applied sciences

MDPI

Review

Degradation of Silver-Coated Conductive Elements in Electronic Textile Interfaces: A Single-Stressor Evidence Map and the Case for Multi-Stressor Testing

Chai Young Lee

Fashion Lifestyle Major, School of Fashion, Art and Physical Education, Gyeongkuk National University, Andong 36729, Republic of Korea; chaiyounglee@gknu.ac.kr

Abstract

Silver-coated yarns, hook-and-loop fasteners, dry electrodes, and snap connectors are the most common means of establishing electrical contact in smart garments, owing to silver's favorable conductivity, lower cost relative to gold, and compatibility with flexible fiber coatings. In practice, however, these components fail in a recurring pattern: the silver coating wears away or corrodes, and the electrical path is interrupted. This problem has, until now, been studied by separate research communities that rarely cite one another: tribology researchers have characterized how silver connectors wear under vibration, textile researchers have examined how they degrade during washing and sweat exposure, and coating researchers have investigated how the coating itself is applied. This review systematically maps evidence across these three strands of the literature and evaluates, pathway by pathway, the strength of support for each. Six degradation pathways are examined, namely vibration, repeated plugging and unplugging, laundering, sweat exposure, atmospheric exposure, and fiber or debris entrapment, and all six are found to be consistent with a single underlying mechanism: loss of the silver layer and a consequent reduction in working contact points, with three of these pathways, fretting, laundering, and perspiration corrosion, supported by direct measurement. One study further shows that short-term sweat exposure can transiently increase conductance before longer exposure reduces it, indicating that this degradation is not strictly a one-way process. The review also compares coating deposition methods and identifies a mitigation strategy proposed independently for two of the six pathways: adding a second conductive layer, such as carbon nanotubes or a thin gold overcoat, that remains functional after the underlying silver is depleted, although this strategy has not yet been cross-validated between pathways. Because nearly every study reviewed here tests only a single stressor at a time, with genuine combined-stress evidence limited to one study, this review argues that more realistic, combined-stress testing is still needed and proposes a concrete framework for such testing.

Keywords: silver coating; electronic textile; conductive yarn; contact resistance; corrosion; fretting wear; laundering durability; wearable connector; coating deposition

Check for updates

Academic Editors: Lan Luo and Zhengxian Liu

Received: 3 September 2026
Revised: 19 September 2026
Accepted: 24 September 2026
Published: 26 September 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Smart garments integrate sensors, batteries, and communication modules into fabric. The electrical joints between these components and the textile circuit are widely regarded as the primary weak point limiting the reliability of such garments [1,2]. Smart garments are now employed for health monitoring, sports applications, and even for harvesting energy

from the body [3–5]. Among the many conductive materials used to form these joints, silver is by far the most common, owing to its high electrical conductivity, lower cost relative to gold, and suitability for coating onto flexible fibers. For these reasons, silver coating is the default choice for conductive yarns woven or stitched into circuits, hook-and-loop fasteners used as plug-in connectors, dry electrodes for measuring body signals, and snap or button connectors that attach modules to a garment.

Although these components differ considerably in form, they fail through the same underlying mechanism. Electrical current crosses each joint through a set of microscopic contact spots where silver surfaces touch. As the coating wears away, corrodes, or is otherwise removed, fewer of these contact spots remain, and the electrical resistance increases. To date, this shared weakness has been studied along three largely separate research paths.

The first research path originates in the tribology of industrial and automotive connectors. Motivated by the problem of fretting corrosion in connectors exposed to low-frequency vibration, this body of work has characterized how the contact resistance of silver joints, including conductive hook-and-loop fasteners, varies with vibration frequency, load, and cycle count. It has also evaluated surface coatings such as carbon nanotubes as a means of maintaining stable resistance under long-term vibration [6,7]. This line of research is grounded in mechanical and electrical engineering and builds on an established theory of electrical contact behavior [8,9].

The second research path originates in textile and materials science, motivated by the fact that garments must be laundered and worn against the skin. This work has shown how silver-coated yarns and electrodes degrade through washing [10–12] and how silver reacts with chloride ions in sweat, in some cases losing conductivity within hours [13]. A related study found that combined sweat exposure and washing accelerates the buildup of silver chloride and silver oxide on the coating [14], and another found that atmospheric exposure can contribute to the resistance rise observed over repeated washing [15]. As with the tribology literature, this body of work generally tests a single stressor, most often washing, in isolation.

The third research path originates in coating science and addresses how silver is deposited onto textile fibers, most commonly by electroless plating, and how bath chemistry and surface preparation determine the coating's thickness, resistance, and adhesion [16]. This work has largely been conducted independently of the degradation studies described above, so the deposition parameters most likely to influence how quickly a coating wears, washes out, or corrodes have not been linked to the failure data produced by those other studies.

A further, related line of work addresses detachable connectors for wearable devices in general. This work has evaluated how many times a connector can be plugged and unplugged, reporting that a few thousand cycles is a common target for wearable connectors and converting that target into an equivalent service life in years [17,18]. It has also examined alternative connector designs, such as spring-loaded pins adapted from other industries [19]. A broader review of connectors for electronic textiles found that connectors designed specifically for this purpose remain rare, and that standards for materials, manufacturing, and durability testing are largely absent [1].

Taken together, these three bodies of work describe at least six distinct ways in which a silver coating can fail in a wearable electronic textile: vibration and fretting, repeated plugging and unplugging, washing, sweat and chloride corrosion, atmospheric exposure, and lint or dust entrapment at the contact. A broader review of aging in conductive textiles has likewise noted that these aging processes are strongly interrelated, and that chemical aging from sweat and washing has been studied far less than mechanical aging [20].

The present review builds on that observation and applies it specifically to silver-coated conductive parts. Each of the six pathways has largely been studied in isolation, using test methods and sample geometries specific to whichever research group first investigated it, without reference to how the underlying coating was fabricated. What has not yet been examined is the extent to which these six pathways converge on a common failure mechanism, whether the coating deposition method alters this picture, and whether a fix developed for one pathway, such as the carbon nanotube coating developed against vibration, could also protect against a pathway studied mainly by a different research community, such as sweat corrosion.

This review addresses that gap. It brings together findings across the six pathways listed above, connects them to the coating deposition literature that determines the silver layer's initial thickness and adhesion, and organizes these findings around a single shared cause: loss of the silver coating and the resulting reduction in working contact points. It shows that two fixes reported independently in the tribology and materials chemistry literature, carbon nanotube coating and a partial gold overcoat, rely on the same underlying principle of adding a second conductive path that remains functional once the underlying silver is depleted, and it catalogs the test standards that already exist, even if only partially, for each pathway. On this basis, the review argues that testing a single stressor at a time, still standard practice across all three research paths, is likely to underestimate how severely a garment degrades in real-world use, where several of these pathways act concurrently, and it outlines directions for developing combined, multi-stress test methods to evaluate the reliability of silver-coated parts in electronic textiles.

1.1. Literature Identification and Screening Criteria

To make the coverage of this narrative review as transparent as possible, the literature was identified through targeted keyword searches of the scientific literature, supplemented by citation chasing from the reference lists of retrieved articles and by the standards catalogues of IEC, ISO, AATCC, and ASTM. Search terms combined the coating material ("silver coating" OR "silver-coated" OR "Ag coating") with the application domain ("electronic textile" OR "e-textile" OR "smart garment" OR "wearable connector" OR "conductive yarn" OR "hook-and-loop" OR "Velcro" OR "snap connector" OR "dry electrode") and the degradation process ("fretting" OR "vibration" OR "wear" OR "corrosion" OR "sulfidation" OR "tarnish" OR "laundering" OR "washing durability" OR "perspiration" OR "sweat" OR "mating cycles" OR "connector durability"). A source was included if it met criteria (i) and (ii), or criterion (iii): (i) it studied a silver-coated, or, for comparison, an alternative-metal-coated, conductive element used, or directly usable, in an electronic textile interface; (ii) it reported at least one quantitative or semi-quantitative outcome relevant to one of the six degradation pathways addressed in this review, namely contact resistance, coating loss, corrosion rate, or connector durability; and (iii) it was a foundational theoretical or standards source directly relied upon by such studies, for example, the electrical contact resistance theory discussed in Section 3.1 or the connector and textile testing standards discussed in Section 7. A source was excluded if it addressed textile conductivity in general without a silver coating, if it addressed silver coatings entirely outside a textile or wearable-connector context, such as catalysis or antibacterial finishing, or if it was a non-peer-reviewed source such as a blog post or an uncurated preprint. As this is a narrative rather than a formal systematic review, exact counts of records identified, screened, and excluded at each stage were not tracked, and no fixed publication-date window was applied; Figure 1 summarizes the identification and screening logic in qualitative terms. The 46 sources retained under these criteria and cited throughout this review comprise the primary research and review articles discussed in Sections 2–6 and the standards documents discussed in Section 7.6.

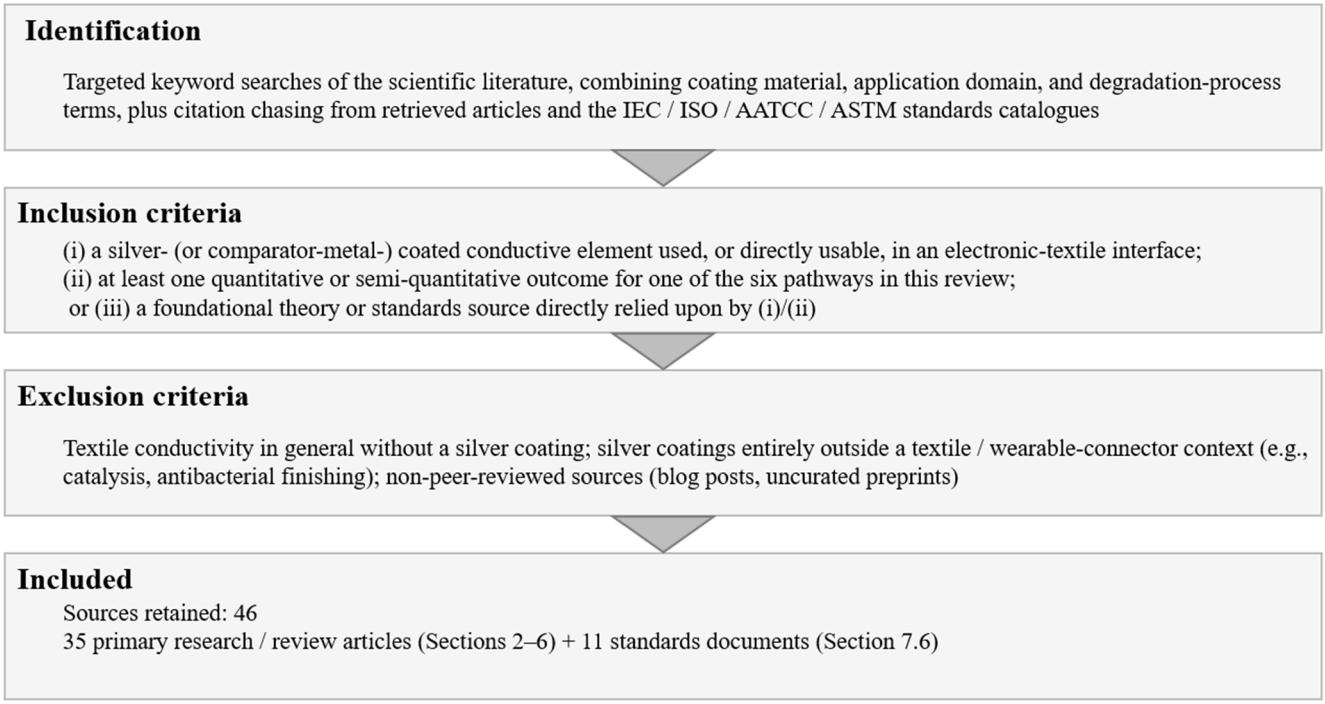


Figure 1. Literature identification and screening logic for this narrative review. This diagram shows the search and eligibility criteria used; because this is a narrative rather than a formal systematic review, intermediate record counts were not tracked, and only the final number of sources retained is reported.

