

Article

Durability of Wearable Buckle and Snap Magnetic Connectors—Impact of Mating/Unmating Cycles, Mating Force, and Interconnect Methods

Prateeti Ugale ¹, Shourya Lingampally ¹, James Dieffenderfer ² and Minyoung Suh ^{1,*}

¹ Department of Textile and Apparel Technology and Management, Wilson College of Textiles, North Carolina State University, Raleigh, NC 27695-8301, USA

² Department of Electrical and Computer Engineering, College of Engineering, North Carolina State University, Raleigh, NC 27695-8301, USA

* Correspondence: msuh2@ncsu.edu

Abstract

The advent of wearable electronic textiles (e-textiles) is transforming human–computer interaction by enabling seamless, comfortable, and continuous connectivity between users and digital systems. Although the wearable e-textile market is poised for significant growth, there is a need for durable, reliable connectors to link e-textiles to digital systems. This study presents and evaluates two novel magnetic connectors—buckle and snap—integrated into textile substrates using conductive epoxy, conductive stitches, and solder as interconnect methods. Durability testing involved 5000 mating/unmating cycles at low, medium, and high forces, with electrical performance assessed through resistance and impedance measurements. Results showed significant increases in resistance and impedance with 1000-cycle intervals. However, both connectors retained robust electrical and mechanical integrity, with all resistance values remaining below 1.6 Ω , indicating no critical degradation. Buckle connectors consistently outperformed snap connectors, which is attributed to their design that reduces mechanical stress on interconnects. Conductive epoxy demonstrated superior stability and slower degradation compared to conductive stitches and solder, particularly under higher mating forces. Impedance results mirrored resistance trends, confirming reliability. These findings advance durable, user-friendly connectors for long-term e-textile use, addressing both mechanical endurance and electrical performance to enhance wearable computing and interactive environments.

Keywords: e-textiles; connectors; interconnects

Academic Editor: Rajesh Mishra

Received: 15 August 2025

Revised: 22 November 2025

Accepted: 7 January 2026

Published: 6 February 2026

Copyright: © 2026 by the authors. 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](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

E-textiles, the fusion of electronics and textiles, are rapidly becoming ubiquitous, introducing unprecedented possibilities to the industries like healthcare, military, sports, and fashion [1,2]. E-textiles comprise functional components, such as sensors and actuators, which make the textiles smart/intelligent [3]. These components are electrically connected to a ‘puck’ using interconnects. The puck is a typically rigid electronic component, housing microprocessors and relevant circuits with data and power management capabilities. This rigid component can either be permanently attached to the textiles or designed to be removable [4,5]. The advantage of removable connection is that it allows for

easy, user-friendly, modular, and on-demand attachment of digital systems or electronics to textiles for specific tasks like real-time health monitoring [6] or charging [7]. They can be easily detached when not in use. The ability to detach also enhances comfort and washability by preventing permanent integration of bulky and water sensitive electronics into the garment, making them more wearable and washable [8].

State-of-the-art removable connections in e-textiles employ several strategies and designs, each with distinct advantages and challenges. The removable wearable connectors seen are in the form of physical fastening such as metal snap fasteners [9–12], conductive hook and loop [13–16], conductive zippers [17,18], pocket connectors [19,20], and plug connectors [21]. Metal snap fasteners are one of the most popular connectors used in e-textiles due to wide availability, cost effectiveness, conductive metal body, and textile compatibility. Hook-and-loop fasteners (Velcro®) offer adjustable and reusable attachment but can exhibit inconsistent electrical contact depending on the number of engaged hooks and loops. Additionally, it can also wear out over repeated cycles and accumulate lint or debris. Zippers provide continuous electrical contact over longer distances; however, they can be prone to mechanical failure and teeth misalignment. Apart from physical fastening, another useful method for creating removable connectors is through magnets. Magnetic connectors enable secure attachment without the need for physical interlocking, hence eliminating the need for dexterous handling. Magnetic connectors also allow quick, self-guided alignment, making them ideal for applications where convenience and speed are important. Magnetic connectors can be user friendly for patients due to their ease of attachment or for military soldiers to make a speedy connection in the field. Due to its unbeatable advantages, magnetic connectors have been explored in the past [1,22–24]. E-textile connectors are application dependent customized for specific devices, and unique to a particular system [25].

Along with making physical connections, wearable connectors also need to make electrical contact when mated. The electrical connection is usually achieved by having the contact points conductive. Pogo pins are one of the common elements adopted in customized connectors [22]. The total number of galvanic connection points included in a connector is usually determined by the communication protocol required for e-textile systems to function for specific applications [26]. A higher number of connection points may increase the overall size of the connector, depending on the connector design and form factor [27]. The removable connectors require an attachment site on textiles, where the connector can be mounted [5]. This site is permanently fixed on textiles using non-removable connections by various methods such as conductive adhesives, mechanical links, or thermal welding (e.g., soldering) [5,28].

Despite the wide application of removable and non-removable connections in e-textiles, their durability has not been extensively explored [4,29]. Over the lifetime of a wearable connector, it undergoes multiple attaching (mating) and detaching (unmating) cycles. Therefore, to assess long-term reliability of the connector it is critical to evaluate its longevity (i.e., the ability of the connector to withstand repeated use without degradation) for prolonged use of e-textiles [30]. The durability of a wearable connector is heavily governed by the longevity of non-removable connections (used for fixing the connector attachment site onto the textile).

The scientific contribution of this work lies in its comprehensive analysis of how connector design, interconnection methods, and mechanical stresses influence electrical performance metrics such as resistance and impedance magnitude of a removable connector. By addressing the challenge of creating durable, removable connectors for e-textiles, this research is expected to advance the field by enabling more practical and long-lasting wearable systems for diverse applications where repeated connection and disconnection are essential, such as in healthcare, military, and consumer wearables.

2. Materials and Methods

In this study, two novel removable magnetic connectors—a buckle and a snap—were designed and developed. Each connector consists of two parts: a textile-side component and a non-textile-side component. Both connector types were designed to support four channels compatible with the standard USB 2.0 protocol [9]. The textile-side connectors were integrated into the textile substrate using three different permanent interconnect methods: conductive epoxy, conductive stitches, and solder. The durability and electrical performance of these connector configurations were evaluated through 5000 mating and unmating cycles performed at three different mating force levels: low, medium, and high.

The study assessed the impact of mating cycles, connector type, force levels, and interconnect methods on electrical resistance. Additionally, the observed trends in electrical resistance were compared with electrical impedance measurements to further understand the effects of these parameters on the durability and reliability of both connector types.

2.1. Connector Fabrication

Three-dimensional (3D) models of the buckle and snap connector bodies were created in Autodesk Fusion 360 version 2.0.9719 (San Francisco, CA, USA) and exported as Standard Tessellation Language (STL) files, then prepared for fabrication in Formlabs Pre-Form 3.21.0. Connector housing was additively manufactured on a Formlabs Form 3+ (Somerville, MA, USA) using low-force stereolithography (SLA) with Formlabs polymer resin RS-F2-GPGR-04, selected for its high resolution and mechanical performance (ultimate tensile strength 65 MPa; tensile modulus 2.8 GPa). Printed parts were rinsed in 90% isopropanol (IPA) and post-cured in a Formlabs Form Cure (FH-CU-01) for 60 min under 405 nm ultraviolet light at 60 °C to enhance material properties. The configuration of each connector type is detailed in the sections that follow.

