

Article

Conductive Textile Structures for Haemorrhage Detection: Electrical Resistance-Based Sensing and Performance Evaluation

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Abstract

The electrical response of conductive textile structures to liquid exposure was investigated as a basis for electrical resistance-based haemorrhage detection. The sensing principle relies on changes in the electrical resistance of the conductive network following liquid exposure, with the resulting resistance variation used as the sensing parameter. Nine conductive textile variants were developed and evaluated, comprising three knitted structures (K1–K3) and six woven structures produced in raw and finished states (W1–W3). The structures incorporated silver-coated polyamide and stainless-steel conductive yarns and were exposed to water, acidic perspiration (pH 5.5), alkaline perspiration (pH 8.0), and saline solution. Saline solution was used as a controlled conductive aqueous medium for comparison and does not reproduce the physical, chemical, rheological, cellular, or biochemical properties of whole blood. Electrical resistance measurements, together with physical and mechanical characterization, scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR), were performed to assess structural stability and electrical response. Saline solution produced the largest resistance variations among the tested liquids, whereas water and perspiration resulted in lower responses. Localized mechanical deformation further induced pronounced resistance changes in several woven structures. Among the evaluated variants, W2 exhibited the most favorable combination of structural stability and electrical responsiveness. These results support further investigation of W2 (conductive yarn: Filix DA5393 yarn) as an electrical resistance-based sensing structure for potential haemorrhage-related liquid detection applications.

Keywords: conductive textiles; smart textiles; electrical resistance; textile sensors; liquid exposure



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1. Introduction

Traumatic haemorrhage remains one of the leading preventable causes of death worldwide in both military and civilian trauma, accounting for a substantial proportion of fatalities occurring before definitive medical care can be provided [1,2]. The probability of survival is strongly dependent on rapid haemorrhage recognition and immediate intervention, making the first minutes after injury critical for patient outcome [3,4]. Current haemorrhage control strategies, including tourniquets [5], haemostatic dressings [4], and compression techniques [2,6,7], have significantly improved trauma management; however, their effectiveness still relies on the prompt identification of bleeding by either the casualty or trained medical personnel. Consequently, delayed recognition remains a major

limitation during combat operations, remote rescue missions, mass casualty incidents, and other situations where immediate medical assistance is unavailable [8–10]. These challenges have stimulated increasing interest in intelligent medical systems capable of continuously monitoring trauma victims and supporting earlier therapeutic intervention through autonomous sensing technologies [3,11,12].

Recent advances in smart textiles, flexible electronics, and wearable sensing technologies have transformed conventional textile materials into multifunctional platforms capable of simultaneously providing protection, physiological monitoring, and real-time signal acquisition [13–17]. Conductive textile structures incorporating metallic yarns, conductive polymers, silver-coated fibers, carbon-based nanomaterials, and hybrid conductive coatings are increasingly being investigated for applications ranging from human motion analysis and physiological monitoring to intelligent protective equipment and personalized healthcare [16,17]. Compared with conventional rigid electronic sensors, textile-based sensing platforms offer superior flexibility, breathability, low weight, and conformability to complex body geometries, enabling their seamless integration into garments intended for continuous health monitoring [18–20]. Recent reviews consistently identify textile-integrated sensing as one of the fastest-growing research directions in wearable biomedical systems, highlighting its potential for next-generation healthcare and military protective applications [21–23].

Among the different sensing mechanisms employed in wearable textiles, electrical resistance-based sensing has emerged as one of the most mature and industrially compatible approaches due to its simple operating principle, low power consumption, and compatibility with conventional textile manufacturing technologies. Conductive textile architectures can respond to mechanical deformation, environmental conditions, or interaction with conductive liquids through measurable variations in electrical resistance. Previous studies have demonstrated the feasibility of woven conductive fabrics for conductive liquid leakage detection, while more recent investigations have extended textile sensing applications toward physiological monitoring, flexible bioelectronics, and non-invasive biofluid analysis [24]. Simultaneously, recent developments in wearable biofluid sensing have demonstrated that the electrical properties of sweat, saliva, tears, interstitial fluid [25], wound exudate, and blood can be exploited for real-time physiological monitoring [26,27]. These advances provide a solid scientific basis for extending conductive textile sensing toward autonomous haemorrhage detection [28].

Despite these advances, current research remains largely focused on monitoring routine physiological parameters such as body motion, respiration, pressure, temperature, and perspiration, whereas comparatively few studies address textile-based sensing systems specifically intended for traumatic haemorrhage detection. Furthermore, most investigations primarily evaluate the electrical response of conductive materials, with limited attention given to the influence of textile architecture on sensing performance. Parameters such as fabric construction, yarn arrangement, porosity, finishing treatments, washing durability, and structural stability directly influence liquid transport, conductive pathway continuity, mechanical integrity, and long-term sensor reliability [29]. Moreover, comprehensive studies correlating physical, mechanical, morphological, chemical, and electrical properties within a unified experimental framework remain scarce. Consequently, the engineering principles governing the selection of conductive textile architectures for autonomous haemorrhage detection have not yet been systematically established.

Based on these considerations, the present study aims to establish a comprehensive textile engineering framework for evaluating conductive textile architectures intended for autonomous haemorrhage detection. To the best of the authors' knowledge, this is among the few studies to simultaneously investigate conductive woven and knitted structures from

the perspectives of physical and mechanical performance, morphological and chemical stability, and electrical resistance-based sensing under simulated haemorrhage conditions. Nine conductive textile structures, manufactured from silver-coated polyamide yarns and stainless-steel yarns, were comparatively evaluated, with some structures being used in their raw (unfinished) state and others after undergoing finishing processes, such as washing and degreasing. The evaluation was carried out following exposure to water, acidic perspiration, alkaline perspiration, and saline solution, which was used as a controlled conductive aqueous medium.

The obtained results establish practical engineering guidelines for selecting conductive textile architectures suitable for future smart protective garments integrating autonomous haemorrhage detection and primary haemostatic response systems, as schematically illustrated in Figure 1.