1.2. Terminology

Several related terms are used throughout this review and are defined here to avoid ambiguity. Degradation is used as the general umbrella term for any change that reduces the electrical or mechanical performance of a silver-coated element. Deterioration refers specifically to the underlying physical or chemical change in the coating itself, such as a loss of thickness or a change in surface chemistry, as distinct from its electrical consequence. Aging denotes the cumulative effect of exposure time or cycle count on a sample, independent of which specific pathway is responsible. Damage refers to a discrete, localized change, such as a worn patch or a corrosion pit, that may or may not yet be severe enough to affect function. Failure is reserved for the point at which contact resistance crosses a stated threshold, or conduction is lost entirely, and is used only when a study defines such a threshold explicitly. Service lifetime refers to the exposure time or cycle count required to reach that failure threshold under a given test condition, and is not used interchangeably with the calendar lifetime of a garment. These terms are applied consistently in this sense throughout the abstract, main text, figure captions, and Conclusions; where a cited study used a different convention, this review reports the study's findings using the definitions above rather than the source's original terminology.

2. Silver-Based Conductive Materials in Electronic Textiles: An Overview

2.1. Why Silver Is the Default Coating

Several metals could, in principle, form the conductive components of an electronic textile, including copper, gold, platinum, stainless steel, and silver, yet silver has become the default choice for most flexible conductive coatings. This preference does not simply reflect silver's conductivity; rather, it reflects a trade-off among conductivity, cost, and

chemical stability. Copper is inexpensive and easy to process, and its conductivity per unit volume is comparable to or slightly better than that of silver, but it oxidizes rapidly in air, which raises its surface resistance and typically necessitates an additional tin or silver overcoat, adding cost and offsetting some of copper's price advantage [13]. Stainless steel resists oxidation and withstands washing better than silver-coated yarn, but it is more costly to produce and too stiff for the flexibility a garment interface requires [13]. Gold resists corrosion effectively, but its cost typically limits its use to a thin, partial coating rather than a full conductive layer, a point revisited in Section 6. Silver, by contrast, combines high conductivity with a coating process well suited to fine fibers and fabric surfaces. This combination has made it the default choice across electronic textile components, despite the corrosion problems discussed throughout this review.

2.2. Forms of Silver-Coated Conductive Elements

Silver-coated conductive components take several distinct physical forms in electronic textiles, but they share the same basic construction: a thin silver layer on a non-conductive fiber or fabric substrate.

Conductive yarns. The most common form is silver-plated nylon or polyester fiber, twisted or wrapped into a yarn and then woven, knitted, or embroidered into the textile to form circuit paths or sensing elements [3,15,16]. Because the yarn is integrated into the fabric itself, it bends, stretches, and is washed along with the rest of the garment. A recent review of yarn-based woven interconnects notes that a conductive yarn's electrical performance depends not only on the yarn itself, but also on how it is woven, factors determined during fabric manufacture rather than during coating [21]. This introduces a further, largely untested variable to the deposition comparison in Section 2.4.

Hook-and-loop fasteners. Conductive hook-and-loop fasteners are formed from silver-coated nylon fibers arranged into interlocking hook and loop surfaces. They function both as a mechanical fastener and as a plug-in electrical connector, and have been studied most extensively in the automotive and transport connector literature [6,7].

Dry electrodes. Silver-coated fibers are also used to fabricate dry electrodes, which measure physiological signals such as heart rhythm without a conductive gel. The elastic, hook- or brush-like fiber bundle contacts the skin directly, keeping the coating in constant contact with sweat [13].

Snap and button connectors. Silver- or nickel-plated metal snaps, adapted from conventional garment fasteners, are widely used to attach detachable modules such as sensors and battery packs to a garment, and their plug-in durability has been directly evaluated for wearable applications [17,18].

These four forms differ considerably in shape and purpose, ranging from a fastener repurposed to carry an electrical signal, to a yarn woven into a circuit, to an electrode in direct contact with the skin, yet they share the same basic construction and, as Section 4 explains, the same underlying failure process [1,4]. Table 1 indicates, for each form, which of the six degradation pathways covered in Section 3 apply most directly.

Every cell in Table 1 carries one of the four ratings defined above; no cell is left blank. The Perspiration column warrants brief explanation, since it is not immediately apparent why the dry electrode is rated Yes while the hook-and-loop fastener and the snap/button connector are rated No. Conductive yarn is rated Yes because the electrochemical corrosion measurement reported in Section 3.4 was performed directly on a silver-coated conductive yarn [13]. The dry electrode is likewise rated Yes: Section 2.2 describes it as being in constant, direct contact with sweat on the skin, and it shares the same silver-coated fiber-bundle construction as the yarn tested in [13], so this measurement is treated as directly informative for this element type as well. The hook-and-loop fastener and the snap/button

connector are rated No rather than Partial: exposure to sweat during wear is physically plausible for both, but no perspiration measurement, and no discussion of perspiration exposure, was found for either element type in the studies reviewed in Section 3.

Table 1. How closely each of the six degradation pathways applies to each element type, based on the authors' reading of the literature reviewed here. Yes = directly relevant, with electrical evidence for this specific element type somewhere in this review; Partial = indirect or analogous evidence for this element type; No = physically plausible exposure, but no direct or indirect evidence was found for this element type in the literature reviewed; — = not normally relevant given this element's shape.

Element Type	Fretting/ Vibration	Mating/ Unmating	Laundering	Perspiration	Sulfidation	Debris
Conductive yarn (woven/embroidered)	Yes	—	Yes	Yes	Yes	—
Hook-and-loop fastener	Yes	Yes	—	No	Yes	Yes
Dry electrode	Partial	Yes	—	Yes	Yes	—
Snap/button connector	—	Yes	Partial	No	Yes	—

2.3. A Shared Structural Weakness

In every form described above, electrical current does not flow through a single continuous solid conductor. Instead, it flows through a silver layer only a few micrometers thick, deposited on a non-conductive core, and, at the point of contact, through a small number of microscopic spots where two silver surfaces, or a silver surface and another contact, actually touch [6]. This construction gives rise to two problems that recur throughout Section 3. First, because the silver layer is thin, removing or chemically altering even a small fraction of its thickness can interrupt the conduction path. Second, because conduction depends on a limited number of discrete contact spots rather than a continuous solid surface, anything that reduces the number or quality of these spots, whether through mechanical wear, corrosion, or trapped debris, produces a resistance rise disproportionate to the small area actually affected. It is this shared structural weakness, rather than any single stressor, that motivates the pathway-by-pathway review in Section 3 and the convergence argument developed in Section 4.

2.4. How the Coating Is Applied, and Why It Matters

The six degradation pathways discussed in Section 3 do not act upon a uniform coating. The thickness, adhesion, and microstructure of the silver layer, all determined by the deposition method, likely influence how quickly each pathway inflicts damage. This connection has not been addressed in Sections 2.1–2.3, nor, to the authors' knowledge, in the pathway-specific studies reviewed in Section 3, yet it represents a natural link between the six pathways and the coating-science literature on silver deposition.

Electroless plating is the most common method for depositing silver on textile fibers, because it requires no conductive base to initiate and can coat a fiber's entire surface rather than only one exposed face. The process typically begins with a seeding step, in which a reducing agent such as tin(II) forms silver seed particles on the fiber, followed by continued chemical buildup of the coating from a silver salt [16]. The resulting resistance is highly sensitive to bath strength and reaction time; resistance per unit length has been reported to range from approximately 3 to 70 ohms per centimeter depending on silver concentration alone [16]. How well this layer adheres to the fiber is itself a variable that subsequently affects resistance to several of the pathways discussed in Section 3: pretreatments that roughen the fiber surface, or add supplementary bonding sites for the seed layer, have

been reported to improve adhesion through a physical anchoring effect, whereby the silver becomes mechanically interlocked with the roughened surface rather than adhering through chemical bonding alone.

Sputtering and other physical vapor deposition methods, by contrast, produce thinner, more uniform coatings on the exposed portion of a fiber, but because they coat only what lies within a direct line of sight, they cannot fully coat the far side of a yarn or the inner fiber-to-fiber contacts within a woven or braided structure. This limitation is directly relevant to the hook-and-loop fastener discussed in Sections 3.1 and 3.2, since its conduction path depends on contact at the tips and shanks of the hook and loop fibers, locations that a line-of-sight process may coat unevenly compared with a solution-based electroless process.

These fabrication-level differences are expected to connect to the degradation pathways reviewed in Section 3 in specific, testable ways, although no study reviewed here has directly examined this connection. Weak adhesion arising from insufficient anchoring during electroless plating should, in principle, aggravate fretting wear (Section 3.1), because a poorly anchored coating is more readily removed by the same sliding contact that a well-anchored coating would merely burnish; this remains plausible reasoning rather than direct evidence, since the fastener studied in [6,7] used a manufacturer-applied coating whose adhesion was not reported, and it is proposed in Section 7.5 as a testable factorial variable rather than as an established result. Coverage defects and gaps left by a line-of-sight process such as sputtering are expected to serve as initiation sites for both mechanical fretting wear and chemical attack, since an exposed or thin patch of the underlying fiber or seed layer would be the first point at which either sliding contact or chloride and sulfur exposure could penetrate to bare fiber; this reasoning links the coverage limitation discussed above directly to the perspiration corrosion data in Section 3.4 and the sulfidation discussion in Section 3.5, where coating coverage is not reported for any of the studies cited. When degradation data are cited pathway by pathway in Section 3, the corresponding fabrication conditions, where reported at all, are noted again to keep this fabrication-to-degradation link visible rather than leaving Section 2.4 as a self-contained aside.

Figure 2 illustrates this idea through a simplified cross section: a single-layer silver coating loses its conduction path entirely wherever the coating is worn, corroded, or blocked, whereas a coating supplemented by a second conductive network can maintain a conduction path across that same damaged spot. This schematic is an original illustration prepared by the authors for this review and does not reproduce material from another source.