2.1.1. Buckle Connector Fabrication

The textile (Figure 1a) and non-textile side connector (Figure 1b) used block magnets (Figure 1c,d) of three different magnetic strengths (BX022, BX042, BX082) which were sourced from K&J Magnetics, Inc. (Pipersville, PA, USA) to manipulate the mating force of the buckle connector. This resulted in low (9.82 N), medium (13.50 N), and high (22.86 N) mating/unmating forces between the textile and non-textile side connectors. The magnets were housed inside the 3D-printed connector bodies on both sides (Figure 1e,f). Two different PCBs (Figure 1g,h) were constructed for both side connectors with FR-4 Kingboard TG150 which was sourced from AllPCB (Hangzhou, China) in hot air solder leveling (HASL) and non-leaded finish. They were glued to the slots in the 3D-printed buckle connector bodies (Figure 1a,b).

Buckle-type mating was designed to take place parallelly to the fabric plane. Attached to each trace of the PCB (Figure 1g) were four Omniball® Spring-Loaded contact pins (part number: 0945-0-15-20-09-14-11-0) (see Figure 1i) from Mill-Max (Oyster Bay, NY, USA) to accommodate sliding motions during mating and alleviate the potential variations in contact pressure for stable electrical connections. They were designed to make reliable, low-resistance electrical connections even with the contact surfaces not perfectly leveled. Figure 1 illustrates the buckle connector schematic, including both component-level and assembled views, while Figure 2 shows an optical photograph of the fully assembled buckle connector.

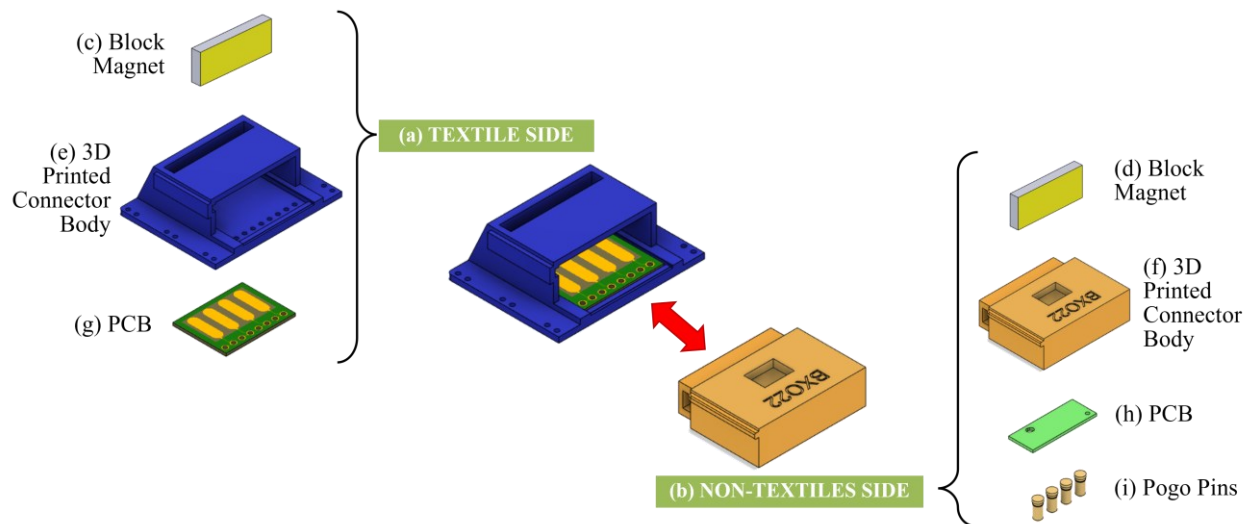


Figure 1. Schematic illustration of magnetic buckle connector showing both (a) textile side and (b) non-textile side connector. Components include (c,d) block magnets, (e,f) 3D printed plastic body (g,h) PCBs, (i) pogo pins. Red arrow shows the mating direction of textile and non-textile side of the buckle connector.

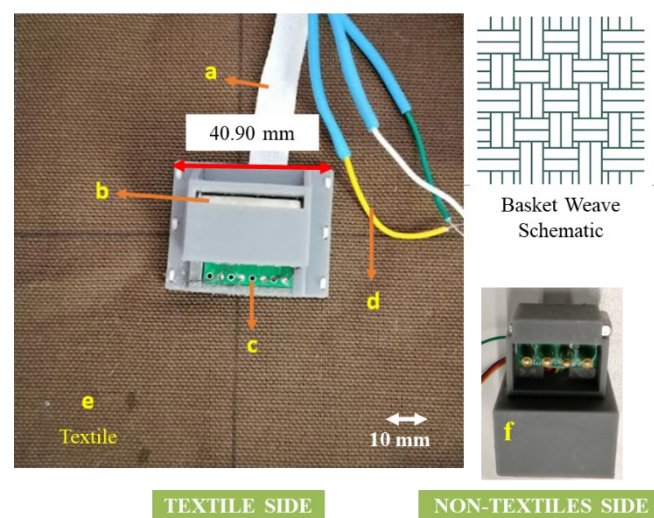


Figure 2. Optical photograph of buckle connector assembly, consisting of (a) textile data cable, (b) block magnet, (c) PCB, (d) hook up wires for measurements, (e) textile substrate, (f) additional block 3D printed to grip the electronics side connector firmly on the motorized test stand during mating/unmating cycles.

2.1.2. Snap Connector Fabrication

The textile (Figure 3a) and non-textile side connector (Figure 3b) used ring magnets (RX082) (see Figure 3c,d) which were sourced from K&J Magnetics, Inc. to provide mating force for snap connectors. Due to the limited dimensional options for the magnets, and to achieve three different magnetic strengths without increasing the diameter of the snap connector, the resin thickness of 1.0 mm, 1.7 mm, and 3.0 mm was added to the non-textile side connector during 3D printing. Adding the extra thickness to the design ultimately achieved the three different magnetic forces of low (10.04 N), medium (15.46 N), and high (22.93 N) between the two connector sides. In the same manner as the buckle connector, the magnets were inserted and glued into the 3D printed connector bodies on the textile and non-textile side (Figure 3e,f). Two different PCBs (Figure 3g,h) were made for both sides.

Unlike the buckle connectors, the snap-type mating takes place perpendicularly to the fabric plane. Sleeve-and-plunger spring-loaded pogo pins (part number: 0985-1-15-20-71-14-11-0) from Digi-Key (Thief River Falls, MN, USA) (see Figure 3i) were soldered into the non-textile connector to provide consistent, repeatable electrical contact. A protective shroud design (Figure 3j) was incorporated on the non-textile side to prevent misaligned engagement and protect the pogo pins. This shrouded feature also enforced precise alignment between the non-textile side pogo pins and the PCB traces on the textile-side connector. Figure 3 illustrates the snap connector schematic, including both component-level and assembled views, while Figure 4 shows an optical photograph of the fully assembled snap connector.

