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Evaluation of the Electrical Integrity of E-Textiles Subjected to Abrasion

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ABSTRACT

The overall goal of this research was to evaluate wearable e-textiles in terms of their electrical integrity while they are subjected to environmental conditions and abrasion. In a previous publication (Bogan, Seyam and Slade, submitted to JOTI 2016), different woven samples of electronic improved outer tactical vest (EIOTV) with two narrow conductive traces woven in warp direction were subjected to range of temperatures and RHs, including extreme conditions. It was found that electrical resistance of networks was affected by changes in air temperature and RH and the quality of the weld had the greatest impact on electrical integrity of the conductive network, especially in more extreme environmental conditions. This part of the study dealt with the evaluation of electrical integrity of range of EIOTVs while they were subjected to two different modes of abrasion tests to simulate everyday wearing that occurs between EIOTV and standard woven abradant (using Martindale abrasion testing) and against environmental terrain such as sand (using Wyzenbeek abrasion testing). The effects of e-yarn type, number of e- yarns/trace, and weld quality on electrical integrity, assessed by increase in the network electrical resistance as the key indicator of network failure, of the EIOTVs while subjected to abrasion resistance were evaluated. The electrical resistance of all EIOTV samples remained unchanged after 50,000 cycles of Martindale abrasion testing. The results of Wyzenbeek abrasion testing showed that EIOTV fabrics from higher number of e-yarn/trace or e-yarns with higher tex-content exhibited higher electrical integrity compared to those from less number of e-yarns/trace or less tex-content.

Keywords: electronic textiles (e-textiles), smart textiles, weldability, electrical resistance, electrical integrity, abrasion resistance

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Introduction

The research during the last fifteen years in the field of electronic textiles (e-textiles) resulted in developing quite a few smart products for civilian and defense applications such as thermal clothing for protection from cold weather, musical jackets, flexible foldable computer keyboard, antenna, acoustic array that can locate source of noise, structure health monitoring and automotive seat occupancy sensing (Bogan, 2016, Chiolerio and Stoppa, 2014, Dhawan, Ghosh and Seyam, 2005, Suh, 2010, Tao, 2001) and research papers such as in (Grant et al., 2004, Haroglu, Powell, and Seyam, 2016, Seyam and Hamouda 2016).

Wearable e-textiles for civilian and defense applications are exposed to environmental conditions and wear and tear, including environmental terrain such as sand, and they are expected to provide comfort to the users and endure repeated home launderings (Charette, 2009, Honarvar and Latifi, 2016, Vervust et al, 2012, Cherenack and Pieterson, 2012). Regardless of the environmental degree of severity that e-textiles ae subjected to, their electrical integrity must be maintained to provide reliable data and signal processing and they should be designed to withstand these conditions. Electrical conductivity is the main physical property that is capable of transforming a textile material into a smart material. Conductivity must be high enough or electrical resistance must be low enough to allow a flow of electric energy for power and data transmission through e-textiles. Any break in a wire, surface abrasion, surface corrosion, or unreliable interconnection will result in adverse change in electrical resistance, which will result in circuit failure.

The overall goal of this research was to evaluate wearable e-textiles in terms of their electrical integrity while they are subjected to environmental conditions and abrasion. In a previous publication (Bogan, K., Seyam, A.M., and Slade, J., 2018), different woven samples of electronic improved outer tactical vest (EIOTV) with two narrow conductive traces woven in warp direction, which are formed into networks by the addition of ultrasonic weld points following method explained in (Slade, Houde, and Wilson, 2015), were subjected to range of temperatures and RHs, including extreme conditions. This part of the study dealt with the evaluation of electrical integrity of range of EIOTVs while they were subjected to two different modes of abrasion tests to simulate normal everyday wearing that occurs between EIOTV and standard woven abradant (using Martindale abrasion testing) and against environmental terrain such as sand (using Wyzenbeek abrasion testing). The electrical integrity of EIOTVs was evaluated by monitoring the electrical resistance while they were subjected surface abrasion. The data collected from these tests will help to interpret the factors that adversely affect electrical resistance, which may help guide the design and manufacturing of future e-textiles. The procedures and equipment used to monitor the electrical resistance explained in our previous publication (Bogan, Seyam and Slade, submitted to JOTI 2016) were followed and omitted from this paper to avoid redundancy.