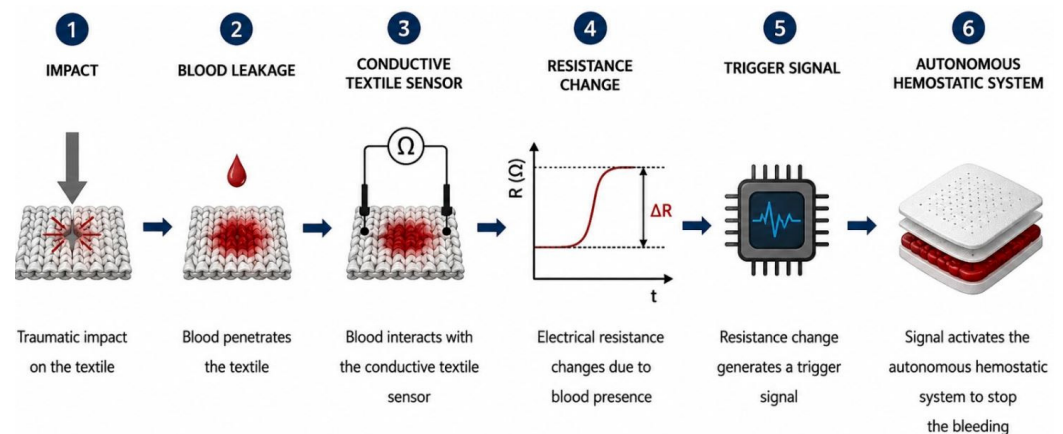


Figure 1. Working steps for the autonomous haemostasis system.

2. Materials and Methods

2.1. Conductive Yarns

The sensing approach investigated in this study is related to the operating principle of resistive textile-based humidity and moisture sensors, in which the interaction of moisture or liquid with a conductive textile network results in a measurable change in electrical resistance. The electrical response of such structures can be influenced by the conductive yarn composition, textile architecture, moisture distribution, and properties of the contacting liquid. Based on this principle, the conductive textile structures investigated in this study were evaluated as resistive sensing elements for differentiating their electrical response to different liquid exposure conditions.

Textile specimens measuring 10×5 cm were prepared with embroidered conductive pathways positioned at opposite ends of the electrical circuit. Electrical resistance measurements were performed using a digital multimeter in a two-point measurement configuration, with the embroidered conductive elements serving as the electrical contact points. For each specimen, the electrical resistance was first measured in the dry state to establish the baseline resistance (R_0). Subsequently, 5 mL of the test liquid was applied to the textile specimen. After a controlled exposure period of 5 s, the electrical resistance was measured again using the same two-point configuration, and the measured value was recorded as R_1 .

The resistance variation was calculated as the difference between the resistance measured after liquid exposure and the corresponding dry-state resistance:

$$\Delta R = R_1 - R_0 \quad (1)$$

The resulting ΔR value was used as the primary electrical sensing parameter. The electrical responses obtained following exposure to water, acidic perspiration (pH 5.5), alkaline perspiration (pH 8.0), and 2% saline solution were compared. The same specimen dimensions, liquid volume, exposure time, and measurement configuration were maintained for all experimental conditions.

The saline solution was used as a controlled conductive aqueous medium for evaluating the electrical response of the textile structures. It was not considered a blood substitute and does not reproduce the physical, chemical, rheological, cellular, or biochemical properties of whole blood. Therefore, the electrical response obtained with saline solution was interpreted only as a reference response to a conductive aqueous liquid and not as direct evidence of blood detection.

The experimental design comprised one knitted structure and two woven structures, three conductive yarn variants, and four liquid exposure conditions, resulting in a total of 36 tested specimens. One electrical resistance measurement was performed in the dry state and one measurement after liquid exposure for each specimen.

The proposed sensing sequence is illustrated schematically in Figure 2.

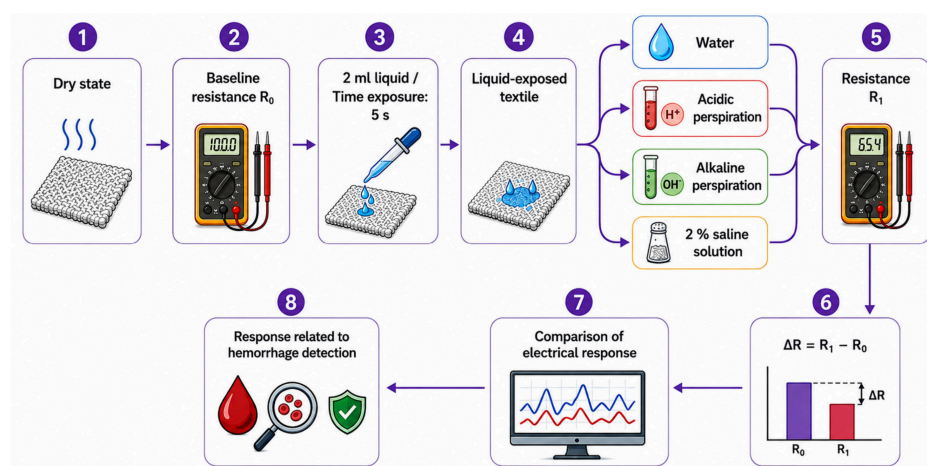


Figure 2. Principle of resistive textile moisture sensing.

The schematic represents the transition from the dry conductive textile structure, characterized by a baseline resistance (R_0), to the liquid-exposed state, characterized by a changed resistance (R_1). The resulting resistance variation (ΔR) constitutes the electrical parameter used to differentiate the responses of the textile structures to the tested liquid conditions.

In this study, two types of silver-plated polyamide-based conductive yarns and a stainless steel-based yarn were selected for use in the production of conductive textile structures (woven and knitted fabrics). The main physical characteristics of the 3 yarns are presented in Table 1.

Table 1. Conductive yarn parameters.

Parameter	Y1: Statex Shieldex® 2-PLY 280 Dtex	Y2: Filix DA5393 Yarn	Y3: Statex Shieldex® 2-PLY HC + B TPU
Composition	pure silver plated PA6.6	30% stainless steel/70% PES/elastane	silver-plated PA6.6 core protected by a TPU coating
Linear electrical resistance RL [Ω/m]	440	940	150
Electrical conductivity σ [S/m]	46,930	52,776	146,991

Table 1. Cont.

Parameter	Y1: Statex Shieldex® 2-PLY 280 Dtex	Y2: Filix DA5393 Yarn	Y3: Statex Shieldex® 2-PLY HC + B TPU
Fineness: Tex (g/km)/Nm (m/g)	15 × 2/66.6/2	12.67 × 2/78.93/2	14.0 × 2/71.42/2
Young's modulus <i>E</i> [GPa]	27.9	1.76	1.13
Optical diameter (μm)	240	160	248

2.2. Knitted Structures

Knitting technology was selected for the development of conductive textile structures due to its high flexibility, elasticity, breathability, and ability to maintain electrical continuity under deformation. The conductive knitted structures were produced using two types of textile yarns—100% cotton yarns and cotton/Celo blended yarns (50% cotton/50% Celo)—together with metallic yarns.

Knitting experiments were carried out on a Shima Seiki SIR 122 G14 flat knitting machine. The conductive knitted structures were designed using the intarsia knitting technique, allowing localized integration of conductive yarns without floating yarns on the backside of the fabric. The conductive pattern consisted of alternating sequences of two conductive yarn rows and four base yarn rows, generating conductive textile areas with controlled electrical distribution. Three variants of conductive knitted structures (K) were developed: K1—using Y1 yarn, K2—using Y2 yarn, and K3—using Y3 yarn. Experimental geometric analysis of the knitted structures revealed an average density of approximately 70 rows per 10 cm in the warp direction and approximately 100 stitches per 10 cm in the weft direction, indicating a compact structure with favorable potential for the continuity of conductive pathways.