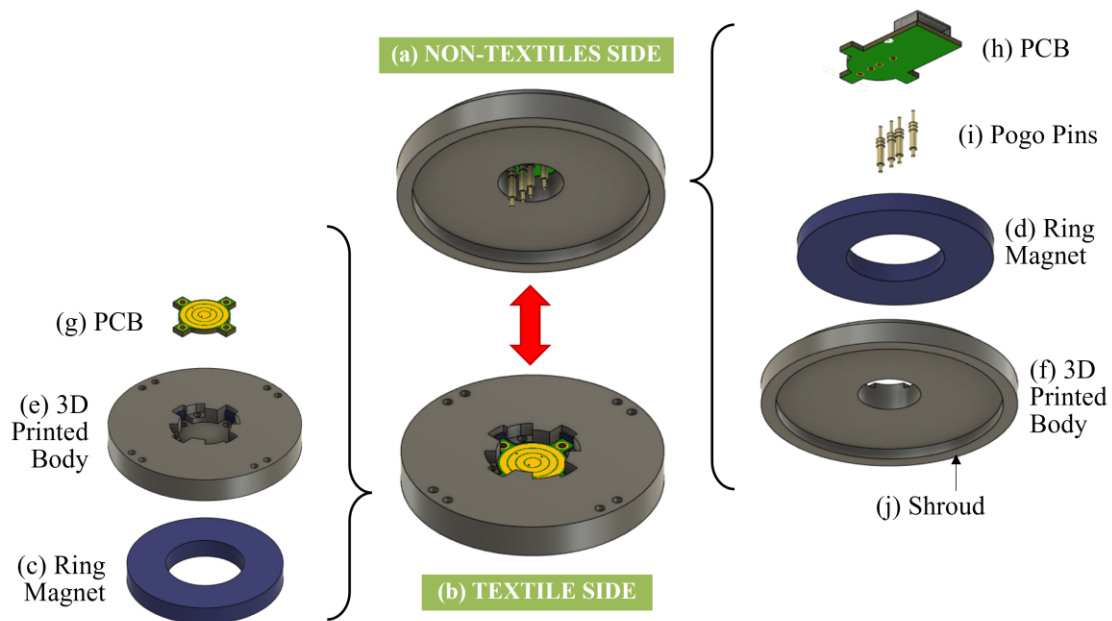


Figure 3. Schematic illustration of magnetic snap connector showing both (a) textile and (b) non-textile side connector. Components include (c,d) ring magnets, (e,f) 3D printed plastic body (g,h) PCBs, (i) pogo pins, (j) shroud. Red arrow shows the mating direction of textile and non-textile side of the snap connector.

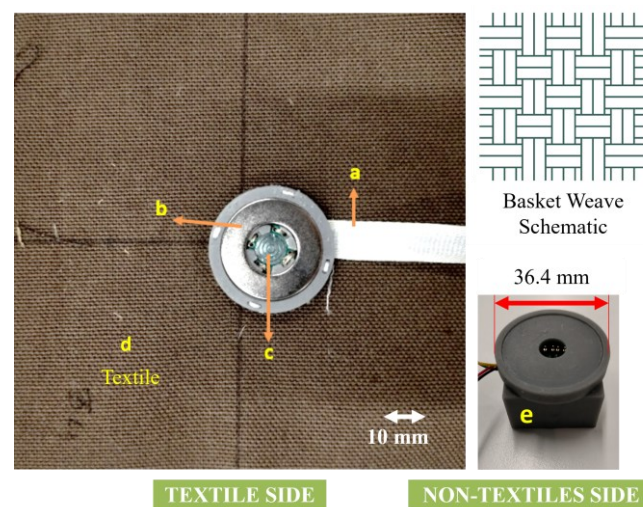


Figure 4. Optical photograph of snap connector assembly, consisting of (a) textile data cable, (b) ring magnet, (c) PCB, (d) textile substrate, (e) additional block 3D printed to grip the electronics side connector on the motorized test stand during mating/unmating cycles.

2.2. Creation of Interconnects and Process of Attachment to the Textiles

Interconnects were created to electrically join the textile-side connectors to the textile data cable on the textile substrate using three methods: conductive epoxy, conductive stitching, and soldering. These interconnects linked the connector PCB traces to a textile data cable on a basket-woven cotton polyester fabric (201.38 g/m², 0.510 mm thick). Low-temperature silver epoxy (S-CEP7-SF4) from SunRay Scientific Inc. (Wall Township, NJ, USA)—a two-part, silver-filled conductive adhesive—was used to form flexible, robust epoxied interconnects. Conductive stitches were made with Madeira HC-40 embroidery thread (Freiburg, Germany; 117/2 dtex; <300 Ω /m) on a Juki DDL-8700 industrial sewing machine (Tokyo, Japan) under controlled tensions (needle: 1.75 N; bobbin: 0.25 N). Soldered interconnects employed MG Chemicals 60/40 resin-core leaded solder (Burlington, ON, Canada; 0.81 mm diameter; melting temperature 456.15 K).

For both the textile side of buckle (Figure 5a) and snap connectors (Figure 5b), all three interconnect materials were applied to pre-arranged holes (orange arrows in Figure 5c). Conductive stitches were passed through each hole four to five times; each interconnect hole was filled with conductive epoxy and solder, respectively. Additional holes in the textile-side connector housing allowed the connector body to be physically attached to the fabric using non-conductive stitches (yellow arrows in Figure 5d).

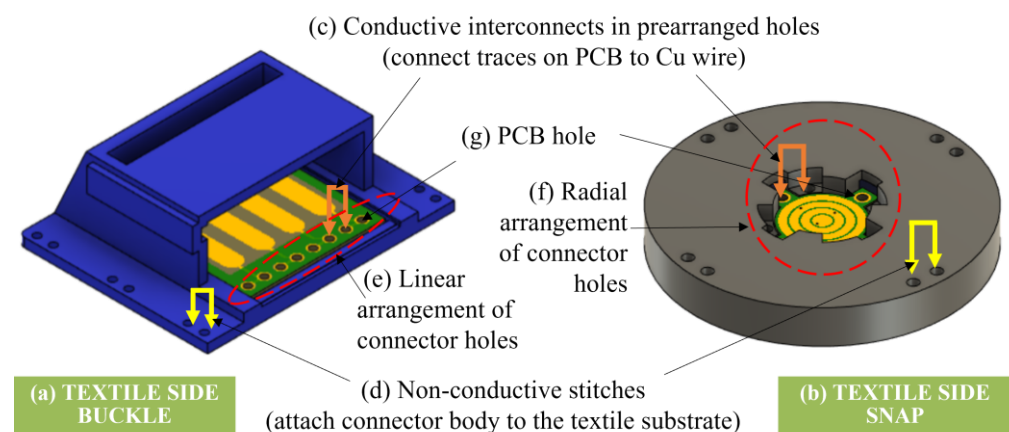


Figure 5. Interconnect sites for textile side (a) buckle and (b) snap connector—(c) conductive interconnects to textile cables (orange arrows), (d) non-conductive stitches to textile substrates (yellow arrows), (e) linear arrangement of holes on buckle (red dashed circle—left), (f) radial arrangement of holes on snap (red dashed circle—right), (g) PCB hole or VIA (vertical interconnect access).

A textile data cable from WEEL Technology (Greensboro, NC, USA) was employed to establish on-fabric power and data lines. The cable is a woven tape, 1.00 mm wide by 0.70 mm thick, with a polyester sheath enclosing four copper conductors (Figures 2a and 4a). Each copper wire comprises 14 filaments, with an approximate resistance of 1.5 Ω /m.