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Experimental Design

The experimental design was constructed to identify and understand the change in electrical resistance of the woven conductive networks, in terms of e-textile formation factors, caused by abrasion. The formation factors (yarn type, number of e-yarns/trace (yarns containing electrically conductive elements), and weldability rating) along with fabric samples identification and their dimensions are identified in Table 1. Network A and B assigned to the two separate woven traces that run in the warp direction of the test sample. The electrical resistance of Network A and Network B was measured independently. It should be noted that the term trace refers solely to the woven trace of the conductive network; whereas the term network refers to the woven trace that encompasses weld points.

Table 1. Fabric Samples, Formation Factors, and samples' dimensions (Figure 1) for Abrasion testing

Fabric	Sample ID	Network	**Formation Factor 1:** Yarn Type	**Formation Factor 2:** No. of E-Yarns/Trace	**Formation Factor 3:** Weldability	Length of Sample, fabric edge to fabric edge (inch)	Length of wire from fabric edge to end of pin plug, total (inch)	Length of measured Network (inch) [Absolute Electrical Resistance]	Length between main weld points (inch) [Adjusted Electrical Resistance]	th of Sample (inch)
EIOTV 2	2.1	A	UEY	6	Moderate	12.250	5.000	17.250	11.625	2.250
		B	UEY	6			4.500	16.750	11.625	
	2.2	A	NEY	6		12.500	4.750	17.250	12.125	2.375
		B	NEY	6			4.500	17.000	12.125	
EIOTV 3	3.1	A	UEY	8	Poor	12.000	4.000	16.000	11.500	2.625
		B	UEY	8			3.750	15.750	11.625	
	3.2	A	UEY	8		12.000	4.000	16.000	11.375	2.625
		B	UEY	8			3.125	15.125	11.500	
	3.3	A	NEY	8		13.000	4.500	17.500	12.250	2.500
		B	NEY	8			2.875	15.875	12.125	
EIOTV 4	4.2	A	UEY	8	Good	12.000	2.500	14.500	11.250	2.750
		B	UEY	8			3.125	15.125	11.375	
	4.3	A	NEY	8		13.000	3.000	16.000	12.250	2.750
		B	NEY	8			2.875	15.875	12.375	

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Two different e-yarns were used NEY and UEY and their description is shown in Table 2. Formation factor 2 levels were 6 or 8 e-yarns/trace. Formation factor 3 is weldability rating, which may be best considered as a processing or performance characteristic that is attributed to factors 1 and 2. Weldability rating is judged by the weld point's ability to form a low electrical resistance weld on the fabric (poor, moderate, good). These observations were provided from Infoscitex (IST). The weldability ratings is based on the amount of tex-yarn (refers to yarn formed from textile materials) present at the weld point. More tex-yarn would interfere with connection of the weld point to the conductive Cu alloy wires in the yarn by reducing the pressure between conductive elements.

Materials and Methods

Yarn

Two different e-yarns were used in the e-textile samples. The specifications of the two e-yarns used to form the e-textile fabrics are given in Table 2. The NEY e-yarn has higher content of tex-yarns compared to UEY e-yarn. Where e-yarns are not present in the warp sequence, a 500 denier air textured nylon yarn was used. The 500 denier air textured yarn was used for the filling.

Table 2. E-Yarn Details

E-Yarn	# of wires in E- Yarn	Description
NEY	12	-Blend of enameled Cu alloy filament and conventional tex-yarns - **Higher content of tex-yarns** compared to UEY -Wire is a Cu alloy with a 40μm diameter and ~2.00E-08 resistivity
UEY	12	-Blend of enameled Cu alloy filament and conventional tex-yarns - **Lower content of tex-yarns** compared to NEY -Wire is a Cu alloy with a 40μm diameter and ~2.00E-08 resistivity

Fabric Formation

All e-textile fabrics were formed using a CCI sample loom (Model: SL8900 Evergreen) with a single rapier filling insertion system. The specifications for the fabrics are the same with the exception of e-yarn type and the number of e-yarns woven in the conductive trace as indicated in Table 1.