2.3. Woven Structures

Three conductive woven fabric (W) variants were designed and developed using Nm 60/2 100% cotton yarns in the warp and Nm 60/2 100% cotton yarns and conductive yarns integrated into the secondary weft system. The woven structures were developed in a 2/1 twill weave configuration, with a warp density of 320 yarns/10 cm and a weft density of 250 yarns/10 cm for variants W1 and W2, and 220 yarns/10 cm for variant W3. The three conductive woven variants were: W1–Y1 weft yarn, W2–Y2 weft yarn, and W3–Y3 weft yarn. The fabrics were manufactured on a conventional shuttle weaving loom equipped with a dobby shedding mechanism. Warp preparation included sectional warping, drawing-in, and reed denting, while the conductive weft yarns were prepared through winding operations performed at 900 m/min and a yarn tension of 25 cN/yarn. The technological experiments were carried out using the experimental weaving equipment of INCDTP. The 3 woven structures were used in both raw (greige) (W1r–W3r) and finished (W1f–W3f) states. Finished woven fabrics were prepared by subjecting the greige fabrics to a standard laboratory washing procedure using a non-ionic detergent at 60 °C for 30 min. After washing, the samples were thoroughly rinsed and dried under controlled laboratory conditions. This pretreatment was performed exclusively to remove processing contaminants and residual lubricants originating from yarn manufacturing and weaving operations. No additional chemical functionalization or conductive finishing was applied prior to testing.

2.4. Method of Testing

The conductive structures were tested from a physical and mechanical point of view (tensile strength—strip method, according to SR EN ISO 13935-1:2013 [30] using a Titan

Universal Strength Tester; abrasion resistance—Lissajous motion, according to SR EN ISO 12947-2:2016 [31] using a Martindale 404 tester; and washing durability, according to SR EN ISO 105-c06:2010 [32] using a Giro HW-Jams Heal washing machine). Resistance to acidic and alkaline perspiration was determined following SR EN ISO 105-E04:2013 [33]. SEM imaging revealed the surface morphology of the conductive textiles after durability tests, while EDS confirmed their elemental composition. FT-IR analysis identified both organic and inorganic compounds present in the materials.

The nine samples were evaluated under four different wetting media: tap water, acidic perspiration (pH 5.5), alkaline perspiration (pH 8), and a 2% saline solution (as a controlled conductive aqueous medium). The acidic and alkaline perspiration solutions were prepared according to the standard SR EN ISO 105-E04:2013 [33], using L-histidine hydrochloride, sodium chloride, and phosphate salts, while the pH was adjusted with 0.1 M HCl or NaOH. The saline solution was prepared using 20 g NaCl/L distilled water. A saline solution was selected as a controlled conductive aqueous medium because the sensing principle investigated in this study relies primarily on ionic conductivity and moisture-induced resistance changes rather than on the rheological or cellular properties of blood.

3. Experimental

The performance evaluation of the conductive textile structures was carried out using 5 mL of liquid, applied over a circular test area with a diameter of 5 cm and a wetting duration of 5 s (Figure 3). Electrical resistance measurements were performed while maintaining, as consistently as possible, the same conductive yarn length, considering the high elasticity of the textile structures. Particular attention was given to the variation in electrical resistance values for each textile structure under the four moisture conditions, as well as to the resistance ranges obtained, in order to correlate them with the activation parameters of the primary haemostasis monitoring system. Electrical resistance values [Ω] were determined in three distinct states: in the initial dry condition, after wetting, and after wetting within a molded “bullet imprint” configuration. Measurements were conducted using a Fluke 179 Digital Multimeter, with a measurement range from 0.1 Ω to over 50 M Ω .

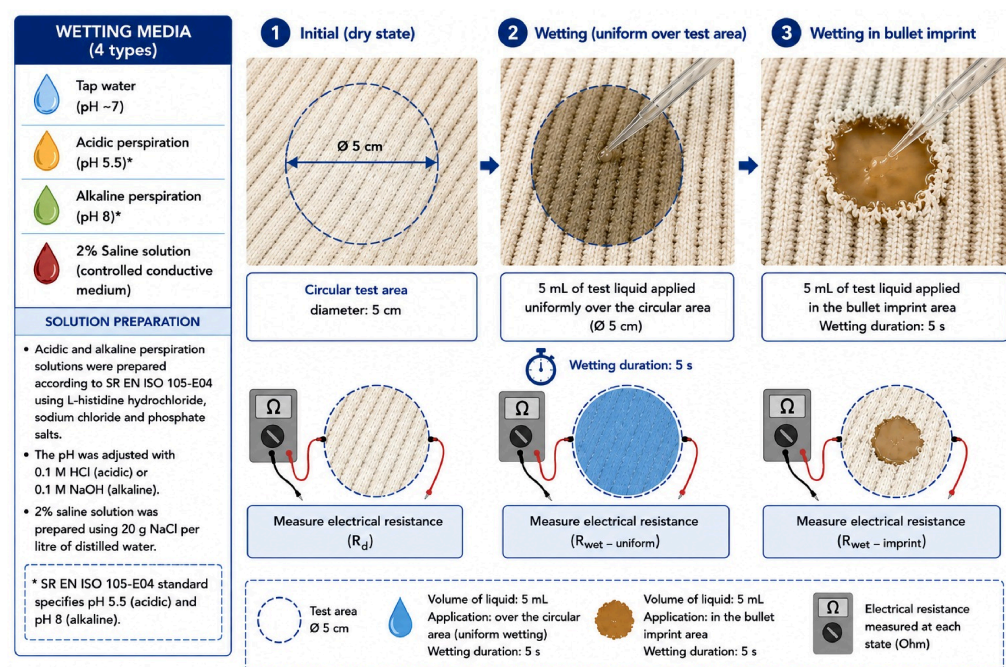


Figure 3. Experimental set-up, wetting media and testing conditions for electrical resistance measurements under the different wetting media.

4. Results and Discussion

4.1. Physical and Mechanical Properties

The physical characteristics of the conductive textile structures are presented in Figure 4. The washing pretreatment significantly increased both the areal density and thickness of all woven fabrics ($p < 0.01$ – 0.001), indicating improved yarn packing, enhanced inter-yarn cohesion, and structural consolidation following the removal of processing residues. Compared with woven fabrics, the knitted structures (K1–K3) exhibited lower areal density while maintaining comparable or even greater thickness, reflecting their looped architecture and higher compressibility. Air permeability measurements clearly differentiated the two textile architectures. Knitted fabrics exhibited values of approximately 3200–3500 L/m²/s, nearly one order of magnitude higher than those measured for woven fabrics (approximately 300–600 L/m²/s), confirming their more open pore network and superior breathability. Such differences are expected to influence liquid transport, wetting behavior, and sensor response, since fluid penetration into the conductive structure governs the electrical resistance variation used for haemorrhage detection. Therefore, the physical characteristics of the textile substrate are expected to play a crucial role in both wearer comfort and sensing performance.

