PRELIMINARY EXPERIMENTAL INVESTIGATION OF CUT-RESISTANT MATERIALS: A BIOMIMETIC PERSPECTIVE

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Abstract:

The objective of the work was the preliminary experimental investigation of cut-resistant materials including a biomimetic perspective. The effects of the cutting were expressed as static and dynamic cut resistance of the following materials: knitted fabrics, woven fabrics, continuously coated knitted fabrics, and dot-coated knitted fabrics. The cutting process gives rise to frictional forces, but the current test methods for cut-resistant gloves are not designed to measure them. Therefore additionally, the cut resistance of the material was evaluated using a modified procedure based on the standard EN 1082-1, taking into consideration grip strength tests to assess if there is a potential correlation between cut resistance and anti-slip properties.

Keywords:

Protective gloves; cut-resistant materials; grip strength properties; biomimetic

1. Introduction

One way of preventing hand injury is the use of gloves that are fit for purpose in protective and ergonomic terms [1–3]. Worker's hands, involved in all occupational tasks, are directly exposed to various hazardous workplace factors. Indeed, upper limb injuries comprise the largest group of accidents at work (as much as 39.2% in 2017) [4].

Except for some specialist protective devices (such as metal mesh gloves), cut-resistant gloves are usually manufactured from p-aramid yarns (Kevlar®, Kevlar® Kleen®, Kevlar® Plus®, and Kevlar® Armor from DuPont; Twaron® and Twaron® Premium Line from Teijin) or core-spun yarns, with cores made of stainless steel or cut-resistant textile yarns and with sheaths made of textile yarns, polyethylene yarns (Dyneema® from DSM; Spectra®, Spectra® Guard®, and Spectra® Guard® CX from Honeywell), glass fibers, a combination of the above, as well as from cotton, polyamide (and nylon), polyester, elastane, and Lycra fibers [5–8]. To impart anti-slip properties and facilitate the gripping of smooth and slippery objects, the palmar or both palmar and dorsal aspects of gloves may be coated with a continuous layer of polymer, usually polyvinyl chloride, polyurethane, silicone, nitrile rubber, or natural rubber. Such treatment not only improves the functional properties of gloves but also enhances their mechanical resistance [9–12].

For gloves to be deemed suitable for protection against mechanical injury, they must meet several protective and functional requirements laid down in Regulation 2016/425 of the European Parliament and the Council [13]. A particularly important protective parameter in this context is cut resistance. The basic standard specifying the requirements and test

methods for cut-resistant gloves is EN 388:2016 + A1:2018 [14], with EN ISO 13997:1999 [15] also being increasingly used. The test methods described in those standards differ in that EN 388:2016 + A1:2018 employs a round cutting blade applying constant (static) cutting force, while EN ISO 13997 uses a straight blade applying variable (dynamic) cutting force.

According to the literature, the higher the force needed to cut through a material, the greater should be its cut resistance. The two major components of cutting force are normal force and abrasive force, which differ between protective materials [16]. According to Lara et al. [17], a greater friction coefficient may either enhance or reduce the cut resistance of a material, depending on its thickness, Young modulus, and macrostructure. It has also been shown that in fabrics knitted from aramid yarns, frictional forces are very low as compared to neoprene materials, which translates into differences in cutting forces between coated and uncoated materials [18].

As mentioned above, the cutting process gives rise to frictional forces, but the current test methods for cut-resistant gloves are not designed to measure them. In the case of protective gloves, this parameter can be determined indirectly by evaluating their anti-slip properties associated with gripping objects during manual work [6, 10]. The friction measurement methods widely described in the literature were designed for evaluating the pilling performance of flat textile materials in the context of the esthetic appearance of clothing; these include the Kawabata method, the sliding fabric method, and estimation of the coefficient of friction between parallel fabric surfaces [19–22].

Measurement of both cutting and frictional forces in cutting is of importance in evaluating alternative bionics-inspired

materials with potential applications for protective gloves. The design of protective devices is becoming an increasingly complex process requiring interdisciplinary knowledge in terms of both product development and assessment, going beyond the prescribed standards. An example of such an approach is seeking inspiration for innovative technological solutions in the natural environment [23–27]. Lightweight structures characterized by high mechanical resistance are indispensable in many engineering applications as biomimetic solutions have been shown to possess superior mechanical properties as compared to conventionally engineered ones [28, 29].

The present paper describes a preliminary study of bionics-inspired textile materials made of cut-resistant yarns, coated and not-coated with polymeric paste. The materials were evaluated both according to the relevant standards and using other methods to reflect the important aspects of the cutting process. The applied methodology accounted for different types of cutting forces (static and dynamic) as well as macroscopic frictional forces, which were assessed using non-standard grip strength measurements. The results obtained from the various methods used were compared and analyzed for correlations to determine whether the methods are suitable for reliable evaluation of cut-resistant materials.