Test Sample

Figure 1. shows a prepared test sample for abrasion resistance tests. Areas for electrical resistance measurement are marked in the figure as (G, H, I). In Figure 1: (A) Trace of Network A. (B) Trace of Network B. (C) Center weld points, two weld points per trace. The center weld points were not connected to the DAQ. (D) Main weld points that connect the test wire to the trace, two weld points per each end of trace are applied. Four weld points in total form the conductive network and enable compatibility with the DAQ system. (E) Location where the pin plug is soldered to the test wire. After soldered, a heat shrink tube is added to protect the connection point. (F) Pin plug that connects to the test lead cable. (G) Represents total length of trace from which the electrical resistance is measured, electrical resistance of this length is referred to as absolute electrical resistance. (H) Represents the adjusted length of the electrical resistance measurement, electrical resistance of this length is referred to as adjusted electrical resistance. (I) The blue square indicates the area designated for abrasion testing. All samples' specifications are depicted in Table 1.

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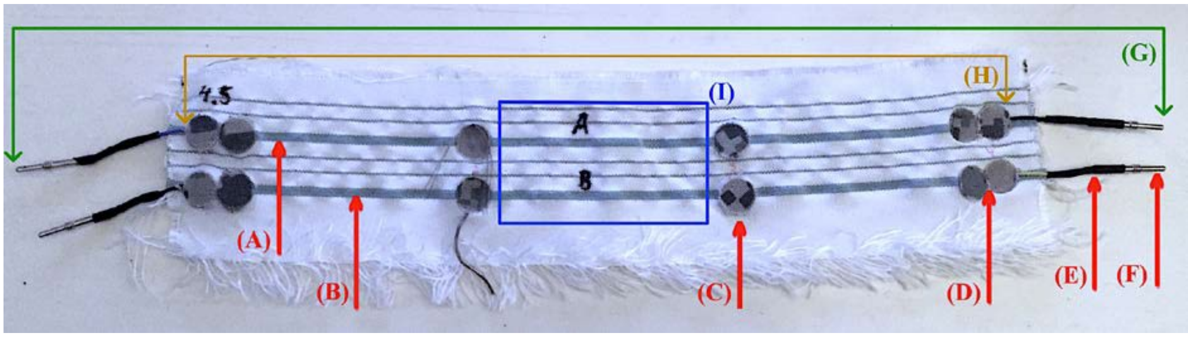

Figure 1. Prepared Test Sample

Apparatus

Electrical resistance measurements were collected with a data acquisition (DAQ) system. The DAQ is explained in detail in (Bogan, Seyam and Slade, submitted to JOTI 2016), Martindale and Wyzenbeek abrasion equipment was used for abrasion resistance testing. This equipment follows standardized test methods for textile testing and is further explained below.

Testing

Test methods used to measure the abrasion resistance are identified in Table 3. These tests were selected because together their results will provide a good indication of the reliability of the conductive network while the e-textiles are subjected to surface abrasion.

The DAQ system set up steps and offset electrical resistance measurement of each channel was noted prior to the start of the testing. After the experimental set up was completed the tester software was started and data logging began. At the end of each experiment data logging was stopped.

Table 3. Test Methods Used in this Study

Test # (if applicable) or Description	Title
ASTM D 4966 *	Abrasion Resistance to Textile Fabrics (Martindale Abrasion)
ASTM D 4157 *	Abrasion Resistance to Textile Fabrics (Wyzenbeek Abrasion)

Note. * Indicates that in addition to the test method listed the DAQ system was used to collect electrical resistance measurements.

Due to the addition of DAQ test equipment it was necessary to modify some of the testing and in those instances, the variations from the standard method will be detailed. Testing was performed under standard atmospheric conditions of 21°C □2°C and a relative humidity of 65% □5%. Abrasion testing was conducted in the NCSU Dame S. Hambly Physical Testing Laboratory.

The intent of these tests was to quantify the abrasion resistance of the central portion of each sample with abrasion test fixtures while monitoring the electrical resistance of the conductive networks with the DAQ system. Electrical resistance is measured following the DAQ resistance-only experimental setup. Two abrasion tests were conducted: Martindale and Wyzenbeek.

Abrasion occurs on fabrics through the wearing and care of a garment. Fabric wear is the amount of deterioration imparted to the fabric because of fiber or yarn breakages, cutting or loss of fibers. As for measuring the electrical resistance of a e-textile under abrasion, the wear and tear translates to electrical failure. The point at which the samples reach failure is when the resistance measures 10 Ω, at such high value of resistance the conductive network fails to function.

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Martindale

Martindale abrasion testing was selected to replicate/simulate the everyday wearing abrasion that occurs between the e-textile and a standard abradant woven fabric. ASTM D 4988 Standard Test Method for Abrasion Resistance of Textile Fabrics (Martindale Abrasion Tester Method) was used along with the DAQ system to assess the electrical resistance of the conductive networks of the e-textile samples.