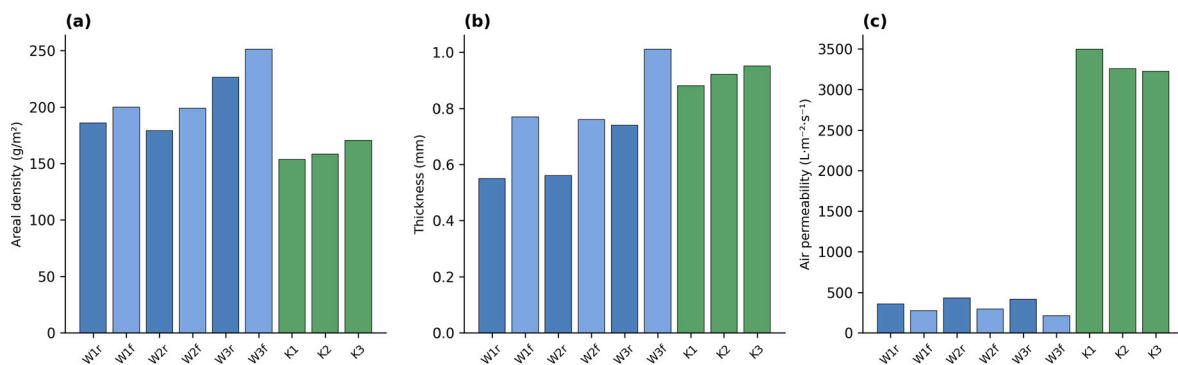


Figure 4. Physical properties of the woven and knitted textile structures: (a) areal density, (b) thickness, and (c) air permeability. W = woven samples, K = knitted samples, r = raw state, f = finished state. Dark blue, light blue, and green bars represent raw woven samples, finished woven samples, and knitted samples, respectively.

The mechanical properties of the conductive textile structures are presented in Figure 5. Woven fabrics exhibited significantly higher breaking force and Young's modulus than knitted structures in both warp and weft directions, demonstrating superior structural stability and resistance to mechanical loading. In most woven variants, the warp direction showed higher breaking force and stiffness than the weft direction owing to the higher yarn density, reduced yarn undulation, and more efficient stress transfer along the warp system. The washing pretreatment generally improved the mechanical behavior of woven fabrics, particularly in the weft direction, where sample W3 exhibited the largest increase in strength. This improvement can be attributed to enhanced yarn cohesion and reduced yarn mobility following the removal of processing lubricants. Conversely, the lower Young's modulus measured for knitted fabrics confirms their greater flexibility and deformability, properties that facilitate conformability to complex body surfaces while minimizing mechanical constraints during wear. From the perspective of haemorrhage detection, the combination of sufficient mechanical stability and flexibility is essential to ensure reliable electrical contact with the wound area while preserving the integrity of the conductive pathways during body movements. Overall, woven fabrics provide superior structural robustness, whereas knitted structures offer enhanced conformability and comfort, highlighting the complementary advantages of both textile architectures for wearable sensing systems.

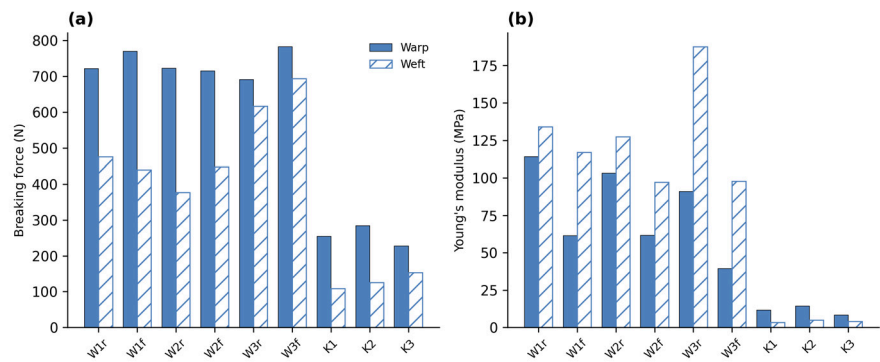


Figure 5. Mechanical properties of the woven and knitted textile structures: (a) breaking force, and (b) Young’s modulus. W = woven samples, K = knitted samples, r = raw state, f = finished state.

Following the determination of the extensibility of the conductive knitted structures using a CETME (Electric Stretch Tester Man), Pearson correlation coefficients were calculated to evaluate the relationships among elongation, Young’s modulus, and extensibility in both the wale and course directions. The complete correlation matrix is presented in Table 2, while the corresponding heatmap visualization is shown in Figure 6.

Table 2. Pearson correlation coefficients between elongation, Young’s modulus and extensibility of conductive knitted structures.

Variable	Vertical Elongation	Horizontal Elongation	Young’s Modulus (Vertical)	Young’s Modulus (Horizontal)	Extensibility
Vertical Elongation	1.000	0.970	0.722	−0.278	−0.474
Horizontal Elongation	0.970	1.000	0.536	−0.314	−0.255
Young’s Modulus (Vertical)	0.722	0.536	1.000	−0.218	−0.951
Young’s Modulus (Horizontal)	−0.278	−0.314	−0.218	1.000	0.200
Extensibility	−0.474	−0.255	−0.951	0.200	1.000

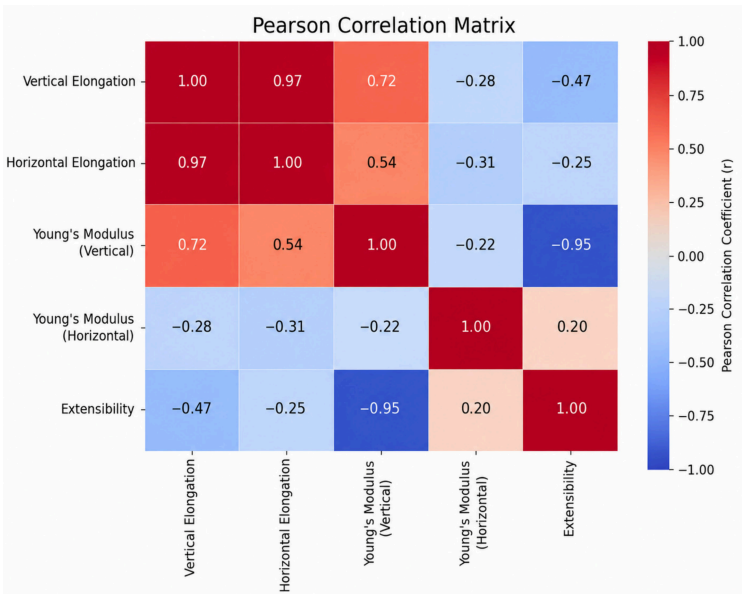


Figure 6. Pearson correlation heatmap illustrating the relationships between the mechanical parameters of conductive knitted structures.