2. Materials

The study involved four commercially available textile materials used in protective gloves, i.e., knitted fabrics, woven fabrics, continuously coated knitted fabrics, and dot-coated knitted fabrics, characterized in Table 1. The studied gloves were made of aramid, glass, and carbon fibers.

3. Methods

The four selected groups of textile materials were tested for static and dynamic cut resistance as well as grip strength. Before testing, samples were acclimatized at $23 \pm 2^\circ\text{C}$ and relative air humidity of $50 \pm 5\%$ for 24 h.

3.1. Static cut resistance testing

Static cut resistance was evaluated according to EN 388:2016 + A1:2018 with a constant load applied to the blade resulting in a force of (5 ± 0.5) N. During the test, a rotating circular blade with a diameter of (45 ± 0.5) mm, a thickness

of (0.3 ± 0.03) mm, and a total cutting angle of $30\text{--}35^\circ$. The horizontal movement was 50 mm long with the blade rotating completely (360°) in the opposite direction. The sinusoidal cutting speed was (8 ± 2) cm/s. Test results were recorded as in Table 2.

$\overline{C}_n$ represents the average number of cycles for the control specimen before and after the cut of the test specimen T_n and is calculated from the following equation:

$$\overline{C}_n = \frac{(C_n + C_{n+1})}{2} \quad (1)$$

A unitless cut resistance index (I) was calculated for every test specimen according to Eq. (2).

$$I = \frac{1}{5} \sum_{n=1}^5 i_n \text{ where } i_n = \frac{(\overline{C}_n + T_n)}{\overline{C}_n} \quad (2)$$

The resulting index values were used to assign cut-resistant performance levels to the specimens according to Table 3.

3.2. Dynamic cut resistance testing

Dynamic cut resistance testing under variable load applied to the blade was conducted by following EN ISO 13997:1999 using an apparatus from P.I. Kontech (Poland). Samples were mounted on a metal cylinder with a radius of (38 ± 0.5) mm and a straight blade was drawn across the curvature of the cylinder with the plane of the blade at an angle of $90 \pm 2^\circ$ to the long axis of the cylinder. The cutting edge of the blade was (74 ± 0.2) mm long, (18.5 ± 0.2) mm wide, and (1.0 ± 0.5) mm thick. The angle of the cutting edge was 22° . During the test, a variable force ranging from 1.0 N to 200.0 N was applied to the blade. The cutting rate was (2.5 ± 0.5) cm/s. Each result

Table 3. Cut resistance requirements [14]

Performance level	Cut resistance (Index, I)
1	1.2
2	2.5
3	5.0
4	10.0
5	20.0

Table 2. Calculation of cut resistance index [14]

Sequence	$\overline{C}_n$ Control specimen	T Test specimen	$\overline{C}_{n+1}$ Control specimen	I Index
1	C_1	T_1	C_2	i_1
2	C_2	T_2	C_3	i_2
3	C_3	T_3	C_4	i_3
4	C_4	T_4	C_5	i_4
5	C_5	T_5	C_6	i_5

Table 1. Textile materials used in the study

Type of material	Sample designation	Photograph	Composition	Area density (g/m ²)	Thickness (mm)
Knitted fabrics	D-1		Aramid fibers	345.9	1.38
	D-2		Aramid fibers	363.8	1.17
	D-3		Aramid fibers	234.1	0.23
Woven fabrics	T-1		Glass fibers	164.6	0.21
	T-2		Aramid fibers	189.3	0.34
	T-3		Aramid and carbon fibers	179.0	0.36
Continuously coated knitted fabrics	DP-1		Silicone-coated aramid fibers	450.0	1.55
	DP-2		Silicone-coated aramid fibers	693.3	0.80
	DP-3		Silicone-coated aramid fibers	540.8	1.27

Table 1 continued. Textile materials used in the study

Type of material	Sample designation	Photograph	Composition	Area density (g/m ²)	Thickness (mm)
Dot-coated knitted fabrics	DN-1		Dot-coated aramid fibers	555.0	3.34
	DN-2		Dot-coated aramid fibers	614.0	2.68
	DN-3		Dot-coated aramid fibers	573.0	2.76

was corrected for blade sharpness. Performance levels were assigned to different cutting force levels according to Table 4.

