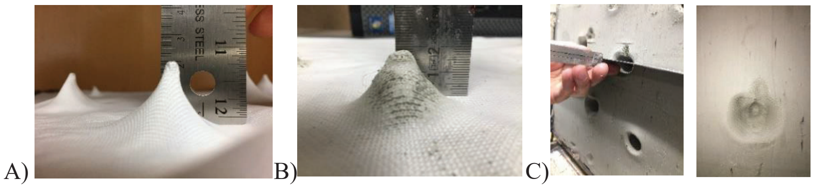

Figure 9 shows a maximum of 20 mm pencilling back face signature after impact of 1.1 g FSP against A) air, and B) clay block. C) Analysis of the imprinted geometry in the clay witness.

Overall, the developments show that balanced elongation enables to increase the amount of kinetic energy being absorbed and dissipate into the knit structure. The structure's density (ρ), in alignment with its elastic modulus (E) dictate the energetic wave transmission within the knit. It is influenced by the yarn paths, and intersection points within the knit construction, while the yarn properties further govern the resistance. The tests show that immediately after impact, significant strain concentration develops under the centre of the impacting fragment, while the constructions allow longitudinal stress waves to spread into the plain. Transverse waves lead to deformation in fragment impact direction. The transverse wave speed (u) differs with changes dependent upon fragment size, mass, and geometry. It is identified that the knit structures respond differently under the change in dynamic loads. Consequently, the physical knit properties are adapted to the fragment types within the development process by differentiating the 0.13 g RCC threat and the 1.1 g FSP threat to provide optimized protection against those.

When the yarn is fully engaged by the projectile, the knit properties go hand in hand with the applied yarn characteristics. During elongation and initial shock, the applied yarn types in the construction take the lead to resist the impactor. The intrinsic yarn properties become the governing factor. The fibre must serve the resistance into the same manner as the textile construction does to achieve the maximum in protection. Knits made of high strength, low density and high modulus yarn absorb the kinetic energy of the intruding fragment in the best possible way, referring to Heisserer and Werff [14] highlighting the potential of UHMWPE fibres in terms of ballistic performance due to their specific properties. Within the knit structure, the yarn characteristics must support the fabric motion to allow optimized dynamics in response to the impacting threat. Low yarn on yarn friction of filament yarns enable a smooth structural movement and a quick structural response to the dynamics of the fragment motion.

Results:

Applying these findings resulted in two knit categories based on UHMWPE Dyneema® yarns and blends with such. Both categories offer a range of knit fabrics to also address individual secondary comfort properties. They are suitable to be applied as single as well as multiple layer systems or being hybridised subjected to the level of protection required and way of integration into the PPE systems.

1. **Knit category 1**: The base knits range between 230 – 300 g/ m² addressing the 0.13 g RCC fragment at a V_{50} of about > 250 - 320 m/ s suitable to be designed into light weight garment solutions as single layers, integrated as multiple layers, and used as lining systems.

2. **Knit category 2:** The advanced knits range between 450 – 650 g/ m² addressing the 1.1 g FSP at a V_{50} of about > 250 - 310 m/ s developed to provide advanced protection suitable to create flexible liners or inserts for PPE systems as single layers, multiple layer constructions, as well as hybrid solutions.

Differences in knit architecture, and underlying yarn mechanical properties result in different stopping values in response to the individual threat. Multiple layer constructions in Figure 10 as well as layer combinations of different knit-types Figure 11 can result in an optimized V_{50} subjected to their elongation behaviour.