Buckle—The four copper conductors were inserted into four designated holes on the buckle connector housing (indicated by red dashed circle in Figure 5e) and PCB (Figure 5g), with each pair of holes connected to one of four straight traces on the buckle PCB (two holes per trace; eight holes total and four straight traces). Thus, each wire was connected to a distinct straight trace using the three interconnect methods. For stitched interconnects, conductive yarn was sewn through both holes associated with a given trace, encasing the copper wire. Conductive epoxy and solder were applied directly at the PCB holes. The straight traces on the textile-side PCB interface with the pogo pins on the non-textile side to make the electrical contact when mated. Block magnets on both side connector housings help mate and secure the textile and non-textile side connector.

Snap—The four copper conductors were inserted into four dedicated holes on the snap connector housing (indicated by red dashed circle in Figure 5f) and PCB (Figure 5g), with each hole connected to one of four concentric traces on the snap PCB (one hole per trace; four holes total and four concentric traces). Thus, each wire was connected to a unique concentric trace using the same three interconnect methods. For stitched interconnects, conductive yarn was sewn from the housing hole to an adjacent PCB hole, enclosing the wire. Conductive epoxy and solder were applied directly at the PCB holes. The concentric traces make an electrical contact with the pogo pins on the non-textile side when mated. Ring magnets on both sides help mate and secure the textile and non-textile side connector. The circular/ring geometry enables non-directional mating between textile and non-textile sides. As noted above, both buckle and snap textile-side assemblies were mechanically attached to the fabric using non-conductive stitching with 27-tex cotton-poly spun thread (see Figure 5d).

To evaluate the mechanical strength of the three interconnects, the MTS Q-test machine (Berlin, Germany) was used. Under the standard ASTM D2261 [31]—Fabric Tongue Tear Test setting [31]—the textile side connector (connector attachment site) was pulled away from the textile cable on the textile substrate until separation. For accurate characterization of interconnect strength, non-conductive stitches were not added. The test was performed at an angle the same as the snap and buckle mating/unmating direction. The conductive stitches gave the highest mechanical strength—217.06 N for buckle and 145.19 N for snap. This was because of the linear arrangement of interconnect holes in buckle connector compared to snap connector design. For the other two interconnect methods, i.e., conductive epoxy and solder, the forces were below 15 N. This low force was attributed to the Cu wire in the textile data cable breaking and not the interconnects itself [10].

2.3. Durability Assessment—Electrical Resistance and Impedance Measurement

Connector durability and performance were evaluated by measuring electrical resistance and impedance. Both connector types along with the three interconnects were subjected to 5000 mating/unmating cycles at three different force levels (low, medium, and high) to assess their robustness under realistic usage conditions. The mating/unmating of the connectors were performed using an Imada ZTS-11 digital force gauge (Aichi, Japan) mounted on an Imada MH2 horizontal motorized test stand. The setup automatically cycled connectors through 5000 mating/unmating cycles at 300 mm/min while recording peak forces. This same equipment was used to measure (or quantify) the low, medium, and high magnetic forces of the magnets, as described in Sections 2.1.1 and 2.1.2. During this process, the connectors were separated while the digital force gauge recorded the peak magnetic force. To provide practical context for interpreting durability, 5000 mating and unmating cycles were selected as a representative benchmark. Assuming a typical use scenario where a wearable connector is mated and unmated twice per day (for example, during wearing the garment, charging, or washing), this corresponds to approximately 6.8 years of use. For reference, the average lifespan of a textile product is around 1–3 years (German Environment Agency, 2022 [32]), suggesting that the tested connectors would likely outlast the functional lifetime of the garment itself. Depending on the frequency of use, 5000 cycles would correspond roughly 13.7 years with one cycle per day, 3.4 years with four cycles per day, or 1.4 years with ten cycles per day.

Electrical resistance and impedance were measured by soldering hook-up wires to the Cu wires in the textile data cable and the corresponding non-textile connectors to ensure stable electrical contact during measurement. Resistance was recorded with a Keysight U1231A multimeter (Santa Rosa, CA, USA) at 0 and every 1000 cycles for all channels in the mated position. A full factorial analysis of variance (ANOVA, conducted

in JMP Pro 18, Cary, NC, USA) examined the effects of mating/unmating cycles, connector type, interconnect method, and force level on resistance. Significance was set at $p < 0.05$. Impedance magnitude across 100 kHz (100,000 Hz)–1 MHz (1,000,000 Hz) was measured using a calibrated Gamry Potentiostat (Philadelphia, PA, USA), aligned with USB 2.0 and I2C protocol specifications. Impedance was measured every 1000 cycles from 0 and 5000 with the connectors in the mated position. The USB 2.0 protocol was chosen due to its widespread usage, familiarity, and compatibility with various devices [33]. Additional setup details and measurement protocols are available in our previous work [9].

3. Results and Discussion

This section analyzes the durability and electrical performance of two removable magnetic connectors—buckle and snap—integrated onto textile substrates using three interconnect methods: conductive epoxy, conductive stitches, and solder. The results are presented in two parts. The first part focuses on electrical resistance, and the second part investigates whether the trends observed in resistance measurements are consistent with impedance magnitude data, providing a complementary frequency-dependent perspective on electrical performance. Together, these analyses offer comprehensive insights into the durability and reliability of textile-mounted detachable connectors.

3.1. Electrical Resistance

Both connectors survived during 5000 mating/unmating cycles. Figure 6 illustrates the change in electrical resistance for each connector type. Overall, resistance increased with the number of cycles, with a more noticeable rise after 3000 cycles in some interconnects. Epoxied interconnects exhibited slightly lower resistance, while stitched and soldered interconnects showed similar but higher resistance, especially beyond 3000 cycles. Resistance remained consistent across all applied force levels for both connectors.