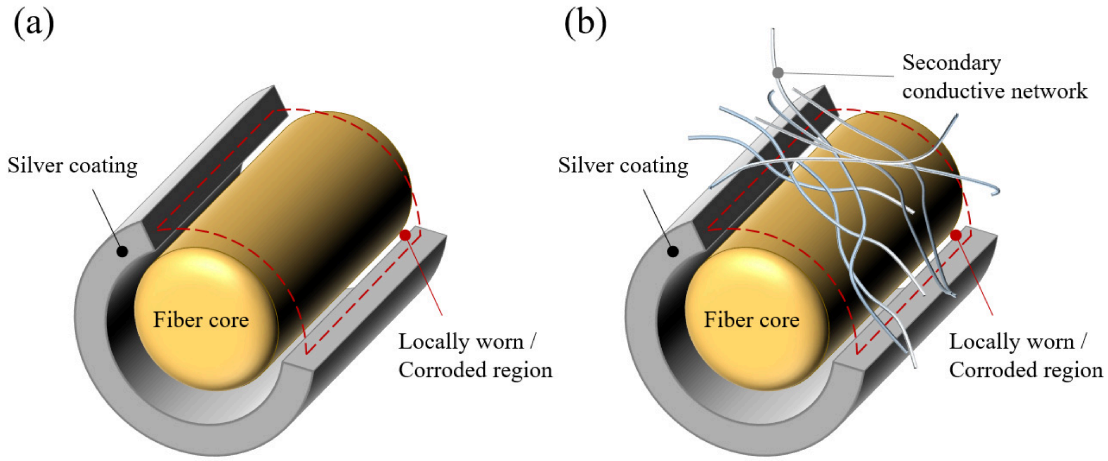


Figure 2. Cross section of a coated fiber, comparing (**a**) a single-layer silver coating, where a worn or corroded spot breaks the conduction path, with (**b**) a coating backed up with a second conductive network, where the same worn spot is bridged.

Table 2 compares the deposition methods described above, together with the ready-made silver-coated nylon used in the hook-and-loop studies reviewed in Section 3, on the points most relevant to the pathways discussed subsequently.

Table 2. Comparison of representative silver coating deposition methods for conductive textile bases.

Method	Typical Resistance	Adhesion	Coverage of 3D Fiber Shape	Source
Electroless plating (chemical reduction)	About 3–70 Ω/cm, tunable via bath strength and time	Chemical bonding; improved by roughening pretreatments ("anchoring effect")	High; solution coats the full fiber surface	[16]
Ready-made silver-coated nylon (hook-and-loop base)	Sub-ohm contact resistance under low-frequency test conditions	Manufacturer-applied coating; adhesion not separately reported	High on exposed hook and loop surfaces	[6]
Sputtering/physical vapor deposition (general)	Thinner, more even films; usually higher process cost	Physical bonding; adhesion strongly depends on the base material	Limited; line-of-sight process under-coats fiber-to-fiber contacts	General coating-science principle (see Section 2.4)

3. Single-Stressor Degradation Pathways: A Literature Review

This section reviews the evidence for each of the six degradation pathways identified in Section 1, drawing on tribology, materials chemistry, coating science, and wearable connector engineering. Each pathway is addressed individually here, consistent with how it has been studied in the source literature; Section 4 then examines the extent to which these separately reported pathways point to a common underlying failure. Table 3 summarizes the evidence reviewed in this section.

Table 3. Summary of the six degradation pathways reviewed in Section 3.

Pathway	Main Loading Type	Key Study	Measurement Technique	Key Quantitative Finding	Evidence Strength (Basis)
Mechanical fretting and vibration	Sideways slip under low-frequency vibration	[6,7]	In situ contact-resistance measurement during vibration; coating loss confirmed by microscopy and X-ray analysis	Resistance peak near 7–10 Hz; about 97% lower with carbon nanotube coating	Direct—resistance and coating loss measured together on the actual hook-and-loop fastener
Repeated mating and unmating	Repeated normal separation	[17–19,22]	Cycle-count durability benchmarks for snap/magnetic connectors [17–19]; direct resistance monitoring during 10,000 fastening cycles reported for snap fasteners specifically [22]	About 5000 cycles is a common benchmark, equal to about 6.8 years of use	Indirect—durability data mainly from analogous snap/magnetic connectors; only [22] measures resistance directly, and not on a hook-and-loop fastener
Laundering	Combined mechanical agitation and moisture	[10–12]	Contact/sheet resistance measured before and after standardized home-washing cycles	Resistance rose 100–300% over 50 wash cycles	Direct—resistance measured on the actual coated yarns/electrodes across wash cycles

Table 3. *Cont.*

Pathway	Main Loading Type	Key Study	Measurement Technique	Key Quantitative Finding	Evidence Strength (Basis)
Perspiration and chloride corrosion	Electrochemical reaction with Cl^-	[13]	Electrochemical (potentiodynamic) measurement of yarn conductance under controlled chloride/sweat exposure	Conductance lost within 2.7 h; extended to 192 h with a gold overcoat	Direct—resistance/conductance measured directly under controlled chloride exposure
Atmospheric sulfidation	Slow chemical reaction with airborne sulfur	[15]	Resistance change attributed qualitatively to sulfidation as a co-factor within wash-cycle testing; not isolated experimentally	Named as a co-factor in wash-cycle resistance rise, not isolated	Indirect—identified only as a co-factor within laundering studies, not isolated or independently measured
Fiber and debris entrapment	Physical blocking of contact spots	None found	No electrical measurement identified in the literature reviewed	No electrical measurement found in the literature reviewed	Reasoned only—mechanistic argument, no electrical data

3.1. Mechanical Fretting and Vibration

The pathway with the strongest evidence is contact resistance loss under low-frequency vibration, studied primarily in the context of automotive and industrial connectors. This general phenomenon, in which vibration induces small sliding movements between mated contacts that generate wear debris and an insulating oxide layer, has been documented for tin-plated automotive connectors with no textile involved at all, with resistance rising sharply once wear debris accumulates past a threshold at the contact [23]. Using a purpose-built micro-sliding tester, one study demonstrated that a silver-coated nylon hook-and-loop fastener exhibits a pronounced resistance rise within a frequency band of approximately 7 to 10 Hz at low sliding distance, an effect attributed to the fastener's own structural resonance and confirmed through separate accelerometer testing [6]. As Table 2 shows, the coating used in this study was a ready-made, manufacturer-applied silver-coated nylon whose adhesion was not separately reported, so the coating-adhesion link proposed in Section 2.4 cannot be verified directly against this dataset and is noted here as an open gap rather than a resolved question. After 100,000 vibration cycles at this amplitude, microscopy and X-ray analysis revealed localized removal of the silver coating from the hook and loop surfaces, most pronounced near the resonance frequency.

The lumped-circuit model employed in [6] to describe the distribution of microscopic contact spots builds on an established line of electrical contact theory, beginning with a model of constriction resistance at rough surfaces [8] and later extended to statistical distributions of contact spots [9], nanoscale contact spots [24], clustered contact spots [25], and multiscale contact resistance in fuel cell plates [26]. This body of theory establishes that contact resistance depends not on the overall contact area, but on the number, size, and distribution of the microscopic contact spots, the same principle underlying the shared structural weakness discussed in Section 2.3 and reiterated across all six pathways in this section.

A follow-up study showed that coating the same fastener with carbon nanotubes reduced resistance to a narrow band of 0.04 to 0.06 ohms, largely unaffected by frequency or vibration distance, representing an improvement of approximately 97% over the uncoated case, and attributed this effect to lubrication and vibration damping provided by the nanotube layer [7]. Together, these studies make fretting and vibration the best-quantified

pathway among the six, with both the resistance response and an effective mitigation measured in detail and supported by an established theory of electrical contact.

3.2. Repeated Mating and Unmating

A separate line of work examines how well wearable connectors withstand repeated plugging and unplugging, a loading type distinct from vibration in that it is driven by pulling the parts directly apart rather than sliding them laterally. One study reported that five thousand mating and unmating cycles is a common benchmark for detachable wearable connectors [17], and a companion study converted this into approximately 6.8 years of use, assuming two matings per day, noting that this exceeds a garment's typical one-to-three-year service life [18]. These studies, conducted mainly on snap and magnetic connectors rather than hook-and-loop fasteners, found that spring-loaded contacts withstand repeated mating better than rigid contacts, because their compliance absorbs small misalignments. A related study evaluated a spring-finger magnetic connector, adapted from another industry, for reliability under repeated use in electronic textiles [19]. In a further study conducted under realistic human movement rather than bench testing, researchers compared spring, screw, and magnetic snap fasteners mounted on a garment during walking and rope jumping, finding that magnetic fasteners maintained stable electrical contact under rapid movement, whereas spring-based snaps exhibited movement-related resistance spikes [27]; this is one of the few studies identified in this review that combines a mechanical stressor with a realistic use scenario, a point revisited in Section 5. Directly testing the mating cycle itself, another study subjected sewn-on snap fasteners to 10,000 rounds of fastening, unfastening, and current interruption, finding that unfastening force decreased with cycling, more markedly for larger snaps, while fastener size had little effect on electrical durability [22]; to the authors' knowledge, this is the only study reviewed here that directly measures resistance change over a large number of mating and unmating cycles for any textile fastener, though it did not measure silver coating loss in the manner of [6] for fretting, so it remains unclear whether the same wear mechanism applies. No study identified in this review, including these two, has directly measured how repeated mating and unmating affects the silver coating of a hook-and-loop fastener specifically, so it remains unclear whether the coating-loss process observed for fretting in Section 3.1 applies equivalently under this different loading type.

The 5000-cycle mating-and-unmating benchmark used in this section is also an order of magnitude smaller than the 100,000-cycle vibration protocol used for fretting in Section 3.1, and this discrepancy warrants comment rather than passing without remark. Part of the gap reflects loading rate rather than severity: a vibration test conducted at several hertz for a fixed duration accumulates cycles far more rapidly than a mating test performed manually or by a mechanical actuator that must fully separate and re-seat the contact each time, so the two cycle counts do not measure comparable amounts of elapsed real-world exposure. The gap may also reflect a difference in failure criteria between the two loading types: the fretting studies in Section 3.1 define failure through a specific resistance threshold tied to coating loss confirmed by microscopy, whereas the mating-and-unmating benchmark in [17,18] is a durability target carried over from general connector practice rather than a threshold derived from a measured resistance rise on a hook-and-loop sample specifically. Consequently, the two cycle counts should not be interpreted as directly comparable severity measures, and this review does not treat the order-of-magnitude difference as evidence that one loading type is inherently more damaging than the other.

3.3. Laundering

Laundering durability has been studied extensively for silver-coated yarns and electrodes integrated into fabric, motivated by the basic requirement that a smart garment withstand ordinary home washing. One study found that damage after washing tends to concentrate at connection points, such as solder joints and connectors, rather than within the circuit base itself, and identified laundering durability as a central reliability concern for circuits permanently attached to textiles [10]. Another study found that the area of silver coating detached from a conductive yarn increased steadily with the number of wash cycles, attributing this to mechanical rubbing between fabric layers during washing [11]. A further study quantified this effect directly, reporting a 100 to 300% resistance rise in silver-based textile electrodes over 50 wash cycles, and identified both sulfidation and mechanical wear as contributing causes, a dual explanation that connects this pathway to the atmospheric-exposure pathway discussed in Section 3.5 [15]. Another study documented similar resistance changes in silver-plated textile electrodes across repeated washing [12]. Using a different conductive material, one study found that carbon-nanotube-based conductive inks for electronic textiles also lose conductivity progressively over combined washing and rubbing cycles, indicating that sensitivity to laundering-related mechanical damage is not unique to silver coatings, even though the underlying loss mechanism differs, coating detachment for silver versus binder breakdown for a nanotube ink [28]. Washing methods across the studies reviewed in this section are not fully standardized; an international standard specifies reference home washing and drying procedures for textile testing in general [29], but none of the studies reviewed here reported testing against this reference standard specifically, a point revisited in Section 7.