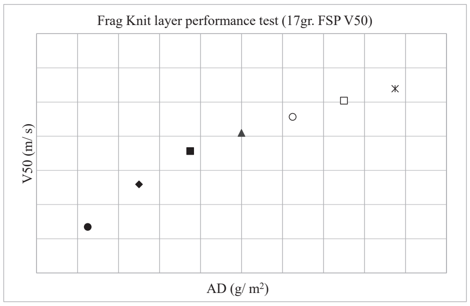

Figure 10: V_{50} (17 grain FSP) plot of frag knits subjected to step wise increase in number of layers (N = +1)

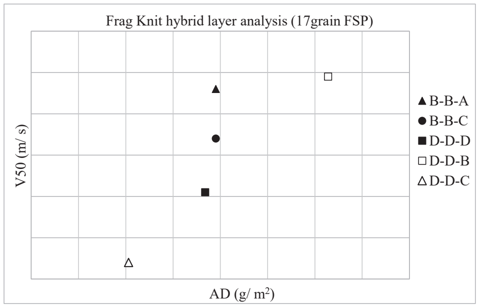

Figure 11: V_{50} (17 grain FSP) comparison of multiple layer combinations of different knit constructions on a weight basis.

3. AN OVERVIEW OF THE PROTECTIVE KNITS COMFORT PROPERTIES

For current PPE users such as military, police officers, and LE, action and rest alternate over prolonged duration, which also applies for first responders. They must carry heavy loads while being agile and mobile within urban terrain as well as confined spaces; therefore, additional burden must be avoided. Uncomfortable clothing can significantly decrease work performance and could become a critical issue for health and safety under these conditions. In worst cases, protective products are rejected to be worn. Thus, comfort has been identified as being mission critical in addition to the protective performance features required. However, comfort is determined by individual preferences in relation to personal wellbeing and individual needs, thereof it cannot be standardized in general. In that regard, three core influencers on comfort are identified that are addressed in the development process of the protective knit products:

1. The environmental/climate conditions
2. The person's active, rest, and stress conditions
3. The near environment (the clothing next to skin)

The human body's response and adaption to these influencers over short-term and prolonged wearing durations are considered for the development process. As a result, the overall knit performance requirements are defined in Figure 12 of which the comfort parameters are down selected to the attributes A – F, listed in Table 1.

Comfort attributes for protective knit textiles	
A	Mobility
B	Durability
C	Heat- stress- management
D	Thermal management
E	Moisture- management
F	Sensory response to the textile constructions and hygiene management

Table 1: Comfort attributes for fragment protective knits

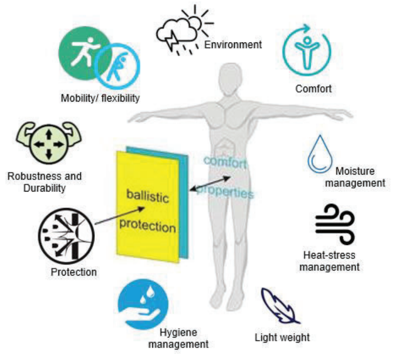

Figure 12: Protective knit performance properties

Empirical fabric comfort studies:
To investigate the comfort of the protective knits, different studies and testing processes have been carried out. Besides wear trials of cloth made of the fabric types, various testing methods have been down selected to empirically study and analyse the fabric behaviour simulating wear and use of the products.

3.1 Comfort attributes for fragment protective knits

A) Mobility:
Active personnel might be on a mounted or dismounted mission. They must march, run, hide, crawl, lay in prone position, cross rivers, manoeuvre in confined spaces in urban terrain or within their armoured vehicles. It is of key importance for the present user-group being agile and mobile in their clothing system. In case the clothing retains movement, activities cannot be carried out to the level required, performance is limited. Moderate movement of the body requires stretch of the cloth with up to 45 % as Shishoo *et al.* [15] introduce, referring to active sports. These stresses might intensify once the product is worn with increasing dynamics of the wearer.

The textile flexibility and drapability response to the demand for mobility and is addressed with the typical stretch characteristics of the knits in the present case. For the knit pattern, the loop itself is key as it elongates in course and wale direction. The high system dynamics are supported by the low yarn on yarn friction of the UHMWPE fibre types that directly response under motion and follow the dynamic change. By this behaviour, the knitted fabrics drape and form alongside the body's individual ergonomic shape and adapts to the movement of the wearer giving full freedom of mobility at high durability. To study the mechanical response of knitted structures to mobility, the tensile testing method DIN ISO 139334-1, the soft armour flexibility test PED-IOP-008, and the Gelbo test ISO 7854-C (ASTM F392) are downs selected. The tests are described in the following section B) durability as mobility and durability of the knit structures go hand in hand.