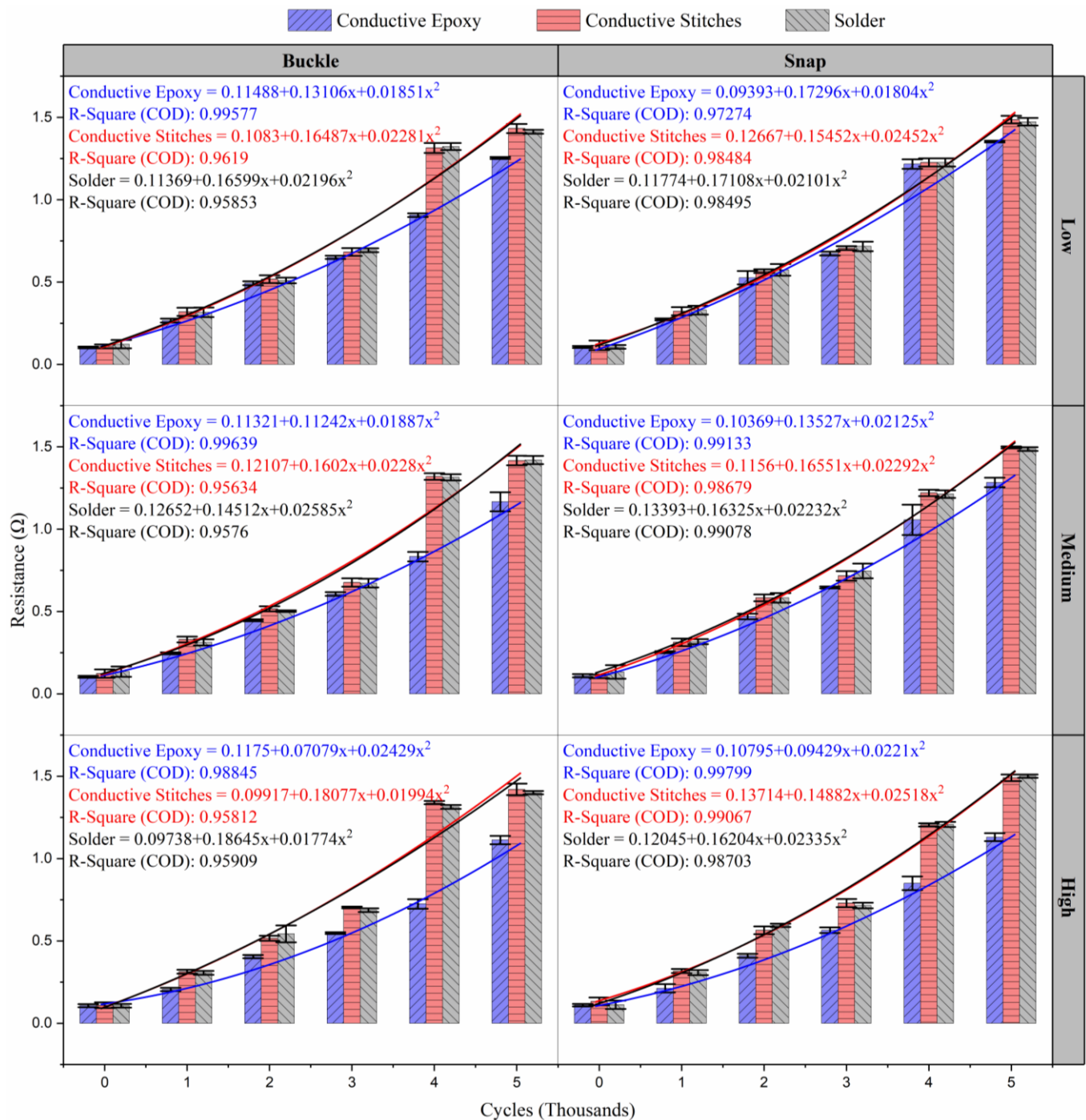


Figure 6. Resistance changes and resulting regression models in buckle and snap connectors from using three force levels (low, medium, and high) across the three interconnect methods (conductive epoxy, conductive stitches, and solder) at every 1000 mating/unmating cycle.

The full factorial ANOVA, which considered mating/unmating cycles, connector types, interconnect methods, and force levels, revealed the most dominant effects of mating/unmating cycles and its interaction ($p < 0.0001$) on resistance. The notable degradation was captured with each 1000 cycles interval. Although resistance significantly increased, it stayed below 1.6 Ω , indicating mechanical wear without substantial degradation in electrical performance. All other main effects and interaction effects were found to be insignificant.

To further interpret the degradation behavior, the resistance trends were analyzed for their mathematical relationship (fitted equations) as shown in Figure 6. The analysis

revealed that the increment follows a polynomial trend, with the coefficient of determination (R^2) values close to 1, confirming an excellent fit of the polynomial model. Using these fitted equations (different colors indicating the different interconnects), the number of cycles at which resistance may exceed a certain resistance level can be predicted for both connector types across all interconnect methods and force levels.

Since both connectors survived over 5000 cycles, their durability was evaluated and compared only at 5000 cycles. Table 1 summarizes the ANOVA results for connector types, interconnect methods, and force levels at 5000 cycles. All three main effects were statistically significant. The interaction effect of interconnect methods and force levels was significant and so was the interaction effect of all other variables, such as connector types, interconnect methods, and force levels. Table 2 shows the Tukey's Honestly Significant Difference (HSD) report for the interaction effects between all three factors—connector types, interconnect methods, and force levels.

Table 1. Effect tests for electrical resistance (* indicates statistical significance).

Source	Degrees of Freedom (DF)	Sum of Squares	F Ratio	Probability > F
Connector Type	1	0.0239	41.5042	<0.0001 *
Interconnect Method	2	0.0913	79.1392	<0.0001 *
Force Level	2	0.0371	32.1372	<0.0001 *
Connector Type × Interconnect Method	2	0.0019	1.6719	0.2001
Connector Type × Force Level	2	0.0016	1.4145	0.2544
Interconnect Method × Force Level	4	0.0769	33.3603	<0.0001 *
Connector Type × Interconnect Method × Force Level	4	0.0105	4.5073	0.0040 *

According to Table 2, buckle connectors performed better than snap. This could be due to the connector design. As illustrated in Figure 7a,b, the PCBs were inserted into pre-arranged sites within the plastic housing that were leveled down for its thickness. In the case of buckle connectors, the unmating load was oriented parallel to the plane of the textile substrate (indicated by horizontal black arrow in Figure 7c). This level difference securely locked the PCB in place (indicated by red dashed circle in Figure 7d), preventing any movement resulting from repeated mating/unmating cycles. This design limited PCB movement and protected the interconnects (indicated by orange lines in Figure 7) from mechanical stress caused by repeated cycling.

Table 2. Tukey HSD connecting letter report for Connector Type × Interconnect Method × Force Level (levels not connected by the same letter are statistically different).

Connector Type, Interconnect Method, Force Level	Connecting Letters Report						Average Resistance (Ω)
Snap, Solder, High	A						1.5000
Snap, Conductive Stitches, Medium	A	B					1.4967
Snap, Conductive Stitches, High	A	B					1.4900
Snap, Solder, Medium	A	B	C				1.4867
Snap, Conductive Stitches, Low	A	B	C				1.4867
Snap, Solder, Low	A	B	C	D			1.4733
Buckle, Conductive Stitches, Low		B	C	D	E		1.4325
Buckle, Conductive Stitches, High			C	D	E	F	1.4200
Buckle, Solder, Medium			C	D	E	F	1.4200
Buckle, Conductive Stitches, Medium			C	D	E	F	1.4167
Buckle, Solder, Low				D	E	F	1.4133
Buckle, Solder, High					E	F	1.4000
Snap, Conductive Epoxy, Low					F	G	1.3533
Snap, Conductive Epoxy, Medium						G H	1.2833
Buckle, Conductive Epoxy, Low						H	1.2533
Buckle, Conductive Epoxy, Medium						I	1.1667
Snap, Conductive Epoxy, High						I	1.1300
Buckle, Conductive Epoxy, High						I	1.1125

In contrast, the load was applied perpendicularly to the plane of the textile substrate to detach non-textile from textile side of the snap connector (indicated by vertical black arrow in Figure 7e). As a result, the level difference did not function as a mechanical fixture to protect the PCB from dislocation. This had the PCB on the textile-side connector solely relying on the interconnects to resist against the unmating force. The repeated mating/unmating cycles subjected the interconnects to significant mechanical stress resulting in relatively higher electrical resistance. This phenomenon likely explained why snap connectors exhibited higher resistance compared to buckle connectors and hence did not perform as well as the buckle connector.

To address this concern in future designs, the snap connector could be modified to include an additional guide or slot (indicated by red dashed circle in Figure 7f) that would restrict the vertical movement of the PCB, thereby preventing mechanical stress from being concentrated solely on the interconnects. This might influence other configurations in connector design and production, but the enhancement is expected to improve the performance and durability of snap connectors under repeated mechanical loading cycles.