The correlation analysis revealed a very strong positive relationship between vertical and horizontal elongation ($r = 0.970$), indicating a highly uniform deformation behaviour of the knitted conductive structures irrespective of the loading direction. A strong positive correlation was also observed between vertical elongation and Young's modulus in the vertical direction ($r = 0.722$), suggesting that the structural configuration influences both tensile deformation and stiffness. Conversely, extensibility exhibited a very strong negative correlation with Young's modulus in the vertical direction ($r = -0.951$), demonstrating that increased structural stiffness is associated with reduced deformation capacity. Other parameter pairs showed weak or moderate correlations, indicating that their mutual influence on the mechanical response is limited.

The heatmap representation (Figure 6) provides a rapid visual assessment of these relationships, highlighting the dominant positive and negative correlations identified in the numerical analysis. The agreement between the correlation matrix and the heatmap confirms the consistency of the statistical evaluation.

From the perspective of wearable haemorrhage detection, these mechanical relationships are particularly important because repeated deformation of the textile substrate may modify the geometry of the conductive network and consequently influence the electrical resistance measured by the sensing element. Textile structures exhibiting controlled extensibility combined with adequate dimensional stability are therefore expected to provide more stable conductive pathways and improved repeatability of the electrical response under realistic operating conditions. Consequently, the correlation analysis demonstrates that the mechanical behavior of the conductive knitted structures is closely associated with their potential reliability as textile-based sensors for autonomous haemorrhage detection.

4.2. Abrasion Resistance

The abrasion resistance of the conductive textile structures was evaluated using the Martindale method under a pressure of 12 kPa for 1000 and 5000 abrasion cycles. Visual inspection demonstrated that both knitted and woven conductive fabrics preserved their structural integrity throughout the test, with no yarn breakage, delamination, or severe surface damage observed after 5000 cycles (Figure 6). Although minor surface modifications associated with frictional wear were detected, the conductive yarns remained firmly integrated within the textile architecture without evidence of structural failure. Representative surface morphologies of samples K1 and W1f after 1000 and 5000 abrasion cycles are presented in Figure 7.

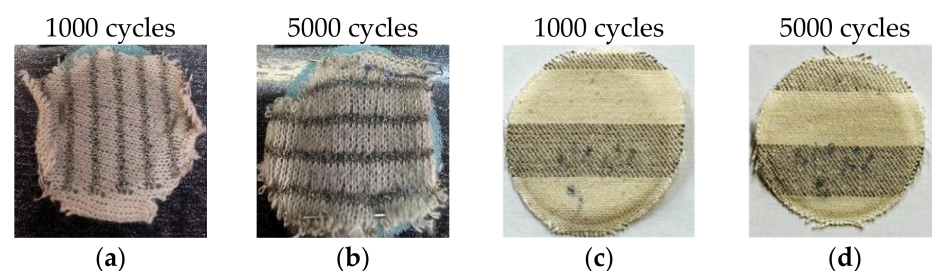


Figure 7. Surface morphology of conductive textile structures after Martindale abrasion: (a) K1 after 1000 cycles; (b) K1 after 5000 cycles; (c) W1f after 1000 cycles; (d) W1f after 5000 cycles.

The excellent abrasion resistance of both textile architectures indicates that the conductive network is capable of withstanding repeated mechanical friction without significant structural degradation. This behavior is particularly important for wearable sensing applications, where continuous contact with the skin, clothing layers, and body movements may progressively deteriorate the textile surface. Preserving the integrity of the conductive yarn network minimises the risk of electrical pathway discontinuities and helps maintain a stable

electrical response during prolonged use. Consequently, the investigated conductive textile structures exhibit the mechanical durability required for reliable and reusable autonomous haemorrhage detection systems.

4.3. SEM and EDS Analysis

The SEM micrographs (1000× magnification) (Figure 8) revealed significant differences in the surface morphology and degradation behavior of the conductive woven structures depending on the fabric variant, finishing treatment and exposure conditions. The comparative SEM analysis revealed that the textile architecture, structural mobility and finishing treatment significantly influence the morphological stability and degradation behavior of conductive textile structures exposed to perspiration media and repeated washing cycles. The knitted conductive structures (K1–K2–K3) exhibited a highly flexible and deformable morphology due to their looped architecture. This structural configuration allows greater filament mobility and reduces localized stress concentration during mechanical deformation. As a result, the conductive coating degradation mainly occurred through localized microcracks, partial exfoliation and gradual surface roughening rather than abrupt large-scale coating detachment. Among the knitted variants, K1 showed the most homogeneous conductive coating distribution and the best overall morphological stability. K2 exhibited a more heterogeneous filament arrangement but maintained relatively good coating continuity under both chemical and mechanical exposure. K3 demonstrated the highest sensitivity to repeated washing cycles, showing more extensive peeling and coating exfoliation after five washing cycles. For all knitted samples, alkaline perspiration produced more pronounced surface deterioration than acidic perspiration. Nevertheless, the conductive pathways generally remained relatively continuous even after repeated washing, indicating that the knitted structures preserve acceptable conductive network integrity despite progressive surface degradation.

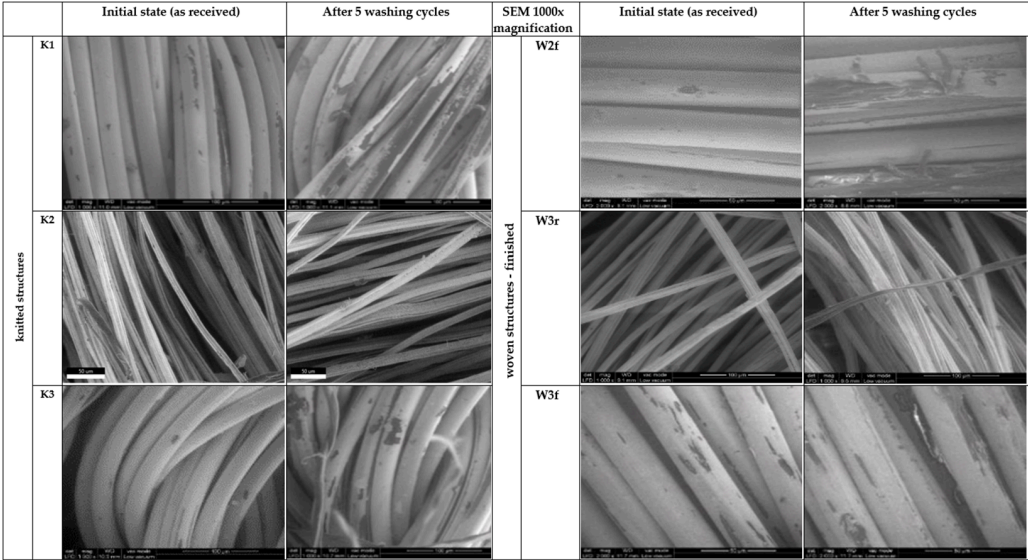


Figure 8. SEM micrographs (1000× magnification) of conductive knitted structures K1–K3 and finished woven samples W1–W3: initial state and after 5 washing cycles.