Overall, in conclusion the high flexible UHMWPE Dyneema® fibres based knits adapt to the user's dynamics and therewith allow full mobility.

B) Durability:
Different testing methods have been down selected to empirically study and analyse the fabric behaviour by simulating the response to dynamic stresses as well as potential wear off due to motion and use.

Besides the investigations on general stress strain behaviour within the tensile tester in accordance with DIN ISO 139334-1, the flexibility on knit concepts are tested with the ball burst tester according to the PED-IOP-008 (Soft Armor Flexibility Test at U.S. ATC [16]) referring to TR-13-003L, ASTM D3787-07 (2001), ASTM D1777-96 (2011)e l, and ASTM E4 13 (Figure 13[16]) [16], [17]. By bending the fabrics under pressure load the force that is needed to deform the fabric gets determined within repetitive cycles, with the result that the less force that is applied to deform the fabric the higher the flexibility is ranked. The dynamic flex testing proves the extreme flexibility of the developed knit structures even for multiple layer constructions. As an example, a layered knit system bends under 1.045 N (3.76 lbf) compared to woven systems that bends only at about 3.89 N (14 lbf) on a weight to V_{50} basis.

Figure 13: Dynamic flex testing, PED-IOP-008 [16].

The Gelbo-test ISO 7854-C (ASTM F392) is generally applied to test the wrinkle resistance of foil materials and to define the fabric's permeability after dynamic stresses (Figure 14). In the present case the Gelbo-test ISO 7854-C (ASTM F392) has been chosen to investigate the knit behaviour under twisting dynamics. In specific, the test shell simulates the fabric dynamics within the bending regions of the body when groin, knees, arm pits, elbows, and joints are in motion. During the test, the fabrics get repeatably twisted and crushed (Figure 14). As of a result of the test the Dyneema® based knits show no fabric, nor yarn destruction after > 2700 cycles in the Gelbo tester.

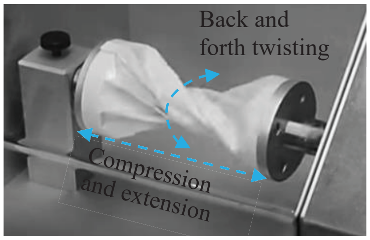

Figure 14: Gelbo test ISO 7854-C (ASTM F392) test twist durability of the knit sample.

The durability of the knits regarding fabric and or fiber destruction as well as pilling behaviour is key when they get exposed and must function under challenging wear conditions. The resistance to wear-off is further investigated with the inflated Diaphragm Test (ASTM D 3886) as well as with the Martindale test according to ISO 12947-2 (ASTM D 4966) Figure 15. Here, the use of different abradant materials have proven the high durability under friction showing no yarn nor loop destructions, and no pilling after > 150.000 cycles Figure 15 B), up to only slight fibral wear on the fabric surface was detected for some of the specimens Figure 15 C), that showed no change or reduction in strength and resistance within the tensile tester afterwards.

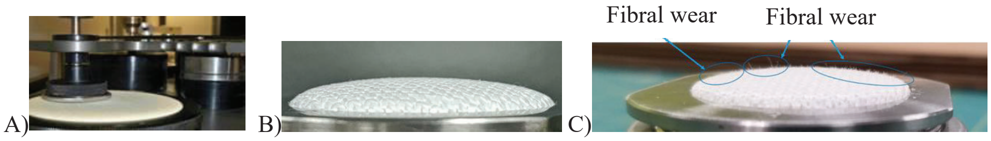

Figure 15: Martindale test ISO 12947-2 (ASTM D 4966); A) testing the abrasion resistance of the knit fabric sample; B), C) Knit specimen after abrasion > 150.000 test cycles, B) shows no wear, C) shows slight fibral wear.

The PPE user is commonly active in various environments in which abrasive, sharp objects or flora and fauna might work to compromise the clothing system. Besides the high abrasion resistance, the durable knit structures are constructed to resist mechanical impact forces such as cut, slash and tear based on the high tenacity of the UHMWPE Dyneema® fibres.