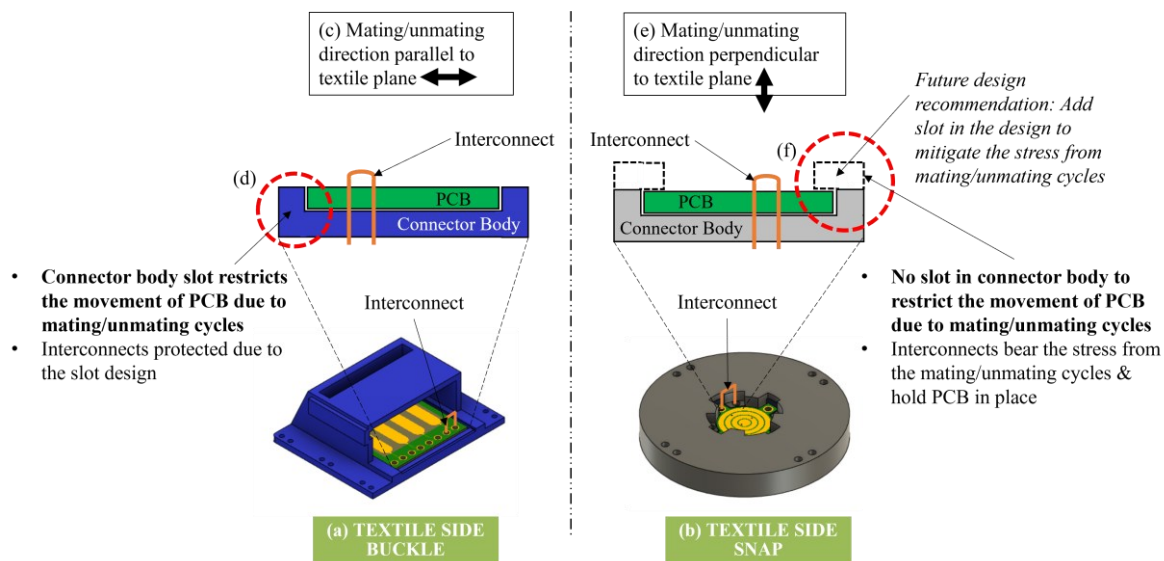


Figure 7. Textile side (a) buckle and (b) snap connector design along with (c) mating direction of buckle (horizontal arrow) and its (d) cross-section; and (e) mating direction of snap connector (vertical arrow) and its (f) cross-section.

Conductive epoxy performed significantly and consistently better than both conductive stitches and solder (Table 2). This may be attributed to the flexibility and strong adhesion of epoxy, which likely maintained better contact integrity over repeated cycles, compared to the rigid nature of solder and the potential displacement or loosening of conductive threads due to vibrations from connector mating and unmating. There was no statistically significant difference between the performance of conductive stitches and solder, possibly because both methods are susceptible to mechanical wear at the contact points, as sewn threads can shift or fray under stress, while solder joints can crack or fatigue locally over time, therefore resulting in similar levels of electrical degradation during repeated cycling.

Table 1 shows that the force level had a statistically significant impact on the resistance of the connectors. A significant difference was found particularly between the high and low force levels. The assumption was that higher mating force could significantly improve electrical contact, resulting in lower resistance. However, this was only true in the case of conductive epoxy but not conductive stitches and solder. The low resistance due to high mating force can be attributed to the enhanced physical interface between the connector terminals and the epoxy interconnects, reducing micro-gaps and contact resistance. Additionally, higher force may help overcome minor surface contaminants or irregularities, leading to more consistent and stable electrical pathways.

While the interaction of connector types with either interconnect methods or force levels was not statistically significant, the interaction between interconnect methods and force levels was. The lack of significance in the interactions involving connector types suggests that the connector design (buckle vs. snap) influenced performance consistently across different interconnect methods and force levels, without strong dependency on specific combinations. In contrast, the significant interaction between interconnect methods and force levels indicates that the effect of mating force on electrical resistance depend heavily on the type of interconnect used.

Conductive epoxy was more sensitive to changes in mating force. For instance, higher force significantly improved the contact quality for epoxy by enhancing adhesion and reducing contact resistance, whereas the performance of conductive stitches and solder remained relatively unaffected by force due to their inherent mechanical limitations. These limitations arise because conductive stitches involve threads that can shift, loosen,

or stretch with repeated movement, reducing the effectiveness of additional force to improve contact. Similarly, solder joints, while rigid, are brittle and prone to cracking or fatigue under mechanical stress, so increased pressure cannot restore lost electrical pathways. Notably, conductive epoxy at low force still outperformed the high-force versions of both stitches and solder. This differential response resulted in a significant interaction effect between interconnect method and force level.

The three-way interaction among connector types, interconnect methods, and force levels was also significant. From Table 2, the best-performing combination was the buckle connector with conductive epoxy under high mating force. However, it is worth noting that under high force and with conductive epoxy, the snap connector's performance was comparable to that of the buckle connector. This supported the explanation that the high mating force applied in this scenario helped compensate for the absence of mechanical fixture in the snap connector holding the PCB in place by improving the contact interface through increased pressure. Additionally, conductive epoxy's flexible and adhesive properties likely enhanced the electrical contact quality despite mechanical stresses, effectively reducing resistance even when the connector design was less optimal. Thus, the combination of high force and conductive epoxy mitigated some of the mechanical disadvantages inherent to the snap connector, resulting in performance similar to that of the buckle connector under these conditions.

3.2. Electrical Impedance

The magnitude of impedance was measured across the frequency range of 100 kHz (100,000 Hz) to 1 MHz (1,000,000 Hz) for both buckle and snap connectors throughout 0 to 5000 mating/unmating cycles. The experimental outcomes were not much different from those of resistance. As illustrated in Figure 8, the impedance increased steadily with the number of cycles for both connector types. This rise is attributed to mechanical degradation from repeated cycling, thereby increasing electrical impedance, similar to the resistance changes discussed earlier in Section 3.1. Among the interconnect methods, conductive epoxy showed consistent and gradual increase in impedance over time with progressive wear. Conductive stitches and solder exhibited occasional irregularities, likely due to fluctuations in contact quality while measuring impedance or visible degradation around 3000 cycles, similar to what was seen in the resistance (Figure 6).

When evaluating the influence of mating force, no clear trend emerged across the low, medium, and high force levels for any interconnect type, as also noted in [10]. This may be because, although higher mating force can improve conductive contact by increasing interface pressure, it might simultaneously accelerate mechanical wear, thereby offsetting its benefits. Based on results from electrical resistance, only the data from high-force level was used for analysis.

At 5000 cycles and high-force conditions, snap connectors with epoxied and stitched interconnects exhibited higher impedance magnitudes than buckle connectors of the same interconnect methods. These results align with earlier resistance findings, especially with conductive epoxy, and further support the conclusion that buckle connectors offer slightly better overall performance than snap connectors.

Beyond electrical performance, the direction of engagement relative to the fabric plane influences the user experience. Magnetic snap connectors mate and unmate perpendicular to the fabric surface, whereas magnetic buckle connectors operate parallel to it. Snap connectors may be advantageous for compact wearable systems such as wristbands or modular sensor units where quick, intuitive attachment is important. In contrast, buckle connectors may be more suitable for applications like heated garments or medical wearables that require stable alignment and distributed contact pressure across a larger area. Therefore, the selection between snap and buckle connector designs should consider

not only electrical performance but user experience and comfort in the intended application.