The six-head James H. Heal & Co. Ltd Nu-Martindale Abrasion & Pilling Tester SN#403/97/2073 and the lighter 9kPa mounting weights were used. The abradant was the standard fabric identified in the test method, a new piece of plain weave worsted wool fabric mounted on top of the standard felt padding. This abradant was selected because it has a comparable hand and weight to that of the e-textile test samples.

The woven e-textile is too thick to fit in the test sample holder so there was a variation made to the Martindale sample preparation. The test sample holder was covered with a layer of polyurethane foam and secured in place with a rubber band as pictured in Figure 2.A and 2.B. Then the abrading area of test sample shown in Figure 1 was centered within the sample holder. The length outside the abrading area was then wrapped around the test sample disc and secured in place with a second rubber band. Network A and B of the test sample were tested concurrently. The test lead cables are secured in place with tape to the rotating table that moves the test samples on the abrading surface (Figure 2 C).

To determine the total abrasion cycles for the test a dry run test was performed. It was observed from the dry run test that after 10,000 cycles there was no change to the electrical resistance of both networks. For this reason, Martindale testing ran for 50,000 cycles. A summary of the Martindale test details is outlined in Table 4.

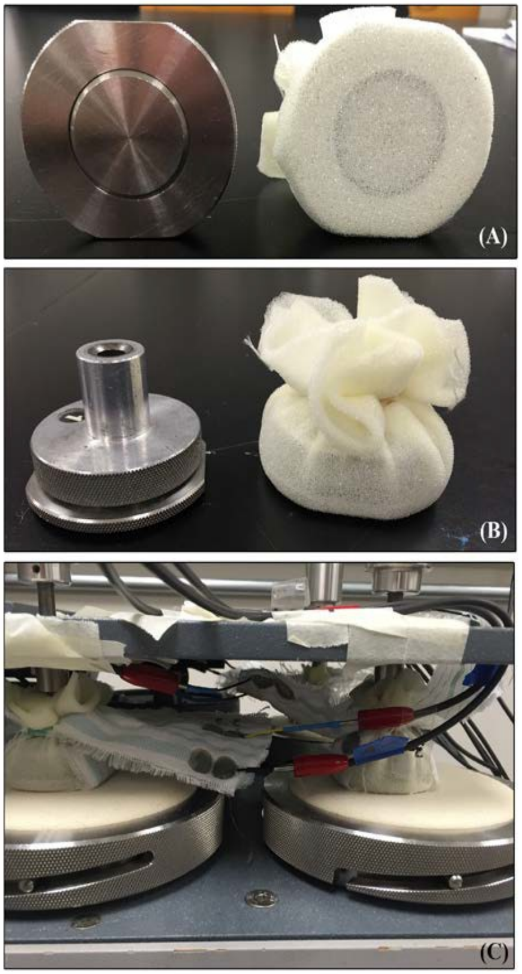

Figure 2. Martindale Test Setup for Sample Holder. (A) Modification made to sample holder. (B) Alternative view of modification made to sample holder. (C) Martindale test set up with all three test samples connected to test lead cables.

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Wyzenbeek

Wyzenbeek abrasion testing was selected to replicate/simulate garment abrasion against environmental terrain, i.e. sand. ASTM D4517 Standard Test Method for Abrasion Resistance of Textile Fabrics (Wyzenbeek Abrasion Tester- Oscillatory Cylinder Method) was used along with the DAQ system to assess the electrical resistance of the conductive networks of the samples.

The Wyzenbeek test fixture (Figure 3) was prepared with a head weight of 3 and tension of 4. The abradant used was 800-grit sandpaper, which was replaced with a new sheet prior to testing each sample. This abradant was selected as to contribute to the data collected from the preliminary abrasion testing conducted by IST at NSRDEC. A summary of the Wyzenbeek test details is outlined in Table 5.

Wyzenbeek test samples were tested one at a time. Network A and B of each sample were tested concurrently. Sample preparation follows that of the test standard. However, it should be noted that positioning the abrading area (Figure 1) and applying even tension to the test sample is crucial to obtain accurate resistance data. Once even tension is applied, and the abrading area is centered within the abrading pad of the Wyzenbeek fixture, the test lead cables were connected to the pin plugs of both networks. Wyzenbeek testing ran continuously and was only stopped after both networks failed. The Wyzenbeek fixture has a counter that tracks the number of abrasion cycles completed.