3.4. Perspiration and Chloride Corrosion

A chemically distinct pathway arises from direct contact between the silver coating and sweat, which is rich in chloride ions. The reaction of silver with chloride ions to form silver chloride, and the subsequent loss of this corrosion product into the surrounding fluid, is a well-studied electrochemical process outside the textile field as well, having been examined in detail for the silver/silver-chloride reference electrode used in laboratories [30]. One study demonstrated electrochemically that this same reaction, occurring at the surface of a silver-coated conductive yarn, causes a complete loss of electrical conductance within 2.7 h of exposure [13]. The same study showed that a partial gold overcoat, applied only along the length of the yarn rather than around its full circumference, maintains a lengthwise conduction path until the silver beneath the gold is fully depleted, extending the conducting lifetime to 192 h despite a measured increase in corrosion rate; this finding is discussed further as a shared mitigation strategy in Section 6. A related study found that fabric exposed to sweat develops a surface layer of silver chloride and silver oxide, becoming rougher and more hydrophilic, and that surface resistance rose steadily with the combined number of sweat exposures and wash cycles, although short-term conductance was occasionally increased by the release of silver ions [14]. This latter finding suggests that the direction of resistance change under sweat exposure may depend on exposure duration, and should be read with this caveat when invoked to support a simple, one-way narrative of degradation. Focusing specifically on the joint rather than the coating itself, one study evaluated soldered and glued joints on conductive textile ribbons using both acidic and alkaline artificial sweat, finding that joints soldered to interwoven conductive fibers withstood sweat-driven resistance change best, while adhesive bonding, though more compatible with textile flexibility, proved more susceptible to sweat aging [31]; this indicates that the choice of joining method between a coated conductor and a rigid component is

itself a factor in sweat-corrosion resistance, in addition to the coating chemistry addressed in [13].

3.5. Atmospheric Sulfidation

Silver is well known to tarnish through reaction with trace sulfur compounds present in ordinary air, a process relevant to electronic textiles that remain in storage, rather than being worn, for extended periods, as with seasonal clothing. This tarnishing reaction, in which silver reacts with hydrogen sulfide and related airborne sulfur compounds to form a silver sulfide layer, has been studied extensively for bulk silver and silver alloys, where the sulfide layer is known to grow at a rate dependent on humidity, alloy composition, and airborne sulfur concentration [32,33]. One such study further demonstrated, using electrochemical impedance spectroscopy, that even a small quantity of a second metal alloyed with silver can alter the tarnishing rate and the location of the most severe attack, indicating that a coating's composition, not merely its exposure conditions, likely affects the rate at which sulfidation proceeds [33]. Within the electronic textile literature specifically, however, this pathway has not been studied independently of washing; rather, one study identified sulfidation as one of two principal contributors, alongside mechanical wear, to the resistance rise observed over repeated wash cycles, without disaggregating their relative contributions [15]. Atmospheric sulfidation therefore remains, within the electronic textile literature specifically, a suspected but not independently measured pathway, even though the underlying chemistry is well established in the broader corrosion literature, a point revisited in Section 5.

3.6. Fiber and Debris Entrapment

It is a well-known characteristic of hook-and-loop fasteners in everyday use that the hooks trap lint, hair, and other fiber debris; mechanistically, this debris is expected to lodge between the hook and loop surfaces as a non-conductive layer, reducing the number of working contact spots at the interface. However, no study identified in the course of this review has measured the effect of such trapped debris on the electrical contact resistance of a conductive hook-and-loop fastener specifically. This pathway is therefore included in the synthesis in Section 4 on reasoned grounds alone, and is explicitly flagged as the pathway with the least evidence among the six, and, correspondingly, as a priority for future measurement.

3.7. Study-by-Study Comparison of Sample and Test Conditions

Sections 2.4 and 3.1–3.6 repeatedly note that silver coating thickness, deposition method, fiber or connector substrate, and test conditions vary from study to study, which is precisely the basis for the argument, developed further in Section 7, that standardized testing is needed. Table 4 renders this heterogeneity explicit by summarizing, for the key studies underlying each pathway, the coating and substrate details as reported in the source, the stress type and loading parameters used, the environmental medium, and the evaluation metric. As the table shows, most of the studies reviewed here do not report coating thickness or deposition method at all, environmental media range from dry laboratory air to chloride solution to combined sweat and laundering, and evaluation metrics are inconsistent even within a single pathway. This heterogeneity means that a resistance value reported in one study cannot be directly compared with one from another without knowing whether the underlying coatings, substrates, and exposure conditions were even broadly similar, which substantiates the case made in Section 7.6 for standardized sample and reporting practices.

Table 4. Sample parameters and test conditions reported for the key studies behind each of the six degradation pathways, illustrating the heterogeneity that motivates the standardization recommendations in Section 7.

Study	Element Type	Coating/Substrate (as Reported)	Stress Type and Loading Parameters	Environmental Medium	Evaluation Metric
[6,7]	Hook-and-loop fastener	Ready-made silver-coated nylon (manufacturer-applied); coating thickness and deposition method not reported	Low-frequency sliding vibration, 7–10 Hz resonance band, up to 100,000 cycles	Ambient laboratory air; dry (no sweat or moisture)	Contact resistance (Ω); microscopy and X-ray inspection of coating loss
[13]	Conductive yarn	Electroless silver coating; thickness not reported; fiber base not specified	Static immersion/electrochemical exposure to a chloride-containing solution, up to 192 h (with Au overcoat)	Chloride solution (sweat-simulant electrolyte)	Electrochemical conductance loss; time to loss of conduction (h)
[14]	Silver-coated fabric	Silver coating; thickness and deposition method not reported; fabric construction not specified	Combined, repeated perspiration exposure and home laundering; exact cycle schedule not fully specified in the source	Artificial sweat plus home laundering	Surface resistance (Ω); SEM/XRD evidence of AgCl and Ag_2O formation
[15]	Conductive yarn	Silver coating; thickness not reported	Home laundering, 50 wash cycles	Wash bath (mechanical agitation + moisture)	Resistance rise (%) over wash cycles
[11]	Conductive yarn (knitted, with POF)	Silver-coated yarn; thickness and deposition method not reported	Home laundering; wash-cycle count not specified in the reviewed text	Home laundering	Detached-coating area (microscopy); resistance
[12]	Silver-plated textile electrode	Silver plating; thickness not reported	Repeated home laundering; cycle count not specified in the reviewed text	Home laundering	Resistance change over wash cycles
[17,18]	Snap/magnetic connector	Silver- or nickel-plated metal snap (Section 2.2); coating thickness not reported	Repeated mating and unmating, 5000-cycle benchmark	Ambient laboratory air; dry	Cycle count converted to an equivalent service-year estimate
[22]	Sewn-on snap fastener	Silver- or nickel-plated metal snap; coating thickness not reported	Repeated fastening, unfastening, and current interruption, 10,000 cycles	Ambient laboratory air; dry	Unfastening force (N); electrical resistance/current interruption

Two patterns emerge from Table 4. First, no study reviewed here reports silver coating thickness quantitatively for the specific sample tested, even though Section 2.4 establishes that thickness generally affects resistance and adhesion; deposition method is reported only in general terms, if at all, for most entries. Second, the environmental medium employed ranges from entirely dry (fretting and mating studies) to a chloride solution (perspiration studies) to combined sweat and laundering (Ref. [14]), such that even the three pathways with the strongest direct evidence (Sections 3.1, 3.3 and 3.4) were never tested on samples prepared and characterized in the same way. This sample-level heterogeneity, distinct from the single-stressor-versus-combined-stressor gap discussed in Section 5, is itself a barrier to comparing pathways quantitatively and is addressed directly by the standardized sample and reporting recommendation in Section 7.6.

3.8. Summary

The six pathways reviewed above differ considerably in how thoroughly they have been characterized. Fretting and vibration (Section 3.1) and laundering (Section 3.3) are covered most comprehensively, each supported by several independent studies with consistent trends and, for fretting, a specific, effective mitigation grounded in an established theory. Perspiration corrosion (Section 3.4) is supported by mechanistic and quantitative evidence from a small group of related studies, with one study raising a caveat regarding the direction of short-term resistance change. Repeated mating and unmating (Section 3.2) is well studied for connectors in general but not specifically for hook-and-loop fasteners. Atmospheric sulfidation (Section 3.5) has been identified only as a co-occurring factor within laundering studies, and fiber and debris entrapment (Section 3.6) remains, for now, a plausible but electrically unmeasured mechanism. Despite this uneven evidence base, Section 4 argues that all six pathways are consistent, at the mechanistic level, with the same underlying process, namely a reduction in the number of working contact spots at the silver interface, though, as the final paragraph of Section 4 makes explicit, this remains a working hypothesis that is strongly evidenced for three of the six pathways and not yet directly evidenced for the remaining three.

4. Convergence on a Common Failure Mode

The six pathways reviewed in Section 3 differ considerably in loading type, environment, and timescale: mechanical fretting operates through lateral slip under vibration; repeated mating and unmating operates through repeated straight-apart separation; laundering operates through combined mechanical agitation and moisture; perspiration corrosion operates through an electrochemical reaction with chloride ions; atmospheric sulfidation operates through a slow chemical reaction with trace sulfur compounds; and fiber entrapment operates through a foreign, non-conductive material becoming physically lodged in the joint. Despite this diversity, every pathway examined in Section 3 acts upon the same physical target, namely the thin silver coating and the set of microscopic contact spots through which it conducts (Section 2.3), and every pathway is expected, or, for three of the six, has been shown directly, to produce the same immediate outcome: fewer or degraded contact spots and a corresponding rise in contact resistance, as summarized in Figure 3.

The color of each ellipse indicates the evidence type given in Table 3, and the key study or studies underlying each pathway's classification are printed beneath its label, corresponding to the Key Study column of Table 3; no citation is given for fiber and debris entrapment, since no study measuring this pathway electrically was identified in the literature reviewed. As the mixture of colors indicates, this convergence is a working

hypothesis, strongly supported for three pathways and less so for the remaining three, a distinction revisited in the final paragraph of this section.