In contrast, the woven conductive structures (W1–W2–W3) exhibited more compact and mechanically constrained morphologies due to the fixed yarn intersections characteristic of woven architectures. This structural rigidity generated higher local mechanical stresses during washing and friction between adjacent yarns, leading to more pronounced coating degradation after repeated washing. Among the woven variants, W2 demon-

strated the best overall morphological stability and coating continuity. The conductive layer remained relatively uniform after both perspiration exposure and washing cycles, suggesting improved adhesion and reduced susceptibility to mechanical wear. W1 showed moderate degradation behavior, while W3 presented the most severe deterioration, particularly after five washing cycles, where extensive coating exfoliation and conductive layer discontinuities became evident.

The finishing treatment significantly improved the performance of woven conductive structures. Finished woven samples generally exhibited smoother filament surfaces, fewer coating defects and better preservation of the conductive layer after environmental and mechanical exposure. The finishing process appears to enhance inter-yarn cohesion and improve adhesion of the silver-based conductive coating, thereby reducing friction-induced degradation during washing.

For both knitted and woven structures, repeated washing cycles represented the dominant degradation factor. It should be noted that the washing assessment was limited to five cycles. Therefore, these results provide an initial indication of washing-induced degradation but are insufficient to establish long-term durability or repeated-use sensing performance. Extended washing and cyclic electrical-response testing will be required in future work. The morphological deterioration observed after five washing cycles was substantially more severe than that produced by acidic or alkaline perspiration exposure alone. In all cases, the alkaline medium induced more aggressive surface degradation than the acidic medium, suggesting increased chemical interaction with the conductive silver coating.

Overall, the comparative SEM analysis demonstrates that conductive textile durability strongly depends on the interaction between textile architecture and finishing treatment. Knitted structures provide superior flexibility and reduced stress concentration but are more susceptible to progressive deformation during laundering, whereas woven structures offer greater dimensional stability but experience higher localized mechanical stresses at yarn intersections. Among all investigated variants, the finished W2 structure exhibited the best combination of coating continuity, morphological stability and resistance to environmental and washing-induced degradation.

EDS analysis confirmed the persistence of the conductive metallic components after five washing cycles (Table 3). For the structures incorporating silver-based conductive yarns (K1, K3, W1f and W3f), the measured silver retention ranged from 80.6% to 98.5%. The K2 and W2f structures, produced using the stainless-steel/polyester Y2 yarn, were evaluated based on their Fe content. The Fe retention was 99.1% for K2 and 98.1% for W2f, indicating that the stainless-steel conductive component remained substantially preserved after five washing cycles.

Table 3. EDS elemental composition before and after 5 washing cycles.

Sample	Ag Initial (%)	Fe Initial (%)	Ag After 5 Washes (%)	Fe After 5 Washes (%)	Ag Retention (%)	Fe Retention (%)	O Initial (%)	O After 5 Washes (%)	ΔO (%)
K1	78.3	72.1	67.4	71.5	86.1	99.1	10.4	16.9	+6.5
K2							3.5	5.3	+1.8
K3	70.8		57.1		80.6		9.5	15.3	+5.8
W1f	74.0	70.1	71.5	68.8	96.6	98.1	28.5	33.1	+4.6
W2f							2.2	5.3	+2.1
W3f	60.3		59.4		98.5		28.1	27.1	−1.0

Changes in oxygen content were also observed after washing. The largest increases were recorded for K1 (+6.5%) and K3 (+5.8%), while W3f showed a slight decrease in

oxygen content (-1.0%). K2 exhibited an increase in oxygen content from 3.5% to 5.3% ($+1.8\%$), whereas W2f showed an increase from 2.2% to 5.3% ($+2.1\%$). These changes indicate modifications of the exposed surface composition following washing.

Among the woven structures, W2f retained 98.1% of its initial Fe content after five washing cycles, while the SEM observations showed relatively good preservation of the conductive yarn surface. This combination indicates a high degree of retention of the stainless-steel conductive component under the investigated washing conditions.

4.4. FT-IR Analysis

FTIR analysis (Figure 9) demonstrated that the conductive textile structures maintained their fundamental chemical composition after exposure to acidic perspiration ($\text{pH } 5.5$), alkaline perspiration ($\text{pH } 8$), and single and repeated washing cycles. Although moderate variations in band intensity were observed, particularly in the $1200\text{--}900\text{ cm}^{-1}$ region, no significant spectral shifts or the appearance of new absorption bands were detected. The broad absorption band observed around $3300\text{--}3400\text{ cm}^{-1}$ can be attributed to O–H stretching vibrations associated with cellulose fibers. The bands located near 2900 cm^{-1} correspond to aliphatic C–H stretching vibrations, while the intense absorptions in the $1200\text{--}900\text{ cm}^{-1}$ region are mainly associated with C–O–C and C–O stretching vibrations characteristic of cellulose-based textile substrates. The preservation of these characteristic bands after treatment confirms the chemical stability of the textile matrix.

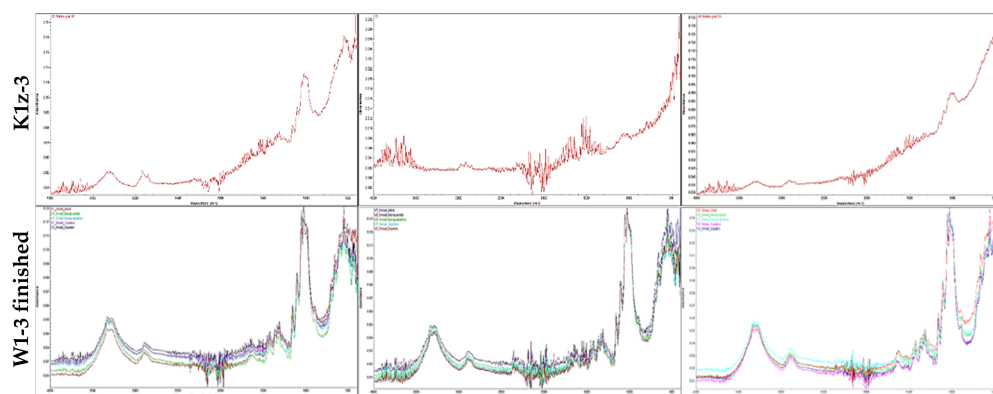


Figure 9. FT-IR spectra of conductive knitted structures K1–K3 and finished woven samples W1–W3 after 5 washing cycles.