Table 4. Test Information for Martindale Abrasion Resistance

Martindale Test Information	
Test method	D4966-12
Total testing hours	17.5
DAQ Sample interval	2,000 ms
Abradant	Worsted Wool (test standard)
Head weight Pressure	9kpa
Configuration motion	Back and forth movement
Sample Preparation	Secure test sample around disc with rubber band, see Figure 2 (A-C)
Testing order	All samples tested concurrently
Abrasion cycles	50,000

Table 5. Test Information for Wyzenbeek Abrasion Resistance

Wyzenbeek Test Information	
Test method	D4517-13
DAQ Sample interval	1,000 ms
Abradant	800 grit sand paper
Head Weight Pressure	3
Tension	4
Sample preparation	Follows test method
Run test until	Network A and B reach failure at 10 □

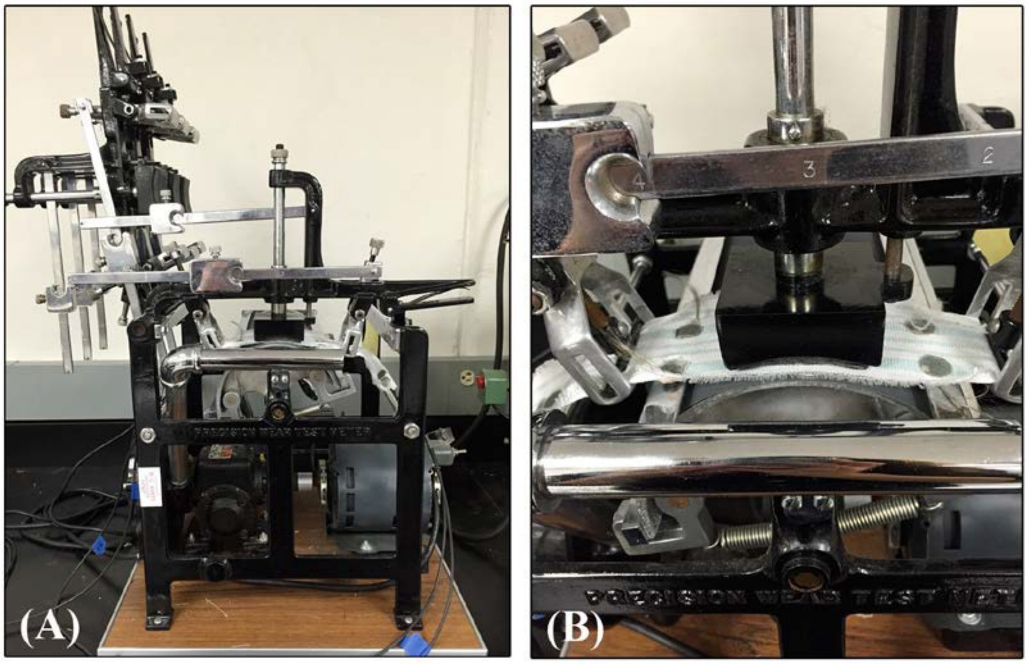


Figure 3. Wyzenbeek Test Setup. (A) Side view of Wyzenbeek Test set up. (B) Close-up of sample during abrasion on Wyzenbeek.

Analytical Approach

An exploratory data analysis was undertaken to understand the effect of surface abrasion testing on the electrical resistance of the conductive networks. This approach was also used to understand the effect of the formation factors, e-yarn type, number of e-yarns per trace, and weldability rating.

To best manage the test factors, data visualization was used to examine the data in graphical form. With this approach trends and relationships between resistance and abrasion cycles were observed.