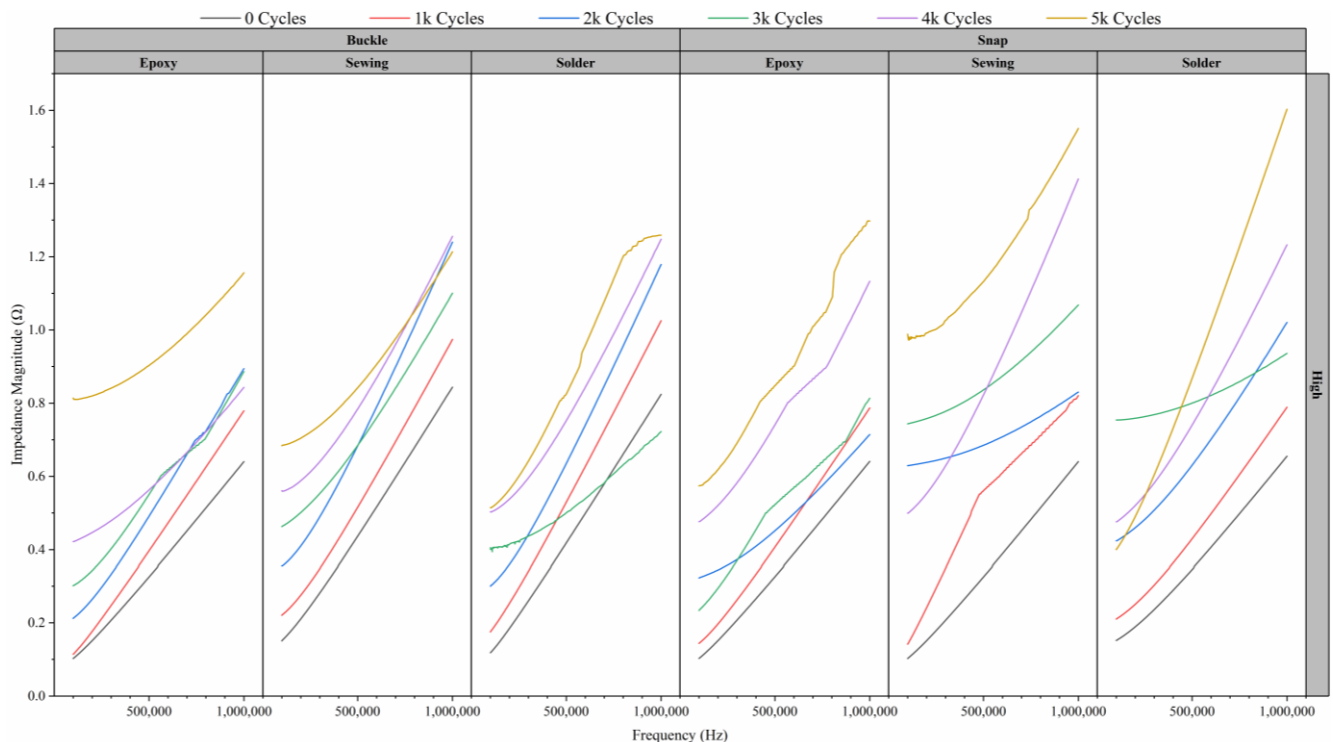


Figure 8. Impedance magnitude of buckle and snap connector across the three interconnect methods (conductive epoxy, conductive stitches, and solder) at every 1000 mating/unmating cycles starting from 0 up to 5000 at high force level.

4. Conclusions

This work presented the development and evaluation of two removable magnetic connectors, buckle and snap, integrated onto textile substrates using three interconnect methods, conductive epoxy, conductive stitches, and solder. To assess durability and electrical performance, the connectors were subjected to 5000 mating/unmating cycles under low, medium, and high force levels. Both connector types showed mechanically and electrically robust performance, withstanding all 5000 cycles. However, resistance and impedance magnitude increased significantly at each 1000 cycles interval due to mechanical wear. However, both connector types showed mechanically and electrically robust performance, withstanding 5000 cycles. All resistance and impedance values remained below 1.6 Ω , indicating no severe electrical degradation.

Buckle connectors generally outperformed snap connectors, likely due to their structural design, which reduced mechanical stress on the interconnects. Among the interconnect methods, conductive epoxy consistently showed better performance than conductive stitches and solder, with a slower and more stable degradation. Higher mating force reduced resistance, particularly for conductive epoxy, by improving electrical contact. This effect was minimal with conductive stitches and solder. Impedance measurements consistently supported these resistance findings.

For future work, the wash durability of the textile-side connectors will be evaluated, since the interconnects permanently attach the connector to the fabric and must endure repeated laundering. The connectors will also be integrated into functional garments for specific applications to assess their performance after defined wear and wash cycles. Furthermore, alternative materials such as flexible 3D-printed polymers will be investigated for the connector body to enhance mechanical compliance and wearer comfort. These

studies will provide valuable insights into real-world functionality and support the continued optimization of connector design and materials for practical wearable textile application.

Author Contributions: Conceptualization, M.S. and J.D.; methodology, M.S. and J.D.; software, P.U., S.L. and J.D.; validation, M.S. and J.D.; formal analysis, P.U. and S.L.; investigation, P.U. and S.L.; resources, M.S. and J.D.; data curation, P.U. and S.L.; writing—original draft preparation, P.U.; writing—review and editing, M.S.; visualization, P.U. and J.D.; supervision, M.S. and J.D.; project administration, M.S.; funding acquisition, M.S. and J.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was, in part, funded by the U.S. Government. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government. This material is based on research sponsored by U.S. Army ARDEC under Agreement number W15QKN-16-3-0001. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author because this research was, in part, funded by the U.S. Government.

Acknowledgments: The authors would like to thank Porticos, Inc. for assisting with prototyping; Sunray Scientific Inc. for mechanical and conductive epoxy application; and WEEL Technologies for providing the textile cable.

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

References

1. Azani, M.R.; Hassanpour, A. Electronic Textiles (E-Textiles): Types, Fabrication Methods, and Recent Strategies to Overcome Durability Challenges (Washability & Flexibility). *J. Mater. Sci. Mater. Electron.* **2024**, *35*, 1897. <https://doi.org/10.1007/S10854-024-13347-0>.
2. Stanley, J.; Hunt, J.A.; Kunovski, P.; Wei, Y. A Review of Connectors and Joining Technologies for Electronic Textiles. *Eng. Rep.* **2021**, *4*, e12491. <https://doi.org/10.1002/eng2.12491>.
3. Koncar, V. Introduction to Smart Textiles and Their Applications. In *Smart Textiles and Their Applications*; Woodhead Publishing: Oxford, UK, 2016; pp. 1–8. <https://doi.org/10.1016/B978-0-08-100574-3.00001-1>.
4. Cohen, J.R. Design and Testing of Connectors for Detachable Joining of E-Textiles to Rigid Electronics. Master's Thesis, California State University, Sacramento, CA, USA, 2024.
5. Rosenberg, Z.B.; Knowles, C.G.; Mills, A.C.; Jur, J.S. Design Strategies for E-Textile Manufacturing. In *Smart Clothes and Wearable Technology*, 2nd ed.; Woodhead Publishing: Oxford, UK, 2023; pp. 485–505. <https://doi.org/10.1016/B978-0-12-819526-0.00001-1>.
6. Stanley, J.; Griggs, K.; Handford, O.; Hunt, J.A.; Kunovski, P.; Wei, Y. Modular E-Textile Platform for Real-Time Sensing. In Proceedings of the ISWC'22: 2022 ACM International Symposium on Wearable Computers, Cambridge, UK, 11–15 September 2022; pp. 131–135. <https://doi.org/10.1145/3544794.3560293>.
7. Hardy, D.; Wickenden, R.; McLaren, A. Electronic Textile Reparability. *J. Clean. Prod.* **2020**, *276*, 124328. <https://doi.org/10.1016/J.JCLEPRO.2020.124328>.
8. Li, Q.; Ran, Z.; Ding, X.; Wang, X. Fabric Circuit Board Connecting to Flexible Sensors or Rigid Components for Wearable Applications. *Sensors* **2019**, *19*, 3745. <https://doi.org/10.3390/S19173745>.
9. 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. <https://doi.org/10.3390/TEXTILES4030019>.
10. Lingampally, S.D. *A Comprehensive Study of Textile-Integrated Connector and Interconnect Design for Wearable Technologies*; North Carolina State University: Raleigh, NC, USA, 2023.