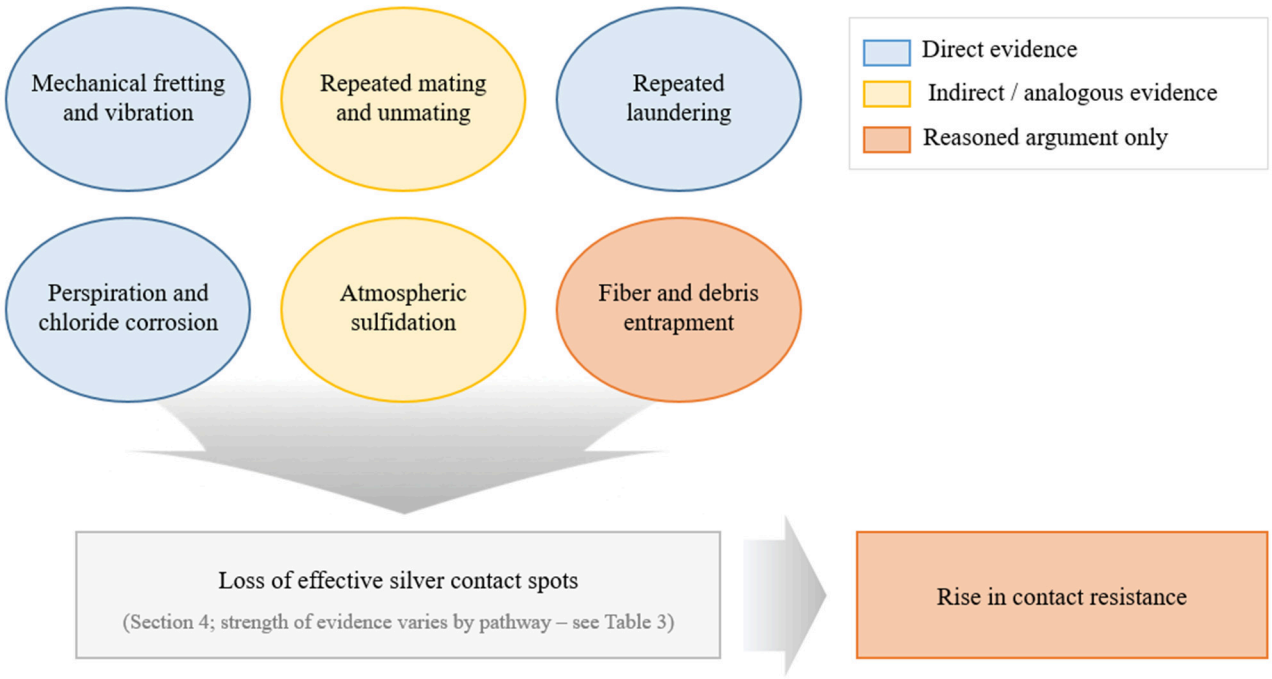


Figure 3. How the six degradation pathways are consistent with one failure mode: loss of working silver contact spots and the resulting rise in contact resistance.

This convergence is stated explicitly in several of the studies reviewed above. Two related studies traced the resistance rise observed under fretting directly to loss of the silver coating at the contact [6,7]. One study reported that the area of detached silver coating increased with laundering cycles [11]. Another traced the loss of conductance under sweat exposure to the formation and subsequent loss of silver chloride from the coating surface [13]. A further study attributed the resistance rise under repeated laundering to the combined action of sulfidation and mechanical wear, both of which act by removing or chemically altering silver at the surface [15]. In each case, the reported mechanism represents a variant of the same underlying process: material is removed from, or chemically altered at, the silver interface, and the number of electrically functional contact spots declines.

The magnitude and timescale of this convergence can be compared directly for the three pathways with the strongest quantitative evidence, together with the two mitigation strategies discussed further in Section 6. Figure 4 places these on a single logarithmic time axis; because two of the five values represent the authors' unit conversions rather than measurements on a common time base, Figure 4 marks the converted values with an asterisk and an indicative uncertainty range rather than presenting them as directly comparable measurements.

Each bar is labeled with its source reference number directly on the chart. The perspiration-corrosion and gold-overcoat values (light blue and yellow bars) are as directly reported in the source study [13]. The fretting/vibration values (light blue and green bars) represent the authors' own conversion to an hourly time base from the vibration-cycle data in [6] (uncoated) and [7] (CNT-coated), assuming continuous vibration at the reported test frequency, and the laundering value is converted from the wash-cycle data in [15], assuming a typical wash cycle requires approximately 1 h; these conversions were not stated this way in the original studies, so the converted values are marked with an asterisk,

and the error bars shown for them represent an indicative two-fold range rather than a measured uncertainty, intended only to indicate that they should not be read as being as precise as the two directly reported values. The carbon-nanotube case is shown as a lower bound, because that study ran for 24 h without observing failure, rather than measuring an exact failure time.

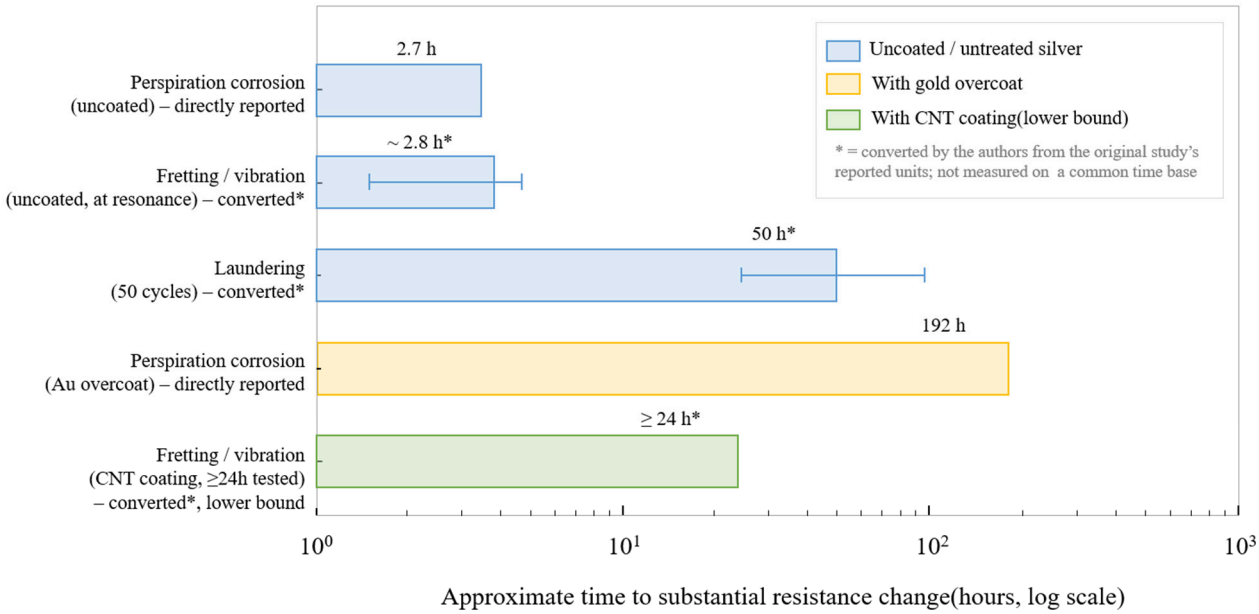


Figure 4. Approximate time to a substantial resistance change for the pathways with the strongest direct evidence, and for their reported fixes. This is an original chart prepared by the authors from the cited sources.

Two conclusions follow from Figure 4. First, once placed on a common time axis, the three uncoated or untreated pathways cluster within roughly one order of magnitude of each other, from approximately 2.7 to 50 h, despite arising from entirely different physical causes; this supports the convergence argument developed in this section by demonstrating that the pathways are not merely similar in mechanism, but also broadly comparable in the time required to produce a substantial resistance rise. Second, both reported mitigation strategies extend this timescale by roughly an order of magnitude or more, consistent with the shared-fix concept examined in Section 6, although the comparison in Figure 4 spans two different pathways and should not be interpreted as evidence that either fix would perform equally well against the other pathway's stressor.

Treating these pathways as a connected whole, rather than as unrelated findings scattered across the literature, carries two consequences that shape the remainder of this review. First, it suggests that a mitigation strategy shown to be effective against one pathway may plausibly be effective against another, provided it targets the shared underlying weakness rather than a symptom specific to one pathway; this idea is examined in Section 6, where two independently developed fixes are shown to rely on the same design principle. Second, it implies that testing pathways individually, standard practice in both the tribology and materials chemistry literature reviewed in Section 3, may not fully characterize how a component behaves in service, where it is exposed to several of these pathways simultaneously or in close succession; this concern is developed in Section 5.

At the same time, the strength of evidence underlying this convergence is not uniform across pathways. Fretting, laundering, and perspiration corrosion are each supported by direct measurement of silver loss and its electrical consequences. Repeated mating and unmating is supported by durability data for wearable connectors in general, but not by

silver-coating-loss data specific to a hook-and-loop interface. Atmospheric sulfidation is only suggested as a co-factor within laundering studies, rather than measured independently. Fiber entrapment is supported only by reasoned argument. The convergence argued for in this section should therefore be read as a working hypothesis, well supported for three of the six pathways and requiring additional evidence for the other three, rather than as an established fact applicable equally to all six.

5. Why Single-Stressor Testing Is Not Enough

Every study reviewed in Section 3 tested its respective pathway in isolation: fretting studies applied vibration to an otherwise untouched sample; laundering studies conducted wash cycles without an accompanying vibration load; and sweat studies applied an electrolyte without accompanying washing or mechanical load. This isolation represents a reasonable and necessary starting point for identifying a single mechanism, and the studies reviewed here accomplished this well. It is a considerably weaker basis, however, for predicting how a silver-coated part will behave in actual use, where several of these pathways are likely to act concurrently or in close succession: a garment worn during exercise is flexed and agitated while simultaneously exposed to sweat, and is subsequently washed while the coating may already be damaged by both stressors. Figure 5 summarizes, across every pair of the six pathways, the extent to which this combined stress space remains untested.

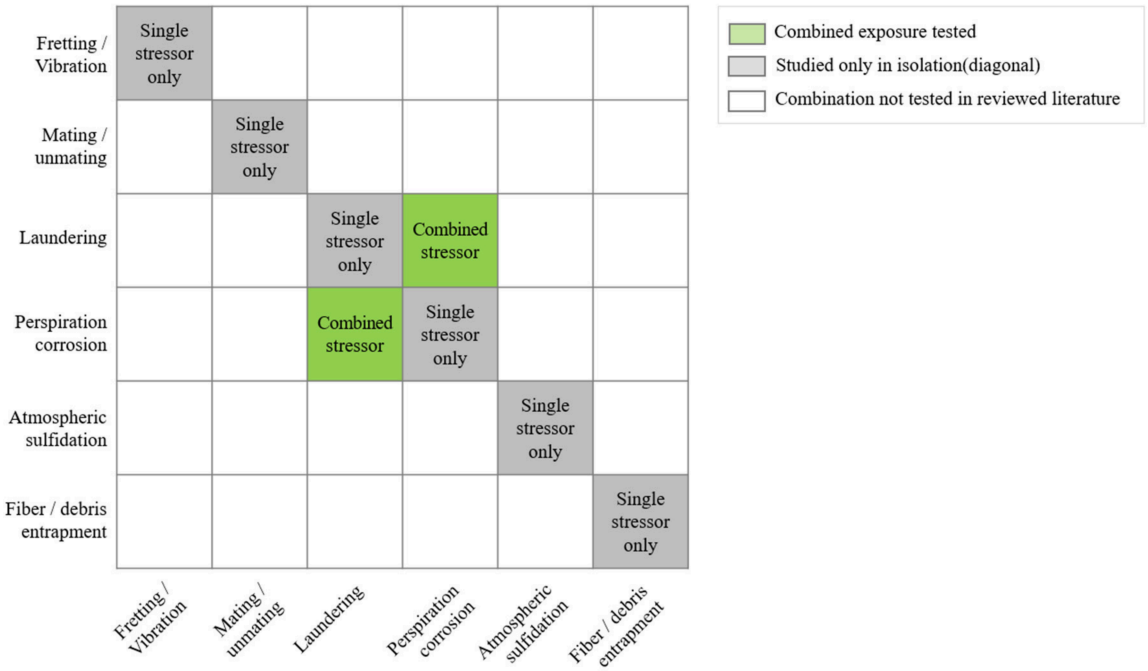


Figure 5. Grid of pairwise combinations among the six degradation pathways, showing that only one combined-exposure condition, laundering combined with perspiration corrosion, has been tested in the literature reviewed in Section 3.