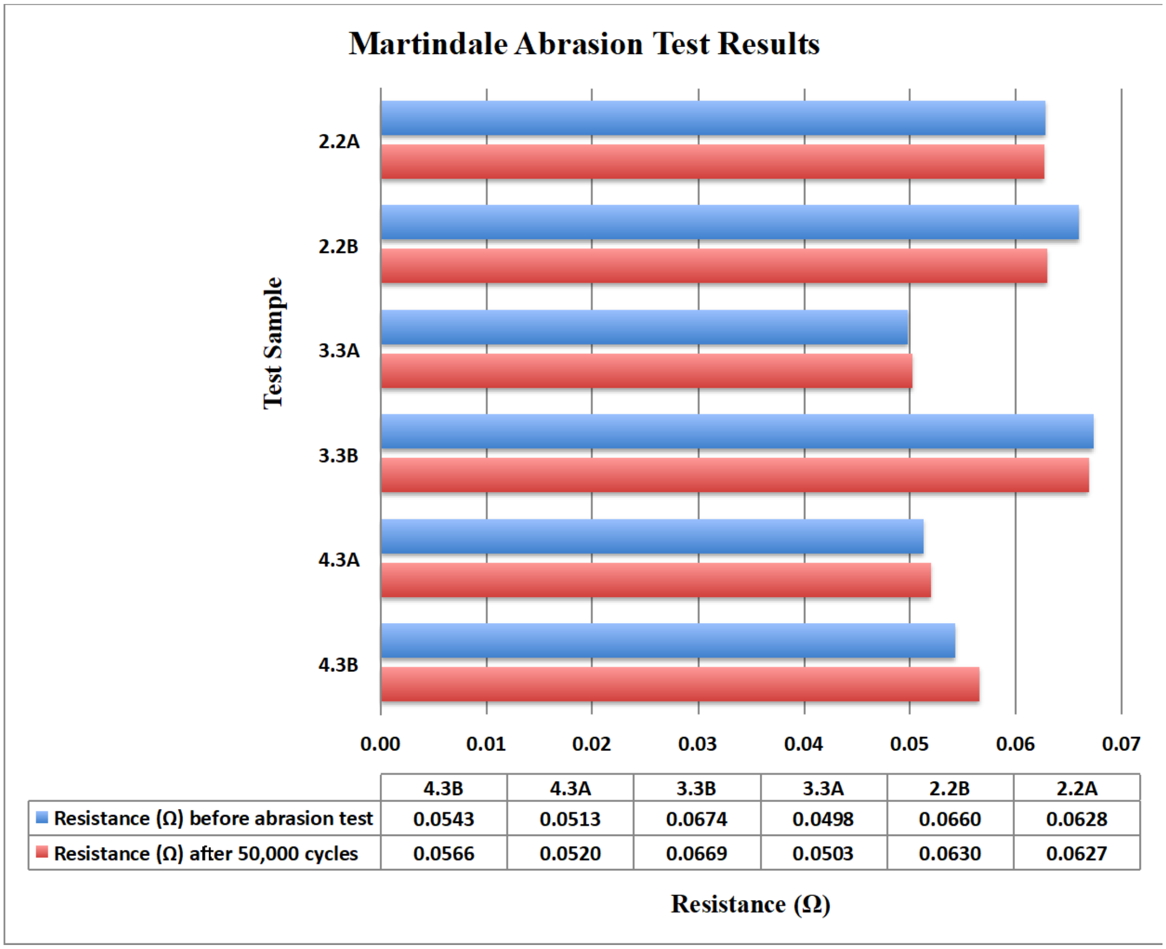
An adjusted data set was used for this exploratory data analysis. The first step in preparing the adjusted data (i.e. adjusted electrical resistance) was to deduct the initial offset measurement from the point-in- time electrical resistance to get the absolute electrical resistance. The adjusted electrical resistance was calculated by dividing the absolute electrical resistance by its measured length (Figure 1.G) and multiplying it by the length of the conductive trace between the main weld points (Figure 1.H).

Martindale test results are based on the adjusted electrical resistance measurements taken before and after testing. Wyzenbeek test results used the adjusted electrical resistance collected continuously from the start of test until network failure.

Results and Discussion

Martindale test results are summarized by the comparison between the initial electrical resistance and electrical resistance post 50,000 abrasion cycles (Figure 4). There was very little to no change in resistance after 50,000 cycles. To support the resistance data, pictures of the test samples are laid out in Figure 5. There was unnoticeable change if any made to the test samples. Based on these findings, samples 2.2, 3.3, and 4.3 pass the standardized test for abrasion resistance testing with the Martindale fixture.

The EIOTV fabrics were designed to endure surface abrasion resistant; therefore, a change in electrical resistance within 50,000 movements is unlikely with Martindale testing parameters. For this reason, an option for future Martindale testing of EIOTV fabrics of similar structures is to measure the resistance before and after the test after given number of incremental cycles until failure using a Keithley meter. Other movement of the abradant such as figure eight should be considered. Furthermore, the traces of these samples would not require soldering to pin plugs. As previously discussed, issues with inaccurate resistance measurements may arise with soldering. Even though the IST DAQ presented these issues during the Martindale test, the Keithley measurements from before and after the 50,000 movements can conclusively show the resistance was not adversely affected by abrasion testing.