These findings indicate that the treatments investigated primarily induced surface-level modifications rather than substantial chemical degradation. Combined with SEM observations and electrical resistance measurements, the results suggest that changes in the performance of the conductive textiles are predominantly governed by morphological alterations and rearrangements in the conductive network rather than by changes in the chemical structure of the textile substrate.

4.5. The Performance Evaluation of the Conductive Textile (Electrical Resistance Tests)

The normalised resistance changes ($\Delta R/R_0$) demonstrate a clear dependence of the electrical response on both textile architecture and testing condition (Table 4).

The exceptionally large $\Delta R/R_0$ values observed for some structures, particularly after bullet imprinting, result primarily from the very low initial resistance values (R_0) of these samples. Since $\Delta R/R_0$ is calculated by normalizing the absolute resistance change to R_0 , small baseline resistance values can produce very large relative changes even when the corresponding absolute resistance variation is substantially lower. Therefore, these extreme normalized values should be interpreted as large relative resistance responses

rather than as proportionally large absolute resistance changes or as a direct linear measure of sensing sensitivity.

Table 4. Normalized resistance changes ($\Delta R/R_0$) of the conductive textile structures after wetting and bullet imprinting under different exposure media.

Medium	Condition	$\Delta R/R_0$								
		K1	K2	K3	W1r	W2r	W3r	W1f	W2f	W3f
Water	Wetting	9.9	−3.0	6.5	−15.2	−11.1	−11.1	−39.9	−80.0	−16.0
	Bullet imprint	−58.0	−100.0	−54.0	3506.9	47,863.8	19,344.4	33.5	−20.0	75
Acidic perspiration	Wetting	2.4	7.7	45.1	−5.8	−28.5	−17.9	−16.4	−36.1	−58.2
	Bullet imprint	−45.0	245,897.1	234.8	−43.9	192	6176.4	−21.8	−11.0	−20.0
Alkaline perspiration	Wetting	−3.6	−14.8	15.6	−55.9	−99.8	−14.9	−56.3	−85.7	−35.0
	Bullet imprint	−43.3	207	13.1	−43.4	545.2	−4.3	1217.4	17,360.3	−10.0
Saline solution	Wetting	−6.2	−15.5	−0.5	−80.6	−100.0	−44.4	−82.7	−93.1	−50.0
	Bullet imprint	−4.9	−81.9	−65.5	−3.9	74.3	−7.4	−23.7	4.2	−27.3

Figure 10 summarizes the electrical resistance response of all conductive textile structures under water, acidic perspiration (pH 5.5), alkaline perspiration (pH 8), and saline solution exposure. The logarithmic representation reveals substantial differences between textile architectures and testing conditions. Special attention was paid to the variation in electrical resistance of each knitted and woven structure under the four humidity conditions, as well as to the ranges within which these values fall, to correlate them with the activation parameters of the primary haemostasis system's control unit.

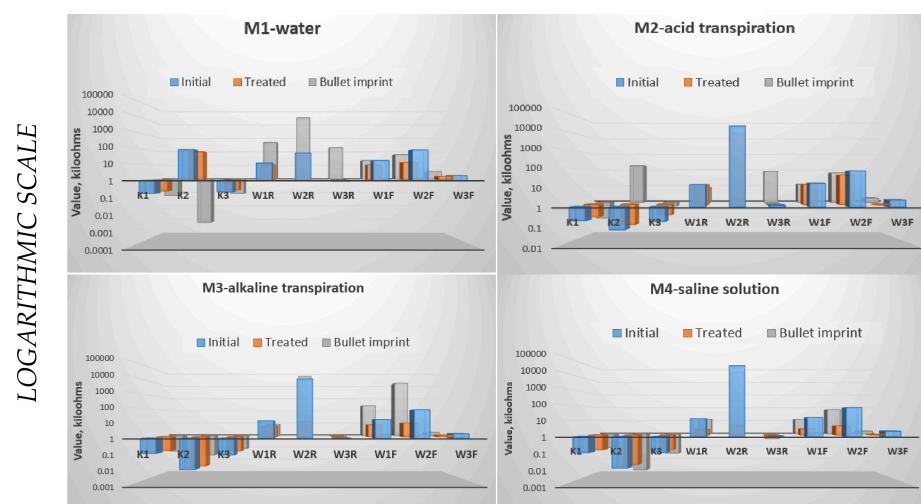


Figure 10. Electrical resistance variation in conductive textile structures (effect of wetting media and mechanical deformation (bullet imprint)).

The conductive textile structures exhibited significantly different electrical resistance behaviors depending on the wetting medium, textile architecture and testing condition.

For all investigated structures, water exposure produced the smallest variations in electrical resistance. Although moisture absorption modified the contact resistance between conductive elements, the resulting changes remained relatively limited, indicating that

pure water does not significantly alter the conductive pathways. In contrast, both acidic perspiration (pH 5.5) and alkaline perspiration (pH 8) generated more pronounced electrical responses, reflecting the influence of dissolved ions on charge transport mechanisms within the conductive coating. The alkaline medium generally induced larger resistance variations than the acidic medium, which is consistent with the FTIR and SEM observations indicating a higher degree of surface interaction and coating degradation under alkaline conditions.

The most significant resistance changes were observed in the saline solution, used as a controlled conductive aqueous medium. The presence of a high concentration of ionic species strongly affected the electrical behavior of the conductive textiles, producing resistance variations several orders of magnitude higher than those recorded in water. This finding is particularly relevant for haemorrhage detection applications, as it demonstrates the ability of the textile structures to discriminate between ordinary moisture and fluids with elevated ionic conductivity, such as blood.

A notable feature of the results is the pronounced effect of the bullet imprint condition. Following localized mechanical deformation, several structures exhibited abrupt increases in electrical resistance, indicating substantial disruption of the conductive network. Such behavior can be attributed to localized coating cracking, separation of conductive fibers, modification of contact points between yarns, and partial interruption of conductive pathways. These mechanisms are particularly important for autonomous haemorrhage management systems, as they provide a clear electrical signal associated with traumatic impact. Among all investigated variants, the W2 structure demonstrated the highest electrical sensitivity. In all wetting media, and especially in the saline solution, W2 generated substantially larger resistance variations than the other textile configurations. Interestingly, SEM observations revealed relatively good morphological stability of this structure, while FTIR analysis indicated only minor chemical modifications. This apparent contradiction suggests that small changes in conductive pathway geometry can produce large electrical responses without requiring severe morphological or chemical degradation. Such behavior is highly advantageous for sensing applications because it enables high detection sensitivity while preserving structural integrity.