The gray diagonal cells, each studied only in isolation, are supported by the key studies identified in Table 3 for that pathway: fretting/vibration [6,7], mating/unmating [17–19,22], laundering [10–12,15], perspiration corrosion [13,14], and atmospheric sulfidation [15]; no diagonal citation is given for fiber/debris entrapment, consistent with Table 3, since no electrical measurement for that pathway was identified in the literature reviewed. In the single green cell, Ref. [14], the two stresses were applied sequentially and repeatedly, alternating blocks of sweat exposure with laundering cycles on the same samples, rather than simultaneously; this distinction matters mechanistically, since sequential exposure

allows each stressor to act on a surface already modified by the other, whereas simultaneous exposure would test their instantaneous interaction.

The clearest illustration of why this matters, within the literature reviewed here, comes not from an external field, but from a study that already moves beyond strict single-stress testing. One study examined the combined effect of sweat exposure and laundering on the same silver-coated fabric, reporting a more complex pattern than a simple summation of the two separately reported effects would suggest: sweat exposure was linked to silver chloride and silver oxide formation and, in some cases, a short-term rise in conductance from released silver ions, while surface resistance rose steadily as the number of combined exposures accumulated [14]. Considered independently, the perspiration-corrosion study in [13] predicts a steady, relatively rapid loss of conductance, whereas the laundering studies reviewed in Section 3.3 predict a slower, cycle-dependent resistance rise. Neither prediction, taken alone, anticipates the mixed short-term and long-term pattern that emerged once the two exposures were combined. This single example of combined-exposure testing in the reviewed literature demonstrates, using directly relevant evidence rather than an analogy to an unrelated field, that the trajectory of degradation under combined stressors cannot simply be inferred from the separate single-stress results, even when both contributing pathways are individually well studied.

No study identified in this review tested mechanical fretting or vibration together with either laundering or sweat exposure, even though both represent everyday, overlapping conditions for any garment worn during physical activity. This constitutes a genuine gap, clearly evident in Figure 5. Mechanical wear and chemical corrosion are plausible candidates for mutual aggravation, in either direction: fretting-driven removal of the silver coating could expose fresh, unprotected silver to accelerated chloride attack, while chloride corrosion could roughen the coating surface and alter the distribution and area of the microscopic contact spots on which the fretting resistance model in [6] is based, potentially shifting the frequency response reported there. Neither direction has been tested.

This gap is notable because combined-stress testing is not a novel concept in connector engineering more broadly. A widely used international standard series for testing electronic and electromechanical connectors specifically provides for combined climatic and mechanical stress tests, on the stated rationale that real operating conditions rarely involve a single stressor alone [34]. The fact that this principle is already embedded in mainstream connector standards, yet has not been applied to any of the six pathways reviewed in this paper for silver-coated textile interfaces specifically, suggests that the gap identified in this section reflects the need to apply existing know-how to a new setting, rather than a broader absence of methods in connector engineering.

Two additional limitations compound this gap. First, the samples and coating parameters used across the studies in Section 3 are not standardized; silver coating thickness, deposition method, and fiber substrate vary from study to study, as shown by the range of deposition methods compared in Table 2, making it more difficult to combine findings from separate single-stress studies even in a rough, qualitative manner. Second, as a broader review of electronic textile connectors has noted, standardized test methods and reporting practices remain largely absent from this field [1], a deficiency that applies with particular force to the combined-exposure conditions discussed here, for which no standardized protocol yet exists. Section 7 returns to this point with specific recommendations, including a list of existing single-pathway standards.

6. Convergent Mitigation Strategies

6.1. Two Fixes Developed Independently

Against this background of largely separate, pathway-specific research, one finding emerges independently in two otherwise unrelated studies and merits closer examination, as it points to a general design principle rather than a fix specific to a single pathway. Working within the fretting and vibration literature reviewed in Section 3.1, one study found that coating a conductive hook-and-loop fastener with carbon nanotubes reduced contact resistance to a stable 0.04 to 0.06 ohms, largely unaffected by vibration frequency or amplitude, and attributed this to two mechanisms: the nanotubes provided an additional conduction path at locations where the underlying silver coating had already worn away, and they provided lubrication and damping that reduced further mechanical wear of the silver itself [7].

Working independently within the perspiration-corrosion literature reviewed in Section 3.4, another study found that a partial gold overcoat, applied along the length of a silver-coated conductive yarn rather than around its full circumference, extended the electrical conducting lifetime under chloride exposure from 2.7 h to 192 h [13]. The reported mechanism was structurally analogous to that of the carbon nanotube coating: the gold overcoat provided a continuous lengthwise conduction path that remained functional even as the underlying silver was progressively depleted by corrosion, with failure occurring only once the silver along the entire length had been consumed. Table 5 compares the two mitigation strategies directly.

Table 5. Comparison of the two shared fix strategies found in the reviewed literature, evaluated across a common set of dimensions so that a shared design concept is not allowed to obscure the differences in how, and under what stress, each strategy has actually been validated.

Strategy	Pathway First Tested Against	Second Material	Mechanism	Effect on Flexibility/ Wearability	Relative Processing Cost	Reported Improvement	Cross-Pathway Validation Status
Carbon nanotube coating [7]	Fretting and vibration	Multi-walled carbon nanotubes	Extra conduction path at worn spots; lubrication and damping	Adds a thin outer nanotube layer; reported to preserve the fastener's hook-and-loop mechanical engagement, though flexibility was not separately quantified [7]	Low-to-moderate (solution coating step added to an existing fastener)	Resistance held at 0.04–0.06 Ω (about 97% lower)	Validated only under vibration/fretting; not yet tested under perspiration/chloride exposure—cross-pathway protection remains a hypothesis, not an established result
Partial gold overcoat [13]	Perspiration and chloride corrosion	Lengthwise gold layer	Extra conduction path once the silver underneath is locally used up	Partial, lengthwise-only coating adds negligible bulk to the yarn cross-section, but bending/abrasion durability of the overcoat itself was not separately tested	Moderate-to-high (gold is costly even applied only partially)	Conducting lifetime extended from 2.7 h to 192 h	Validated only under perspiration/chloride exposure; not yet tested under vibration or repeated mating/unmating—cross-pathway protection remains a hypothesis, not an established result

6.2. A Shared Design Idea

Although the two studies address different degradation pathways, employ different secondary materials, and originate from unrelated research programs, the underlying design principle is identical in both cases: rather than attempting to prevent the primary

silver coating from wearing away in the first place, both strategies incorporate a second conductive network that remains functional after the silver has already been locally depleted. The fact that two independent research groups, working in different fields and addressing different stressors, converged on the same principle lends it greater credibility as a general strategy, rather than as a result specific to one study's particular conditions.

This convergence also points to an opportunity that has not yet been pursued. Neither mitigation strategy has been tested against the stressor addressed by the other study: the carbon nanotube coating has not been tested under sweat or chloride exposure, and the partial gold overcoat has not been tested under vibration or repeated mating and unmating. If the second-network concept is indeed general, as this convergence suggests, both treatments should, in principle, extend service life under stressors beyond the one each was originally developed and tested for. This cross-pathway testing, together with the combined-exposure testing discussed in Section 5, is proposed as a research priority in Section 7.

To keep this claim precise, the "second conductive network" concept is defined here as a design in which a supplementary conductive material is incorporated alongside the primary silver coating, such that, once the silver layer is locally worn, corroded, or otherwise interrupted at a given point, the supplementary material continues to provide a conduction path across that point. As Table 5 makes explicit, the evidence currently supports this concept only within the specific pathway against which each material was first tested: the case for carbon nanotubes rests entirely on vibration/fretting data, and the case for a gold overcoat rests entirely on perspiration/chloride data. Evidence in favor of treating this as a general, cross-pathway strategy is limited to the structural analogy between the two mechanisms and the fact that two independent research groups converged upon it; the case for caution, or at minimum the evidence still lacking, is that neither material has been tested against the other's stressor, that the two materials operate through different physical mechanisms (electrical bridging and lubrication for carbon nanotubes versus a continuous parallel path for gold), and that a material well suited to one stressor is not guaranteed to withstand another, as the humidity sensitivity of certain two-dimensional materials discussed in Section 6.3 illustrates. The second-network concept should therefore be regarded as a promising working hypothesis about a shared design principle, not as a demonstrated cross-pathway solution, pending the cross-pathway testing proposed in Section 7.4.

6.3. Newer Candidates for the Second-Network Idea

If the second-network concept identified in Sections 6.1 and 6.2 is indeed general, materials beyond carbon nanotubes and gold merit consideration as candidates, even though none have yet been tested against the specific degradation pathways reviewed in this paper. Two-dimensional materials, including graphene and transition metal compounds such as molybdenum disulfide, have recently been incorporated into textile substrates at a scale suitable for wearable devices, with one reported graphene/molybdenum disulfide textile electrode retaining nearly its full charge-storage capacity after 1000 mechanical cycles in a supercapacitor test [35]. This demonstrates that two-dimensional material coatings can now be applied to textiles with a durability profile compatible with repeated mechanical loading, though this evidence originates from an energy-storage context rather than from contact-resistance tests under the pathways reviewed here, and should be interpreted as a plausibility argument rather than direct proof against any of the six pathways. This plausibility argument requires an important caveat, however: a recent review of MXene-based textiles notes that these two-dimensional materials are themselves prone to oxidation upon exposure to air or moisture, with accelerated breakdown at high humidity, such that an

unprotected MXene coating may in fact be a weaker, rather than stronger, candidate for the second-network role unless paired with an additional protective treatment [36]. This indicates that candidate secondary materials cannot be assumed superior to carbon nanotubes or gold simply because they exhibit high conductivity in principle; their resistance to the pathways discussed in Section 3 must be demonstrated independently.

Conductive polymers, particularly PEDOT:PSS, constitute a further candidate group, given their growing use as flexible, washable conductors for textiles [37]. PEDOT:PSS-coated yarns have separately been reported to retain conductivity after repeated washing when combined with a suitable supplementary treatment [38], and a layer-by-layer construction combining PEDOT:PSS with silver nanowires has been shown to maintain high conductivity for electronic textile applications [39], suggesting that hybrid silver/conductive-polymer constructions may themselves offer a route toward a more damage-resistant coating rather than serving merely as a silver substitute. None of these candidates, whether silver-free or hybrid, has been tested specifically under the six pathways reviewed in this paper, and their stability under chloride exposure in particular has not, to the authors' knowledge, been examined in this context. None of these candidates should be assumed to perform as well as carbon nanotubes or gold without direct testing; they are noted here as directions consistent with the design principle identified in this review, not as proven solutions, and are included among the priorities set out in Section 7.