Besides the use, the manufacturing process of knitted textile goods is carefully studied regarding durability, as the loop forming processes as well as the high angled loop courses in the final structures create intense stresses on the applied yarn systems. High tensile strength yarn properties especially perpendicular to the yarn axis are key to resist the stress loads, avoid yarn and filament breakage and withstand the process stresses and abrasion.

Overall, in conclusion UHMWPE Dyneema® fibres based knits meet high durability standards as tested.

C) Heat-stress- management:

The user-groups wearing PPE systems encounter the full bandwidth of environmental and climatic conditions The human body constantly generates heat. Heat balance must be maintained to secure the body core temperature level and keep the work energy at moderate range. Heat exchange between the body and the near environment takes place at the skin surface by convection, radiation, conduction, and evaporation (Figure 16) [18], [19]. Once the body becomes off balance the temperature rises or falls. The body counteracts that increase in the energy demand; a drop in performance and endurance with premature fatigue might result [20]. Consequently, it is key that the clothing system adapts to the climatic conditions of the user supporting to maintain the core temperature while balancing heat production and heat loss.

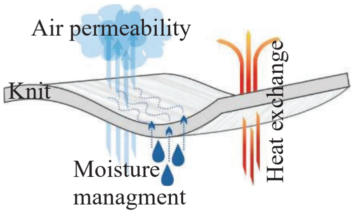

Figure 16: Climate management properties of the protective knit.

It was identified that moisture and thermal management are key parameters the knitted fabrics must manage in order not to create additional burden to the user. The impact on thermal comfort are the result of the textile parameters: fabric weight, thickness, porosity, moisture regain, air permeability and density -all being governed with the knit pattern design. Overall, subjected to the fabric application within the PPE system, the developed knits respond differently to the physical requirements. While the knit category 1 type of base knits is worn next to skin, climate exchange is key. As the knit category 2 type of knits are used in packages and inserts mainly of multiple layer solutions, climate exchange is defined as being secondary and might differ to the category 1 knits.

D) Thermal management:
Next-to-skin the thermal insulation and the barrier to moisture transport by the fabric layer affect comfort. The lab analysis chosen to assess the thermal physiological comfort index for the base knits of category 1 is the "Sweating guarded hot plate method" (Skin model) measuring the RCT (Thermal Resistance Coefficient) and the RET (Evaporative Resistance Coefficient), as well as the Imt (Water vapor permeability) in accordance with ISO 31092:1996 (ASTM F1868). The results have influenced the knit pattern design with the outcome that the lightweight base constructions provide a high level in air-permeability in parallel (Figure 17). Tested in accordance to DIN EN ISO 9237 (100 Pa) an average level of > 1000 l/ m²s is reached for the single layer fabrics, tested under non-stretched textile conditions. Here lower AD and lower fabric thickness increases the passage of air being transported through the textile construction in comparison to the category 2 knits of increased density reaching an average level of about > 250 l/ m²s. A general increase of the values are seen once the fabrics get stretched.


Figure 17: Air permeability test according to DIN EN ISO 9237.

Besides the physical properties of the knit construction, the thermal physiological comfort is addressed utilizing the applied UHMWPE Dyneema® yarns providing unique thermal properties due to their high thermal conductivity along the fibre. The orthorhombic PE enables the surplus heat to flow away from the body through the textile structure as the frag knits have intrinsically low thermal resistance. They provide a high thermal conductivity along the fibre axis of about 20 W/mk [21]. This translates into cool touch and feel while more heat is exchanged with the environment for body climate regulation Figure 18.