	4.3B	4.3A	3.3B	3.3A	2.2B	2.2A
🟦 Resistance (Ω) before abrasion test	0.0543	0.0513	0.0674	0.0498	0.0660	0.0628
🟥 Resistance (Ω) after 50,000 cycles	0.0566	0.0520	0.0669	0.0503	0.0630	0.0627

Figure 4. Martindale Abrasion-Electrical Resistance Test results

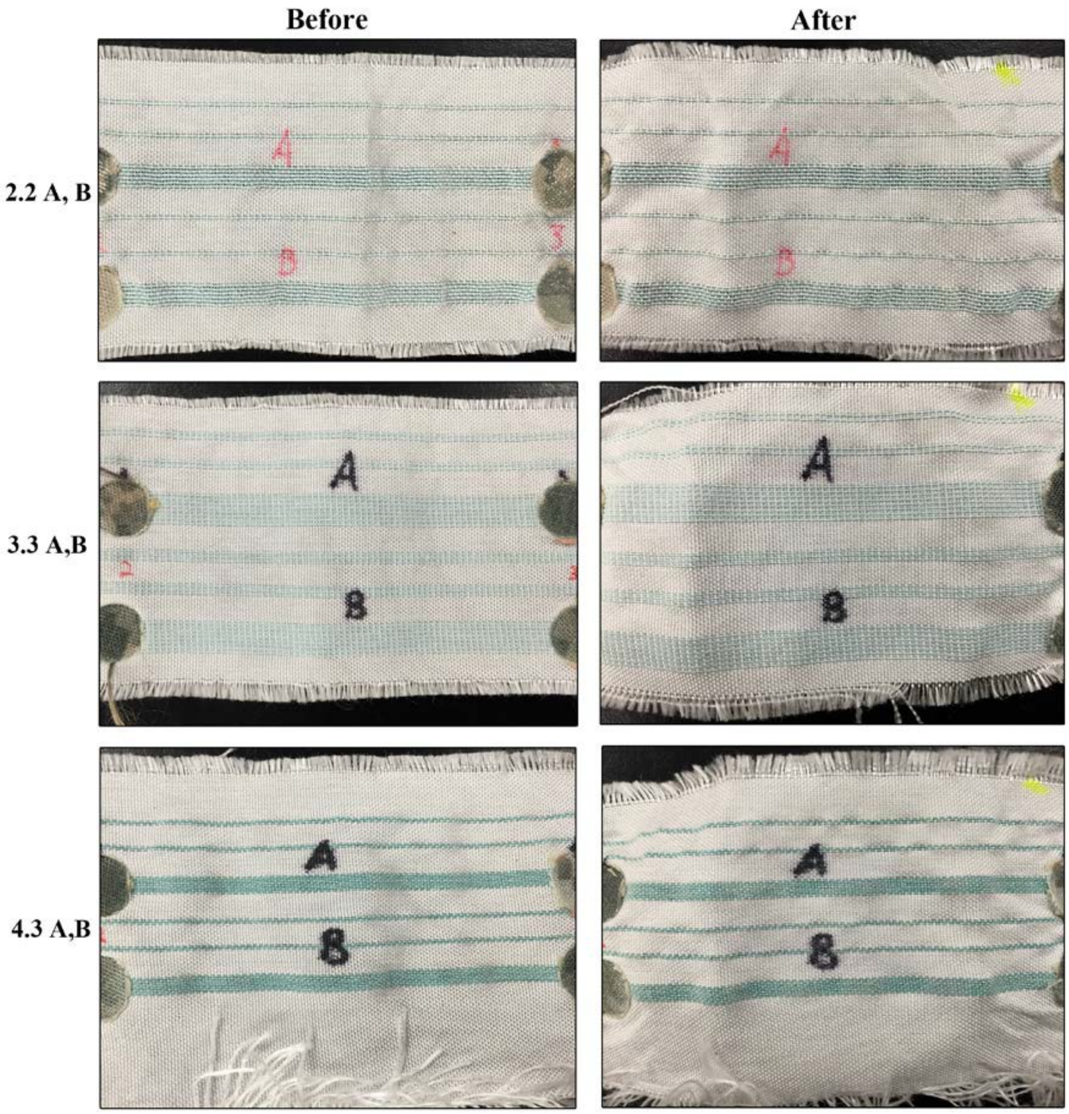


Figure 5. Martindale Test Sample Photos before and after 50,000 cycles. Note. In the after pictures, slight puckers around abrasion testing area is due to pressure from the sample being wrapped around the test sample holder.