7. Recommendations for Standardized Multi-Stressor Test Methods

Building on the gaps identified in Sections 2.4, 5 and 6, this section sets out a list of directions for future testing work, ranked by priority.

7.1. Combined-Exposure Protocols Covering at Least Two Pathways

The most pressing need is for test methods that expose the same sample to more than one degradation pathway, either sequentially or simultaneously, and report how contact resistance changes across the combined exposure rather than for each pathway in isolation. Vibration combined with occasional sweat exposure, and vibration combined with laundering, are the two combinations that best represent ordinary garment use and are recommended as the top priority, given that neither has been tested in the literature reviewed here. To render this recommendation directly implementable rather than a statement of intent, a concrete protocol is set out here for the vibration-plus-sweat case, on the understanding that the vibration-plus-laundering case can be constructed analogously by substituting a wash cycle for the sweat-exposure step. Loading sequence and coupling: samples should be tested under three conditions rather than one: sequential exposure (sweat exposure followed by vibration on the same sample), reverse-sequential exposure (vibration followed by sweat exposure), and simultaneous exposure (vibration applied while the contact remains wetted with artificial sweat), because Section 5 demonstrates that sequential and simultaneous coupling can produce different outcomes, and neither can be assumed to bound the other. Sample preparation and aging pretreatment: samples should be drawn from a single coating batch, characterized for thickness and adhesion prior to testing as recommended in Section 7.5, and a subset should be pre-aged through a single wash cycle before combined-stress testing begins, so that the combined-stress response of a fresh coating can be distinguished from that of a coating already softened by prior exposure. Basis for stress parameters: the vibration frequency band and cycle count should follow the 7–10 Hz resonance condition and 100,000-cycle protocol established in [6,7], and the sweat concentration and exposure duration should follow the chloride solution protocol in [13], so that the combined-stress result can be compared against the two single-stress baselines already established in the literature rather than against a newly

devised condition. Failure criteria and monitoring: contact resistance should be logged continuously, or at minimum before and after each exposure block, against the same order-of-magnitude resistance rise used as the failure criterion in [6,13], so that a combined-stress failure time can be expressed on the same axis as Figure 4; a fixed inspection schedule for coating condition via microscopy, consistent with the approach in [6], should accompany the electrical measurements. Significance of expected results: if the combined-stress failure time approximates the shorter of the two single-stress failure times, this would support treating single-stress data as a conservative bound; if it is shorter still, as Section 5 suggests may be the case based on the single combined-exposure study identified in this review [14], this would demonstrate that single-stress testing is not merely incomplete but actively misleading for design purposes, directly supporting the case made throughout this review for combined-stress standards.

7.2. Direct Measurement of Repeated Mating and Unmating on Hook-and-Loop Fasteners

As noted in Section 3.2, the durability benchmarks established for wearable connectors in general have not been applied specifically to conductive hook-and-loop fasteners, for which only fretting and vibration data currently exist. Applying a mating-and-unmating protocol similar to those used for snap and magnetic connectors [17,18], informed by the existing standard test methods summarized in Section 7.6, directly to a conductive hook-and-loop sample would close a gap raised repeatedly across Sections 3–5.

7.3. Measuring Fiber and Debris Entrapment

Because this pathway currently rests on reasoned argument alone, a controlled study exposing a conductive hook-and-loop interface to a standardized quantity of fiber or particle debris, with contact resistance measured before and after exposure, would convert the least-evidenced pathway in this review into one with quantitative support. The particle-size classes already defined for solid-particle protection ratings on general enclosures [40], although developed for sealed enclosures rather than an open textile interface, could provide a starting point for establishing standard debris size classes for such a study.

7.4. Cross-Pathway Testing of the Two Shared Fixes, and of the Newer Candidates

As discussed in Section 6, the carbon nanotube coating and the partial gold overcoat should each be tested against the stressor for which the other was developed, in order to determine directly whether the second-network concept holds across pathways. Two-dimensional material and conductive-polymer coatings should likewise be tested against all six pathways to assess whether they provide comparable or superior protection.

7.5. A Systematic Study of Deposition Method as a Degradation Variable

As discussed in Section 2.4, no study identified in this review varied deposition method, coating thickness, or adhesion strength while holding a degradation pathway constant. A factorial study pairing the deposition methods compared in Table 2 with at least one pathway from each evidence category in Table 3 would establish whether coating construction is a first-order variable in degradation resistance, as the reasoning in Section 2.4 suggests, or a secondary one.

7.6. Standard Sample and Reporting Details, Informed by Existing Standards

Consistent with the broader lack of standards noted in [1], future studies on any of the pathways addressed in this review should report silver coating thickness, deposition method, and fiber substrate composition in a common format, so that results across studies and pathways can be compared quantitatively rather than merely descriptively, as has been necessary throughout this review. Table 6 lists the existing standards relevant to

each pathway, classifies each as directly applicable or applicable only with adaptation, and indicates what modifications would be required for a silver-coated textile interface; it also highlights the two pathways, atmospheric sulfidation and fiber or debris entrapment, for which no relevant standard was identified in this review.

Table 6. Existing test standards that may be relevant to each degradation pathway, each classified as directly applicable or applicable only with adaptation, and the gap that remains for the conductive hook-and-loop fastener specifically.

Pathway	Existing Relevant Standard(s)	Original Setting	Applicability	Gap for This Application
Mechanical fretting/vibration	IEC 60512-6 series (dynamic stress/vibration tests) [34]	General electronic and automotive connectors	Applicable with adaptation—the vibration/dynamic-stress test method transfers, but load levels and sample fixturing must be adapted from rigid connectors to a flexible textile fastener	Not applied to textile hook-and-loop fasteners specifically
Repeated mating/unmating	IEC 60512-9-1 (mechanical operation/endurance) [41]; IEC 60512-99-003 (endurance schedule for unmating under load) [42]	General electronic connectors	Applicable with adaptation—the cycle-count endurance method transfers, but pass/fail resistance thresholds need re-derivation for a hook-and-loop contact	Not applied to conductive hook-and-loop fasteners
Laundering	ISO 6330 (home washing/drying procedures) [29]; AATCC TM210 (resistance before/after exposure) [43]; AATCC EP13 (resistance of integrated textiles) [44]	Textile- and e-textile-specific	Directly applicable—developed specifically for textile and e-textile washing and resistance testing	Exists, but rarely combined with mechanical or vibration protocols
Perspiration/chloride corrosion	ASTM B117 [45]; ISO 9227 (salt spray corrosion testing) [46]	General metal corrosion testing	Applicable with adaptation—the exposure-chamber method transfers, but salt-spray ion composition, concentration, and pH must be adjusted to approximate human sweat rather than marine salt fog	Salt-spray chemistry and strength differ from human sweat
Atmospheric sulfidation	No dedicated e-textile-specific standard found in this review	—	Not applicable—no existing standard was identified that could be adapted; a new e-textile-specific method is needed	Full gap; the general silver tarnishing chemistry is understood (Section 3.5) but not written into a textile test
Fiber/debris entrapment	IEC 60529 (solid-particle protection rating, general enclosures only) [40]	General electrical/electronic enclosures	Applicable with adaptation—the particle-size classification can be borrowed, but the sealed-enclosure ingress test itself must be reworked for an open, unsealed textile interface	Applies to sealed enclosures, not to an open textile hook-and-loop interface

These six directions are not exhaustive, but they are ranked according to the magnitude of the gap identified in the preceding sections and the extent to which existing test setups,

already largely established within the pathway literature reviewed in Section 3, could be adapted to these directions without requiring entirely new equipment.

8. Conclusions

This review examined six pathways by which silver-coated conductive components in electronic textiles are known, or reasonably expected, to degrade: mechanical fretting and vibration, repeated mating and unmating, laundering, perspiration and chloride corrosion, atmospheric sulfidation, and fiber and debris entrapment. To date, these pathways have largely been studied along three largely separate research paths: one grounded in the tribology of automotive and industrial connectors and centered on fretting and vibration; one grounded in textile and materials chemistry and centered on laundering and sweat exposure; and one grounded in coating science and centered on how silver is deposited onto textile fibers in the first place, with relatively little cross-referencing among the three.

Drawing together evidence across these three research paths, this review found that all six pathways, despite substantial differences in loading type, environment, and timescale, are consistent with the same underlying failure: a reduction in the number of working contact spots at the silver-coated interface, caused by mechanical removal, chemical alteration, or physical blocking of the coating. This convergence was strongly supported by direct evidence for three pathways, fretting, laundering, and perspiration corrosion, which were further shown to cluster within roughly one order of magnitude of each other on a common timescale, and was identified as a plausible but not yet directly proven hypothesis for the remaining three, repeated mating and unmating, atmospheric sulfidation, and fiber or debris entrapment. Within the perspiration pathway specifically, this reduction in contact spots is not a strictly one-way process: one study found that short-term sweat exposure can transiently increase conductance, through the release of silver ions, before longer exposure reduces it, so degradation under this pathway should be interpreted as a net long-term trend rather than a monotonic decline from the outset of exposure. The review also identified a shared mitigation strategy, namely adding a second conductive network that remains functional after the primary silver coating is locally depleted, arrived at independently through carbon nanotube coating in the fretting literature and a partial gold overcoat in the corrosion literature, a convergence that lends the idea credibility as a candidate general design strategy rather than a fix specific to one pathway, though, as Section 6.2 makes explicit, this remains a hypothesis pending cross-pathway testing rather than a demonstrated result; the review also identified newer two-dimensional materials and conductive polymers as further untested candidates for the same role.

At the same time, this review found that testing a single stressor at a time remains the near-universal practice across all three research paths, that this practice has not accounted for deposition method as a variable, and that the one instance of combined-exposure testing identified in the reviewed literature revealed a more complex degradation pattern than either contributing single-stress study would have predicted independently. The review also compiled the existing test standards relevant to each pathway, finding partial coverage for four of the six and no applicable standard for two, atmospheric sulfidation and fiber or debris entrapment. These findings, together with the largely non-standardized sample settings and reporting practices across the studies reviewed, support the ranked set of recommendations set out in Section 7: combined-exposure testing across at least two pathways; direct measurement of mating-and-unmating durability specifically for hook-and-loop fasteners; measurement of fiber and debris entrapment; cross-pathway testing of the two shared fixes and of newer second-network candidates; a systematic study of deposition method as a degradation variable; and standardized reporting of sample and coating details, informed by existing connector and textile standards.

As a review grounded in published literature rather than new experimentation, this paper is necessarily limited by the scope and quality of the studies on which it draws, and its central claims, in particular the convergence argued for in Section 4 and the extent to which the mitigation strategy discussed in Section 6 generalizes, should be regarded as hypotheses supported by the available evidence rather than as settled conclusions. It is offered on this basis as a framework intended to guide, rather than replace, the combined-stress experimental work identified here as the field's most pressing need.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable. This review did not involve new studies on humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: During the preparation of this manuscript, the author used Claude (Sonnet 5, Anthropic) for English-language editing and stylistic polishing.