3.3. Grip strength test

The grip strength properties of materials used in protective gloves were evaluated using a modified procedure based on the standard EN 1082-1 [30]. The modification concerned the type of specimens studied: while the standard test involves entire gloves, the tests performed in this study involved samples of glove materials. The measurement setup consisted of an adjustable height table on which there was a metal cylinder with a diameter of 30 mm coupled to a dynamometer. Samples measuring 150 x 150 mm were cut out from the studied glove materials and placed around the cylinder within the markers. During tests, the human subject lightly squeezed the cylinder with the sample wrapped around it with his or her right hand. Then, the subject pulled the cylinder with maximum force reached over a time of at least 5 s, which could be maintained over 10 s. During a successful trial, the sample could not move to the cylinder markers (its initial position). The grip force exerted on the cylinder with a given sample was read from the dynamometer (Andilog, USA). The test was done in quintuplicate for each sample, with a 15 min rest between consecutive trials. The measurement setup and procedure are presented in Figure 1.

Table 4. Performance levels of materials tested with variable cutting force [15]

Performance levels	Level A	Level B	Level C	Level D	Level E	Level F
Cutting force (N)	2	5	10	15	22	30

3.4. Statistical analysis

The results were analyzed using SPSS Statistics 25.0 software. Pearson's *r* correlation coefficient was calculated by a posteriori bootstrapping with 1,000 replicates. Statistical significance was adopted at $p < 0.05$. The results of static and dynamic cut resistance tests were compared with those of grip strength tests to identify correlations.

Figure 1. Diagram and photographs of the grip strength test.

4. Results and discussion

4.1. Laboratory test results

Cut resistance and grip strength results for four groups of materials are presented below to establish correlations between static and dynamic cut resistance and grip strength. Static and dynamic cut resistance results are given in Table 5 and Figure 2 while grip strength results are shown in Figure 3.

The presented static and dynamic cut resistance results reveal high variability in the performance of commercially available materials used in protective gloves against mechanical hazards. Knitted aramid fabrics were characterized by performance levels 2, 4, and 5 in terms of static cutting and levels B and C in terms of dynamic cutting. Among the tested knitted fabrics, D-1

exhibited the highest resistance in both tests. The woven fabrics made of aramid, glass, and carbon fibers revealed lower cutting performance levels as compared with the knitted materials. The woven glass fiber fabric T-1 and woven aramid/carbon fiber fabric T-3 reached performance level 1 in terms of static cutting and level B in terms of dynamic cutting. Higher static cutting resistance was exhibited by the woven aramid fabric T-2, which revealed lower dynamic cutting resistance (level A). Silicone-coated knitted aramid fabrics were characterized by resistance to dynamic cutting at the same level B. In terms of static cutting, the coated aramid materials DP-2 and DP-3 reached performance level 2, while DP-1 reached level 1. All dot-coated aramid fabric samples exhibited performance level 2 for static cutting resistance and level C for dynamic cutting resistance (the highest possible result, reached by only two other materials – the knitted aramid fabrics D-1 and D-2).

In terms of grip strength tests, the highest values were obtained by silicone-coated knitted aramid fabrics DP-2 (64.8 N) and

Figure 2. Comparison with the results of static and dynamic cut resistance.

Figure 3. Grip strength test results.

Table 5. Static and dynamic cut resistance results

Type of material	Sample designation	Mean static cut resistance (I)	Mean dynamic cut resistance (N)
Knitted fabrics	D-1	17.0	12.3
	D-2	49.5	13.6
	D-3	4.7	6.6
Woven fabrics	T-1	1.2	5.2
	T-2	2.6	3.1
	T-3	1.5	9.0
Continuously coated fabrics	DP-1	1.9	7.9
	DP-2	4.2	8.3
	DP-3	2.9	5.4
Dot-coated fabrics	DN-1	2.9	11.1
	DN-2	3.9	11.3
	DN-3	3.9	10.8

DP-3 (66.3 N), with similar results for the dot-coated knitted fabric DN-1 (62.4 N). The lowest grip strength was found for non-coated woven aramid fabrics T-2 (27.8 N) and T-3 (29.9 N), and the glass fiber woven fabric T-1 (32.5 N).

4.2. Statistical analysis results

Test results were analyzed statistically in terms of potential correlations between cut resistance and grip strength by calculating Pearson's r coefficient. Table 6 presents descriptive statistics for static and dynamic cut resistance and grip strength obtained for the studied materials.

Table 7 contains a matrix of correlations between static and dynamic cut resistance and grip strength results for the studied materials.

Statistical analysis showed that the static and dynamic cut resistance of the studied protective materials was not significantly correlated with their grip force properties.