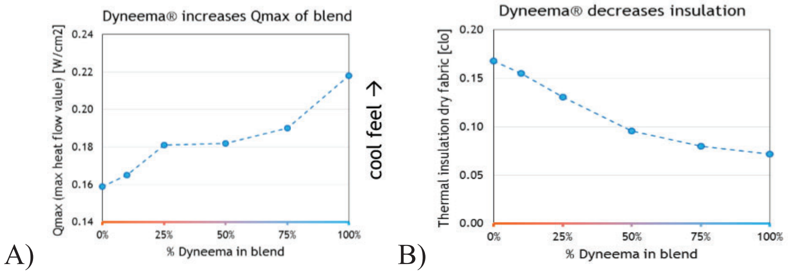

Figure 18: A) Heat Transfer Subjected to the Share of Dyneema® Fiber Influencing the Cool Feel of the Textile, B) Thermal Insulation in Relation to the Dyneema® Fiber Share in the Textile.

Overall, in conclusion the UHMWPE Dyneema® based knits show thermal management properties that are interesting / positive for protective garments.

E) Moisture management:
The protective knit constructions that are made to be worn next to skin provide a capillary effect due to the 3-dimensional pattern construction. Once sweat is produced it is absorbed into the porous open structure of the left fabric side Figure 19 and transport through the pores to the more close surface structure Figure 20 where the surplus in body moisture spreads and evaporates. A delay in moisture transport supports the body climate conditions, while configurations of the structure enable to steer the wetting process. Figure 21 shows the process of droplet absorption and wetting-effect of two different knit specimens made with Dyneema® fibre varying in its architecture regarding pore-size as well as permanent finishing showing a more hydrophilic behaviour in Figure 21: 1 A) – 1D) and rather hydrophobic properties for the knit in Figure 21: 2 A) – 2 D).

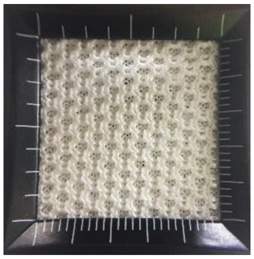
Figure 19: Example of left fabric side with porous structure

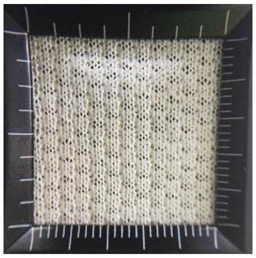
Figure 20: Example of right fabric side with closed surface structure

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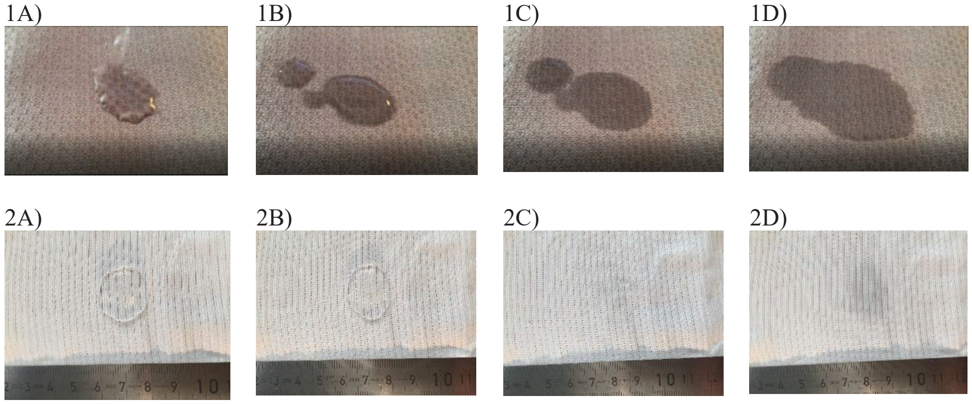

Figure 21: Wetting series with water-droplet of two different porous fragment protective knit specimens made with Dyneema® fibre, 1 A) droplet line breaks during application, sorption into the knit starts (0-1 s); 2 A) clear round droplet with sharp border lines (0-1 s), 1 B) droplet border line breaks up further, sorbs into the knit (2 s); 2 B) clear droplet border line, capillary sorption starts within the centre of the droplet into the structure pores (3 – 4 s), 1 C) wetting, the droplet spreads into the structure (2 – 3 s); 2 C) the droplet is transported into the pores (4 – 5 s); 1, 2 D) complete wetting (1 D) 5 – 8 s; 2 D) 3 – 4 s)

In conclusion, the UHMWPE Dyneema® based knits perform hydrophobic to hydrophillic properties based on the type of knit construction that is adapted to the requirements in the application areas.