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

Abbreviations

The following abbreviations are used in this manuscript:

AATCC	American Association of Textile Chemists and Colorists
ASTM	American Society for Testing and Materials (ASTM International)
CNT	Carbon nanotube
ECR	Electrical contact resistance
IEC	International Electrotechnical Commission
IP (code)	Ingress Protection (code)
ISO	International Organization for Standardization
MXene	Two-dimensional transition metal carbide/nitride material
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate

References

1. Stanley, J.; Hunt, J.A.; Kunovski, P.; Wei, Y. A review of connectors and joining technologies for electronic textiles. *Eng. Rep.* **2022**, *4*, e12491. [CrossRef]
2. Sadi, M.S.; Kumpikaitė, E. Advances in the robustness of wearable electronic textiles: Strategies, stability, washability and perspective. *Nanomaterials* **2022**, *12*, 2039. [CrossRef] [PubMed]
3. Sayem, A.S.M.; Teay, S.H.; Shahariar, H.; Fink, P.L.; Albarbar, A. Review on smart electro-clothing systems (SeCSs). *Sensors* **2020**, *20*, 587. [CrossRef] [PubMed]
4. Yang, K.; McErlain-Naylor, S.A.; Isaia, B.; Callaway, A.; Beeby, S. E-textiles for sports and fitness sensing: Current state, challenges, and future opportunities. *Sensors* **2024**, *24*, 1058. [CrossRef] [PubMed]
5. Dolez, P.I. Energy harvesting materials and structures for smart textile applications: Recent progress and path forward. *Sensors* **2021**, *21*, 6297. [CrossRef] [PubMed]
6. Joo, H.G.; Jang, Y.H.; Choi, H.S. Electrical contact resistance for a conductive Velcro system. *Tribol. Int.* **2014**, *80*, 115–121. [CrossRef]
7. Jang, I.; Joo, H.G.; Jang, Y.H. Effects of carbon nanotubes on electrical contact resistance of a conductive Velcro system under low frequency vibration. *Tribol. Int.* **2016**, *104*, 45–56. [CrossRef]
8. Greenwood, J.A. Constriction resistance and the real area of contact. *Br. J. Appl. Phys.* **1966**, *17*, 1621–1632. [CrossRef]
9. Jang, Y.H.; Barber, J.R. Effect of contact statistics on electrical contact resistance. *J. Appl. Phys.* **2003**, *94*, 7215–7221. [CrossRef]
10. Rotzler, S.; Schneider-Ramelow, M. Washability of e-textiles: Failure modes and influences on washing reliability. *Textiles* **2021**, *1*, 37–54. [CrossRef]

11. Lam, N.Y.K.; Tan, J.; Toomey, A.; Cheuk, K.C.J. Washability and abrasion resistance of illuminative knitted e-textiles with POFs and silver-coated conductive yarns. *Fash. Text.* **2022**, *9*, 39. [CrossRef]
12. Gaubert, V.; Gidik, H.; Bodart, N.; Koncar, V. Investigating the impact of washing cycles on silver-plated textile electrodes: A complete study. *Sensors* **2020**, *20*, 1739. [CrossRef] [PubMed]
13. Park, J.; Park, S.H.; Jeong, S.H.; Lee, J.Y.; Song, J.Y. Corrosion behavior of silver coated conductive yarn. *Front. Chem.* **2023**, *11*, 1090648. [CrossRef] [PubMed]
14. Park, S.; Kim, H.; Lee, S. Changes in characteristics of silver conductive fabrics owing to perspiration and washing. *RSC Adv.* **2023**, *13*, 28444–28461. [CrossRef] [PubMed]
15. Eskandarian, L.; Lam, E.; Rupnow, C.; Alizadeh-Meghrazi, M.; Naguib, H.E. Robust and multifunctional conductive yarns for biomedical textile computing. *ACS Appl. Electron. Mater.* **2020**, *2*, 1554–1566. [CrossRef]
16. Weerasinghe, P.V.T.; Wijesena, R.N.; Tissera, N.D.; Priyadarshana, G.; Wanasekara, N.D.; Dissanayake, D.G.K.; de Silva, K.M.N. Electroless plating of premetalized polyamide fibers for stretchable conductive devices. *RSC Adv.* **2023**, *13*, 18605–18613. [CrossRef] [PubMed]
17. Ugale, P.; Lingampally, S.; Dieffenderfer, J.; Suh, M. Wearable solutions: Design, durability, and electrical performance of snap connectors and integrating them into textiles using interconnects. *Textiles* **2024**, *4*, 328–343. [CrossRef]
18. Ugale, P.; Lingampally, S.; Dieffenderfer, J.; Suh, M. Durability of wearable buckle and snap magnetic connectors—Impact of mating/unmating cycles, mating force, and interconnect methods. *Textiles* **2026**, *6*, 17. [CrossRef]
19. Greig, T.A.; Yang, K.; Torah, R. Evaluation of a spring finger based, magnetic connector concept for reliable e-textile interconnects. *IEEE Trans. Compon. Packag. Manuf. Technol.* **2022**, *12*, 1723–1725. [CrossRef]
20. Biermaier, C.; Bechtold, T.; Pham, T. Towards the functional ageing of electrically conductive and sensing textiles: A review. *Sensors* **2021**, *21*, 5944. [CrossRef] [PubMed]
21. Ahmed, F.; Mills, A.C.; Kwon, C.H. Impact of weaving parameters on the performance of yarn-based interconnects in woven e-textiles: A comprehensive review. *J. Ind. Text.* **2025**, *20*, 55. [CrossRef]
22. Leśnikowski, J.; Szewczyk, M. Effect of cyclic fastening–unfastening and interruption of current flowing through a snap fastener electrical connector on its resistance. *AUTEX Res. J.* **2025**, *25*, 20250046. [CrossRef]
23. Park, Y.W.; Sankara Narayanan, T.S.N.; Lee, K.Y. Fretting corrosion of tin-plated contacts. *Tribol. Int.* **2008**, *41*, 616–628. [CrossRef]
24. Lee, S.; Jang, Y.H.; Kim, W. Effects of nanosized contact spots on thermal contact resistance. *J. Appl. Phys.* **2008**, *103*, 074308. [CrossRef]
25. Lee, S.; Cho, H.; Jang, Y.H. Multiscale electrical contact resistance in clustered contact distribution. *J. Phys. D Appl. Phys.* **2009**, *42*, 165302. [CrossRef]
26. Yoo, S.; Jang, Y.H. Multiscale electrical contact resistance between gas diffusion layer and bipolar plate in proton exchange membrane fuel cells. *J. Fuel Cell Sci. Technol.* **2012**, *9*, 031003. [CrossRef]
27. Fortes Ferreira, A.; Alves, H.; Plácido da Silva, H.; Marques, N.; Fred, A. Exploring the electrical robustness of conductive textile fasteners for wearable devices in different human motion conditions. *Sci. Rep.* **2024**, *14*, 7872. [CrossRef] [PubMed]
28. Abdi, B.; Tehrani-Bagha, A.R. Toward robust electrical heating textiles: Factors influencing electrical heating performance and durability. *ACS Omega* **2025**, *10*, 51354–51367. [CrossRef] [PubMed]
29. *ISO 6330:2021*; Textiles—Domestic Washing and Drying Procedures for Textile Testing. International Organization for Standardization (ISO): Geneva, Switzerland, 2021.
30. Ha, H.; Payer, J. The effect of silver chloride formation on the kinetics of silver dissolution in chloride solution. *Electrochim. Acta* **2011**, *56*, 2781–2791. [CrossRef] [PubMed]
31. Hirman, M.; Navratil, J.; Radouchova, M.; Stulik, J.; Soukup, R. Influence of sweat on joint and sensor reliability of e-textiles. *Energies* **2022**, *15*, 506. [CrossRef]
32. Burstein, G.T. *The Tarnishing Conundrum of Silver*; Assay Office London: London, UK, 2023.
33. Ortíz-Corona, J.; Rodríguez-Gómez, F.J. Role of copper in tarnishing process of silver alloys in sulphide media. *Trans. Nonferrous Met. Soc. China* **2019**, *29*, 2646–2657. [CrossRef]
34. *IEC 60512-6-5*; Connectors for Electronic Equipment–Tests and Measurements–Part 6-5: Dynamic Stress Tests–Test 6e: Random Vibration. International Electrotechnical Commission (IEC): Geneva, Switzerland, 1997.
35. Islam, M.R.; Afroj, S.; Karim, N. Scalable production of 2D material heterostructure textiles for high-performance wearable supercapacitors. *ACS Nano* **2023**, *17*, 18481–18493. [CrossRef] [PubMed]
36. Rupanty, N.S.; Ghosh, J.; Noor, T.; Asif, T.R.; Ahmed, S.; Howlader, S.; Reukov, V. Advances in wearable technology: MXene-based multifunctional and biomedical smart textiles. *ACS Omega* **2026**, *11*, 197–228. [CrossRef] [PubMed]
37. Alhashmi Alamer, F.; Althagafy, K.; Alsalmi, O.; Aldeih, A.; Alotaiby, H.; Althebaiti, M.; Alghamdi, H.; Alotibi, N.; Saeedi, A.; Zabarmawi, Y.; et al. Review on PEDOT:PSS-based conductive fabric. *ACS Omega* **2022**, *7*, 35371–35386. [CrossRef] [PubMed]
38. Pattanarat, K.; Petchsang, N.; Osotchan, T.; Kim, Y.-H.; Jaisutti, R. Wash-durable conductive yarn with ethylene glycol-treated PEDOT:PSS for wearable electric heaters. *ACS Appl. Mater. Interfaces* **2021**, *13*, 48053–48060. [CrossRef] [PubMed]

39. Kim, S.H.; Ko, H.C. Robust and highly conductive PEDOT:PSS:Ag nanowires/polyethyleneimine multilayers based on ionic layer-by-layer assembly for e-textiles and 3D electronics. *ACS Appl. Electron. Mater.* **2022**, *4*, 2413–2423. [CrossRef]
40. *IEC 60529:1989+AMD1:1999+AMD2:2013*; Degrees of Protection Provided by Enclosures (IP Code). International Electrotechnical Commission (IEC): Geneva, Switzerland, 2013.
41. *IEC 60512-9-1:2010*; Connectors for Electronic Equipment—Tests and Measurements—Part 9-1: Endurance Tests—Test 9a: Mechanical Operation. International Electrotechnical Commission (IEC): Geneva, Switzerland, 2010.
42. *IEC 60512-99-003:2023*; Connectors for Electrical and Electronic Equipment—Tests and Measurements—Part 99-003: Endurance Test Schedules—Test 99c. International Electrotechnical Commission (IEC): Geneva, Switzerland, 2023.
43. *AATCC TM210-2025*; Test Method for Electrical Resistance Before and After Various Exposure Conditions. American Association of Textile Chemists and Colorists (AATCC): Research Triangle Park, NC, USA, 2025.
44. *AATCC EP13*; Electrical Resistance of Electronically-Integrated Textile. American Association of Textile Chemists and Colorists (AATCC): Research Triangle Park, NC, USA, 2018.
45. *ASTM B117-19*; Standard Practice for Operating Salt Spray (Fog) Apparatus. ASTM International (ASTM): West Conshohocken, PA, USA, 2019.
46. *ISO 9227:2017*; Corrosion Tests in Artificial Atmospheres–Salt Spray Tests. International Organization for Standardization (ISO): Geneva, Switzerland, 2017.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.