The knitted structures (K1–K3) exhibited a more stable electrical response. Their looped architecture allows mechanical stresses to be distributed more uniformly throughout the textile structure, reducing local stress concentration and limiting abrupt changes in conductive contacts. Consequently, the resistance variations remained relatively moderate under all testing conditions. Although this behavior may reduce sensitivity to localized damage, it provides improved signal stability and repeatability. The woven structures generally displayed greater electrical sensitivity than the knitted counterparts. The more rigid architecture of woven fabrics promotes localized stress accumulation at yarn intersections, amplifying the electrical effects of wetting and mechanical deformation. This characteristic was particularly evident for W1F, W2, and W2F, which exhibited substantial resistance variations under saline exposure and bullet imprint conditions.

4.6. Integrated Performance Assessment of Conductive Textile Structures for Autonomous Haemorrhage Detection

Since the suitability of conductive textiles for autonomous haemorrhage detection depends on multiple performance criteria, a comprehensive comparative assessment was performed by combining the results of mechanical testing, morphological evaluation (SEM), chemical stability analysis (FTIR), and electrical resistance measurements. Table 5 provides a consolidated overview of the investigated structures and highlights the most promising candidates for integration into smart textile-based sensing systems. This approach enables the identification of textile architectures that simultaneously exhibit high durability,

environmental stability, and strong electrical responsiveness under simulated haemorrhage conditions.

Table 5. Integrated performance scores of the investigated conductive textile structures.

Structure	Mechanical	SEM	FTIR	Electrical	Total Score
K1	3	4	5	2	14
K2	3	3	5	2	13
K3	3	3	5	3	14
W1r	5	3	5	3	16
W1f	5	4	5	4	18
W2r	5	5	5	5	20
W2f	5	5	5	4	19
W3r	5	3	5	3	16
W3f	5	3	5	3	16

1 = Poor; 2 = Low; 3 = Moderate; 4 = High; 5 = Very High.

The performance scores (1–5) were assigned based on the comparative ranking of the experimental results obtained for each investigated property. For each performance criterion, a score of 1 corresponded to the poorest performance among the investigated structures, whereas a score of 5 represented the best experimental performance.

The comparative assessment confirms that the woven W2 structures achieved the most balanced performance among all investigated variants. Both W2r and W2f exhibited excellent morphological stability, high chemical resistance to environmental exposure, and the strongest electrical response under saline solution and mechanical damage conditions. In contrast, the knitted structures demonstrated superior flexibility and stability but lower sensing sensitivity.

These findings identify W2-based conductive fabrics as promising candidates for further development of textile-based sensing elements intended for potential haemorrhage-related liquid detection applications. Integration into autonomous haemorrhage detection or haemostatic triggering systems remains a subject for future research.

The integrated assessment demonstrates that the most suitable sensing materials are not necessarily those exhibiting the highest mechanical performance or the lowest morphological degradation alone. Instead, the optimal textile sensor results from a balance between structural stability and electrical responsiveness. In this regard, the W2 conductive woven structures achieved the most favorable compromise, combining excellent environmental durability with the largest resistance variations under simulated haemorrhage conditions. Such behavior is particularly advantageous for autonomous detection systems, where reliable triggering capability must be maintained throughout the operational life of the textile component.

5. Conclusions

This study evaluated conductive knitted and woven textile structures with respect to their mechanical, morphological, chemical, and electrical responses to controlled liquid exposure. Three conductive yarn variants and three textile structures were investigated under exposure to water, acidic perspiration (pH 5.5), alkaline perspiration (pH 8.0), and 2% saline solution.

The mechanical characterization showed distinct differences between the textile architectures. The woven structures exhibited higher tensile strength and dimensional stability, whereas the knitted structure showed greater flexibility and deformability. These differences demonstrate the influence of textile architecture on the mechanical behaviour of conductive textile structures.

SEM observations indicated that washing cycles produced more pronounced changes in the conductive surface than the tested liquid exposures. Among the evaluated woven structures, W2 showed comparatively good preservation of the conductive surface morphology after the applied exposure and washing conditions. FTIR analysis did not indicate substantial changes in the chemical structure of the textile substrates, suggesting that the observed changes in electrical and morphological behaviour were not accompanied by major alterations of the substrate's chemical structure.

Electrical resistance measurements showed that the response of the textile structures varied according to both textile architecture and liquid exposure condition. Water generally produced smaller resistance variations, whereas the tested perspiration solutions and 2% saline solution produced more pronounced electrical responses. The saline solution generated the largest resistance variations among the investigated liquids. These results demonstrate that the conductive textile structures exhibit measurable differences in electrical response under the tested liquid exposure conditions.

Among the evaluated structures, W2f showed a favourable combination of electrical response and morphological stability under the investigated conditions. On this basis, W2f was selected as the most suitable structure among those tested for further investigation as an electrical resistance-based sensing element.

The results demonstrate the feasibility of monitoring liquid-induced changes in the electrical resistance of conductive textile structures. However, the present study does not demonstrate direct blood detection, haemorrhage detection in a clinical or physiological environment, or autonomous haemostatic intervention. The 2% saline solution was used as a controlled conductive aqueous medium and does not reproduce the physical, chemical, rheological, cellular, or biochemical properties of whole blood. Therefore, the electrical response observed with saline should be interpreted as a preliminary reference response rather than as evidence of blood detection.

Further studies are required to evaluate the sensing response using physiologically representative blood analogues or blood, under controlled dynamic flow and bleeding conditions, and to determine the effects of blood composition, fluid volume, flow rate, temperature, and contact configuration on the electrical response. Integration of the selected textile structure into a functional haemorrhage detection system will also require development and validation of the associated signal acquisition, processing, and decision-making components.

Overall, the findings provide an initial experimental basis for the use of conductive textile structures as electrical resistance-based sensing elements for liquid exposure. The W2f structure represents a suitable candidate for further investigation toward textile-based haemorrhage-sensing applications.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Ag	Silver
EDS	Energy-Dispersive X-ray Spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy
HCl	Hydrochloric Acid
K1–K3	Conductive knitted textile structures
NaCl	Sodium Chloride
NaOH	Sodium Hydroxide
O	Oxygen
PA6.6	Polyamide 6.6
PES	Polyester
SEM	Scanning Electron Microscopy
TPU	Thermoplastic Polyurethane
W1f–W3f	Conductive woven fabrics after washing pretreatment
W1r–W3r	Conductive woven fabrics in the greige state
Y1–Y3	Conductive yarn variants used for textile fabrication

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