F) Sensory response and hygiene management:

The moment the textile fabric gets in direct contact with the skin, comfort is affected by touch, friction, drape, and tactile characteristics, so called sensorial comfort perception [19]. The sensory feel of textile materials is related to mechanical stimulation of the sensory skin receptors by thermal affects, pressure, and friction forces [19]. Here, it is identified that the comfort next to skin is based on the sensory response of the individual and is therefore subjective to the wearer. Besides the described test methods, no additional test was identified to test, rate, level and empirically study those properties. It is concluded that the knit architecture in combination with the yarn selection applied for light weight, flexible structures subjectively result in a soft and smooth haptic with a cool touch as being comfortable to be worn next to skin. In addition, the Dyneema® fibre is ECO-TEX certified class II, and as such is certified as being compatible to be worn next to skin.

The chemical inert nature of the UHMWPE-fibre in general does not attract germs keeping the fabric hygienic. Hygiene management is further addressed with simple garment washing under regular household laundering conditions while keeping the full protective- and comfort properties. The moisture transport as well as quick drying characteristics of the knits supports the properties.

Overall, in conclusion the UHMWPE Dyneema® based knits show good sensory response and hygiene management properties that are interesting / positive for protective garment solutions.

4. CONCLUSION

This paper provides a systematic overview of fragment protective UHMWPE Dyneema® based knits. It highlights the key construction elements loop, tuck, and float applied in knitted textiles to reach fragment protective properties while addressing comfort aspects at the same time. It is identified that AD is not the dominating factor in ballistic resistance, but it is a combination of the fabric dynamic response to the impactor as well as the applied fibre properties. Although, the body's soft tissue stress-strain characteristics limit the knit elongation parameters and therewith the stretch that positively influences the energy absorption. The differences in knit architecture, and underlying yarn mechanical properties result in distinct stopping capabilities in response to the deviating threats: the 0.13 g (2grain) RCC fragment and 1.1 g (17 grain) FSP. Overall, this work has resulted in two knit categories based on UHMWPE Dyneema® yarns and its blends of which the category 1 type of knits, the base knits, address the 0.13 g RCC fragment at a V_{50} > 250 - 320 m/ s, and the category 2 type of knits, the advanced knits, address the 1.1 g FSP at a V_{50} of > 250 - 310 m/ s.

At the same time, these textile structures have the knit-typical features providing wear comfort to the individual. As such, the yarn selection, knit pattern, and finishing processes are chosen to provide the lowest possible burden on the wearer. Low weight, flexibility, moisture-, heat stress- and hygiene-management, and the sensory response to the textile constructions create comfort without compromising mobility. Fabric durability and launderability with quick drying capabilities enable easy product maintenance. The performance properties have been proven within in the broad experimental studies of which the present paper highlights the development and analyse on the key features levelling fragment protection and comfort as being relevant to the PPE user. As of a result, the UHMWPE Dyneema® based knit solutions are commercially available and are globally in evaluation and/ or applied in different PPE garment system solutions.