5. Summary and conclusion

The study involved cut resistance tests under constant and varied cutting forces. Besides, a non-standard grip force test was used to investigate potential correlations between the cut resistance of materials and their grip strength properties. Thus, the current paper presents a preliminary study in determining optimum methods for evaluating cut-resistant materials, including biomimetic ones.

According to a considerable body of literature, the cut resistance of glove materials depends on the type of fibers they contain, their structure, and the finish of the fabric [8, 16, 31, 32]. The present study investigated the materials made of aramid, glass, and carbon fibers (Table 1).

The cutting mechanism has been reported to be significantly affected by factors such as the strain associated with the transverse deflection of fibers [33, 34], the intrinsic strength of the material [32], and friction between the blade and cut material [35].

The present study employed the cut resistance test methods prescribed in the standards EN 388:2016 + A1:2018 (static cutting) and EN ISO 13997:1999 (dynamic cutting). Among all the studied materials, the highest resistance to static cutting was found for the knitted aramid fabric D-2, woven aramid fabric T-2, continuously coated knitted aramid fabric DP-2, and dot-coated knitted aramid fabrics DN-2 and DN-3. In terms of dynamic cutting, the highest resistance was also found for the knitted aramid fabric D-2, and then for the woven aramid/

carbon fiber fabric T-3, continuously coated knitted aramid fabric DP-2, and dot-coated knitted aramid fabric DN-2.

Besides, the studied textile materials were evaluated using a grip strength test (Figure 1), which provided indirect information about their anti-slip properties. Those properties are of great relevance to user comfort and ergonomics, as they significantly affect grip strength [1, 10, 36]. The highest grip strength was exhibited by the knitted aramid fabric D-1, woven glass fiber fabric T-1, silicone-coated knitted aramid fabric DP-3, and dot-coated knitted aramid fabric DN-1.

Many authors have investigated the process of cutting protective materials. In their study of cutting mechanics, Vu Thi et al. [37] reported that cut resistance arises from an interplay of two factors: intrinsic material strength and friction [35]. An increase in friction may enhance or reduce cut resistance as the overall energy required to cut through a material depends on the friction coefficient: the loss of energy dissipated by the force compressing laterally the blade sides exerted by the material and resulting from its elasticity (bending rigidity) [35]. Consequently, the present authors found major differences in cutting mechanics between coated and non-coated textile materials. In the former case, the process of cutting involves two types of frictional forces: the force of macroscopic friction arising from the normal force applied to both sides of the blade and the sliding friction associated with the cut being propagated through the material (which occurs along the face of the blade).

This study involved both continuously coated and dot-coated materials (Table 1). The application of polymeric dots, which form spatial, and sometimes layered, structures was to some extent inspired by bionic structures. Indeed, according to a substantial body of research, bionics-inspired solutions can substantially enhance mechanical properties as compared to conventionally engineered ones [38, 39], such as layer [40], plate [29], foam [41, 42], and hybrid layer structures [43, 44]. Although the abovementioned publications reported high mechanical strength of the developed structures, they have yet to be validated and optimized. The present study also involved some bionics-inspired textile materials with biomimetic grip dots (Table 1).

Table 7. Matrix of correlations between static and dynamic cut resistance and grip strength

		Grip strength (N)	
		Pearson's r	p
Cut resistance	Static (I)	-0.19	0.55
	Dynamic (N)	0.22	0.50

Table 6. Descriptive statistics for static and dynamic cut resistance and grip strength tests

		N	Min	Max	M	SD
Cut resistance	Static (I)	12	1.20	49.46	8.02	13.70
	Dynamic (N)	12	3.10	13.55	8.67	3.19
Grip strength (N)		12	27.80	66.26	46.49	13.61

It should be noted that Moreland [45] did not find any correlation between the tensile strength and cut resistance of fibers. While in that study glass fibers exhibited much higher cut resistance than p-aramid fibers with the same area density, the latter were characterized by greater tensile strength. Furthermore, in some cases of polymer-coated materials, cut resistance was enhanced due to the effects of friction. Similarly, also in this study, dot-coated aramid fabrics (DN-1, DN-2, and DN-3) revealed superior dynamic cut resistance as compared to the corresponding non-coated fabrics (D-3, Table 5).

While the highest grip strength was found for the continuously coated knitted aramid fabrics DP-2 and DP-3 as well as dot-coated knitted aramid fabrics DN-1 and DN-3 (Figure 3), statistical analysis (Table 7) did not reveal any correlations between those results and static or dynamic cut resistance.

The study revealed no correlations between the cut resistance of protective materials and their grip strength associated with anti-slip properties. Thus, in the case of cut-resistant materials, including biomimetic ones, the selected grip strength test method is not suitable for objective evaluation of cutting performance as affected by macroscopic frictional forces.

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