11. Liu, M.; Lake-Thompson, G.; Wescott, A.; Beeby, S.; Tudor, J.; Yang, K. Design and Development of a Stretchable Electronic Textile and its Application in a Knee Sleeve Targeting Wearable Pain Management. *Sens. Actuators A Phys.* **2024**, *369*, 115102. <https://doi.org/10.1016/J.SNA.2024.115102>.
12. Ferreira, A.F.; Alves, H.; da Silva, H.P.; 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. <https://doi.org/10.1038/s41598-024-56733-8>.
13. Wang, Q.; Zeng, Y.; Zhang, R.; Ye, N.; Zhu, L.; Sun, X.; Han, T. EmTex: Prototyping Textile-Based Interfaces Through An Embroidered Construction Kit. In Proceedings of the UIST 2023—Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology, San Francisco, CA, USA 29 October–1 November 2023. <https://doi.org/10.1145/3586183.3606815>
14. Pearce, C.; Smith, G.; Choi, J.; Carlsson, I. Ebee: Merging Quilting, Electronics & Board Game Design. In Proceedings of the Conference on Human Factors in Computing Systems—Proceedings, San Jose, CA, USA, 7–12 May 2016; ACM: New York, NY, USA, 2016; pp. 3877–3880. <https://doi.org/10.1145/2851581.2891099>.
15. Joo, H.G.; Jang, Y.H.; Choi, H.S. Electrical Contact Resistance for A Conductive Velcro System. *Tribol. Int.* **2014**, *80*, 115–121. <https://doi.org/10.1016/J.TRIBOINT.2014.06.016>.
16. Seager, R.D.; Chauraya, A.; Zhang, S.; Whittow, W.; Vardaxoglou, Y. Flexible Radio Frequency Connectors for Textile Electronics. *Electron. Lett.* **2013**, *49*, 1371–1373. <https://doi.org/10.1049/EL.2013.2105>.
17. Barnes, K.N. *Zipper Connectors for Flexible Electronic Circuits*; NASA Tech Briefs: New York, NY, USA, 2003.
18. H. Ohno, F. Narui, and S. Hayashi, “Zipper-type electrical connector,” May 23, 1994. <https://patents.google.com/patent/US5499927A/en>
19. Mehmman, A.; Varga, M.; Gönner, K.; Troster, G. A Ball-Grid-Array-Like Electronics-to-Textile Pocket Connector for Wearable Electronics. In Proceedings of the ISWC 2015—Proceedings of the 2015 ACM International Symposium on Wearable Computers, Osaka, Japan, 7–11 September 2015; ACM: New York, NY, USA, 2015; pp. 57–60. <https://doi.org/10.1145/2802083.2802093>.
20. Kozel, C.A. Zero Insertion Force Miniature Grid Array Socket. US5637008A, 1 February 1995
21. Mehmman, A.; Varga, M.; Tröster, G. Reversible Contacting for Smart Textiles. In *Smart Textiles: Fundamentals, Design, and Interaction*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 185–198. https://doi.org/10.1007/978-3-319-50124-6_9.
22. Greig, T.; 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. <https://doi.org/10.1109/TCPMT.2022.3209591>.
23. Righetti, X.; Thalmann, D. Proposition of a Modular I2C-Based Wearable Architecture. In Proceedings of the Mediterranean Electrotechnical Conference—MELECON, Valletta, Malta, 26–28 April 2010; pp. 802–805. <https://doi.org/10.1109/MELCON.2010.5475965>.
24. Li, Y.; Takahashi, R.; Yukita, W.; Matsutani, K.; Caremel, C.; Iwamoto, Y.; Lee, S.; Yokota, T.; Someya, T.; Kawahara, Y. Plug-N-Play E-Knit: Prototyping Large-Area E-Textiles Using Machine-Knitted Magnetically-Repositionable Sensor Networks. In Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction, Bordeaux, France, 4–7 March 2025; ACM: New York, NY, USA, 2025; pp. 1–7. <https://doi.org/10.1145/3689050.3705973>.
25. Gonçalves, C.; da Silva, A.F.; Gomes, J.; Simoes, R. Wearable E-Textile Technologies: A Review on Sensors, Actuators and Control Elements. *Inventions* **2018**, *3*, 14. <https://doi.org/10.3390/INVENTIONS3010014>.
26. Lehn, D.I.; Neely, C.W.; Schoonover, K.; Martin, T.L.; Jones, M.T. e-TAGs: E-Textile Attached Gadgets. 2004. Available online: <https://vtechworks.lib.vt.edu/items/ecc79179-1690-40e1-928e-09d02fe831b4> (accessed on 17 March 2025).
27. Lehn, D.I.; Neely, C.W.; Schoonover, K.; Martin, T.L.; Jones, M.T. Ettachments for E-Textiles. Available online: <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=b0ebc7f2cff08633b1c988e52544213c813e1b48> (accessed on 17 March 2025).
28. Simegnaw, A.; Malengier, B.; Rotich, G.; Tadesse, M.G.; Van Langenhove, L. Review on the Integration of Microelectronics for E-Textile. *Materials* **2021**, *14*, 5113.
29. Leśnikowski, J. Textile Connector for Smart Textile Applications. *Fibres Text. East. Eur.* **2024**, *32*, 33–40. <https://doi.org/10.2478/ftce-2024-0013>.
30. Stanley, J.; Hunt, J.A.; Kunovski, P.; Wei, Y. Novel Interposer for Modular Electronic Textiles: Enabling Detachable Connections between Flexible Electronics and Conductive Textiles. *IEEE Sens. Lett.* **2022**, *6*, 6500104. <https://doi.org/10.1109/LSSENS.2022.3176726>.
31. ASTM International. *Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure (Constant-Rate-of-Extension Tensile Testing Machine)*; ASTM International: West Conshohocken, PA, USA, 2017. <https://doi.org/10.1520/D2261-13R17E01>.

32. From Fiber to Function: Closing the Loop on E-Textiles|Circular Berlin. Available online: <https://circular.berlin/from-fiber-to-function-closing-the-loop-on-e-textiles/> (accessed on 8 November 2025).
33. Winterhalter, C.; Teverovsky, J.; Wilson, P.; Slade, J.; Horowitz, W.; Tierney, E.; Sharma, V. Development of Electronic Textiles to Support Networks, Communications, and Medical Applications in Future U.S. Military Protective Clothing Systems. *IEEE Trans. Inf. Technol. Biomed.* **2005**, *9*, 402–406. <https://doi.org/10.1109/TITB.2005.854508>.

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.