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References

[1] L. Col, D. Tong, and R. Beirne, "Combat Body Armor and Injuries to the Head, Face, and Neck Region: A Systematic Review," *Mil. Med.*, vol. 178, no. 4, pp. 421–426, 2013.
[2] D. Carr and E. A. Lewis, "Ballistic-protective clothing and body armour," in *Protective clothing: managing thermal stress*, F. Wang and C. Gao, Eds. Cambridge, UK; Waltham, USA; Kidlington, UK: Woodhead Publishing, 2014, p. 500.
[3] K. Freier, "Prepared for the next mission abroad? - Blücher's fragment protective clothing (FPC) system closes the gap in current personal protective equipment (PPE)," *C-IED Report; Delta Bus. Media Ltd.*, no. Autumn 2015, pp. 91–96, 2015.
[4] J. A. Centeno *et al.*, "Embedded fragments from U.S. military personnel--chemical analysis and potential health implications.," *Int. J. Environ. Res. Public Health*, vol. 11, no. 2, pp. 1261–78, Jan. 2014.
[5] B. Kneubuehl, R. M. Coupland, M. A. Rothschild, and M. Thali, *Wundballistik: Grundlagen und Anwendungen*, 3rd ed. Heidelberg, Germany: Springer Medizin Verlag, 2008.
[6] P. F. Mahoney, J. M. Ryan, A. J. Brooks, and W. C. Schwab, *Ballistic Trauma. A Practical Guide*, 2nd ed. London, UK: Springer-Verlag, 2005.
[7] M. Hazzerd, U. Heisserer, M. van der Kamp, and K. Freier, "Knitted Fabrics with Dyneema® Fibers for Ballistic Protection: Modelling and Experimental Validation of a Single Jersey Knit," Geleen, The Netherlands, 2020.
[8] A. Dwivedi *et al.*, "Continuous filament knit aramids for extremity ballistic protection," in *28th Annu. Tech. Conf. ASC 2013*, 2013, pp. 767–777.
[9] A. K. Dwivedi, M. W. Dalzell, S. A. Fossey, K. A. Slusarski, L. R. Long, and E. D. Wetzel, "Low velocity ballistic behavior of continuous filament knit aramid," *Int. J. Impact Eng.*, vol. 96, pp. 23–34, Oct. 2016.
[10] K. F. Au, *Advances in knitting technology*. Cambridge, UK: Woodhead Publiching Limited, 2011.
[11] K.-P. Weber and M. O. Weber, *Wirkerei und Strickerei: technologische und bindungstechnische Grundlagen*. Dt. Fachverl, 2004.
[12] J. Breeze, L. C. Allanson-Bailey, N. C. Hunt, R. Delaney, A. E. Hepper, and E. A. Lewis, "Using computerised surface wound mapping to compare the potential medical effectiveness of Enhanced Protection Under Body Armour Combat Shirt collar designs.," *J. R. Army Med. Corps*, vol. 161, no. 1, pp. 22–26, Mar. 2015.
[13] J. Breeze, "Design validation of future ballistick neck protection through development of novel injury models," University of Birmingham, 2015.

https://doi.org/10.52202/078352-0006

[14] U. Heisserer and H. van der Werff, “The relation between Dyneema® fiber properties and ballistic protection performance of its fiber composites,” in *15th International Conference on Deformation, Yield and Fracture of Polymers*, 2012, vol. 3, pp. 242–246.

[15] R. Shishoo, *Textiles in sport*. Woodhead Pub. in association with the Textile Institute, 2005.

[16] “The United States Army Aberdeen Test Center.” [Online]. Available: https://www.atec.army.mil/atc/. [Accessed: 27-Aug-2020].

[17] “NTS Chesapeake (Belcamp, MD) | Ballistic & Materials Testing Lab.” [Online]. Available: https://www.nts.com/location/belcamp-md/. [Accessed: 28-Aug-2020].

[18] V. T. Bartels, “Physiological comfort of sportswear,” in *Textiles in sport*, R. Shishoo, Ed. Boca Raton FL,USA: Woodhead Publishing Ltd. and CRC Press LLC, 2005.

[19] A. Das and R. Alagirusamy, “Improving tactile comfort in fabrics and clothing,” in *Improving comfort in clothing*, G. Song, Ed. Cambridge, UK; Waltham, USA; Kidlington, UK: Woodhead Publishing Limited, 2011.

[20] F. Wang and C. Gao, *Protective Clothing - Managing Thermal Stress*. Cambridge, UK; Kidlington, UK; Waltham, USA: Woodhead Publishing Limited, 2014.

[21] X. Wang, V. Ho, R. A. Segalman, and D. G. Cahill, “Thermal Conductivity of High-Modulus Polymer Fibers,” *Macromolecules*, vol. 46, no. 12, pp. 4937–4943, Jun. 2013.

https://doi.org/10.52202/078352-0006