Figure 6. shows the electrical resistance-abrasion cycles relationship to understand the effect Wyzenbeek abrasion testing had on the change of electrical resistance. Formation factors for the test samples are labeled above each data series. To support the electrical resistance data, images of the test samples post failure (after reaching 10□) are laid out in Figure 7. It is important to note that network 4.2B was omitted from Figure 6 due to issues with preparation of the sample that caused connectivity issues between the sample and DAQ.

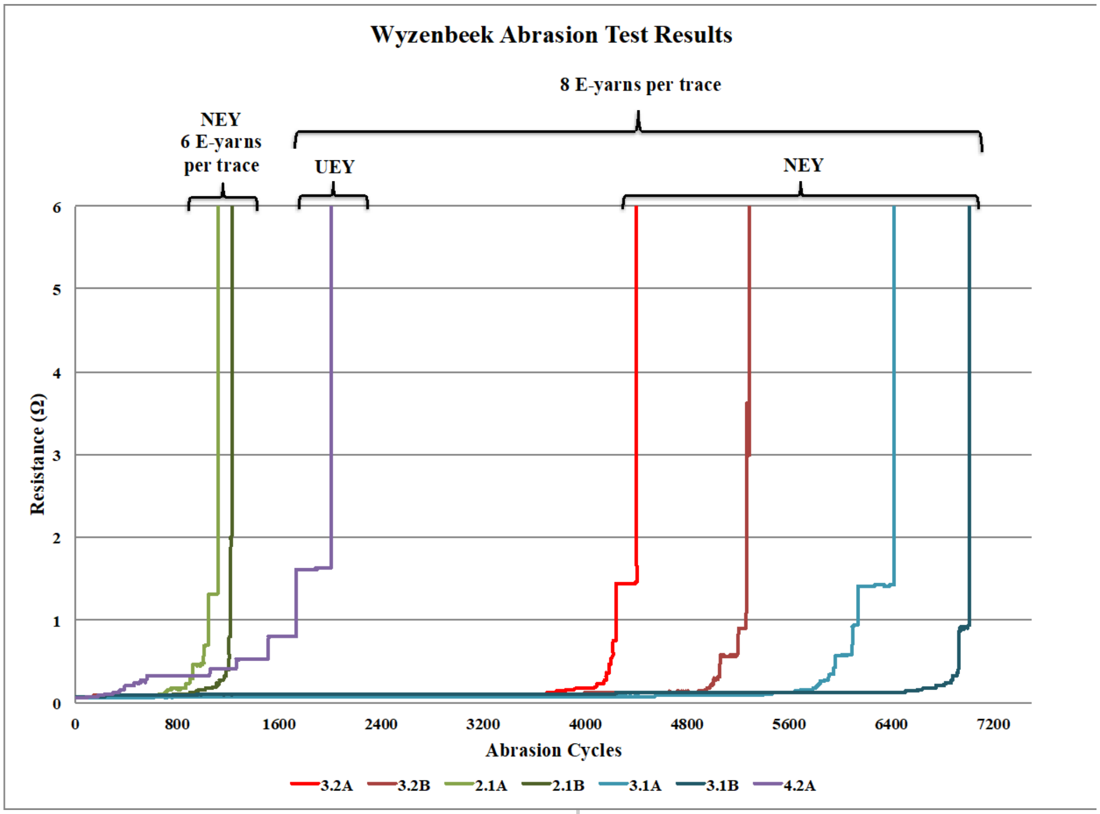


Figure 6. Wyzenbeek Abrasion-Electrical Resistance Test Results.

Prior to this study, IST conducted an initial round of abrasion testing. Observations from this initial test helped guide the observations on the results for this study. The data series for each network shows a clear trend for failure. All samples had fairly steady electrical resistance measurements up to a certain point, beyond which electrical resistance values start to increase slowly. They then tended to reach a point at which they began to increase quickly, with failure soon after. This transition from the slow to rapid values typically occurred when the 0.5-1 ohm resistance threshold was crossed. Therefore, this serves as a useful indicator of the onset failure for these types of fabrics.

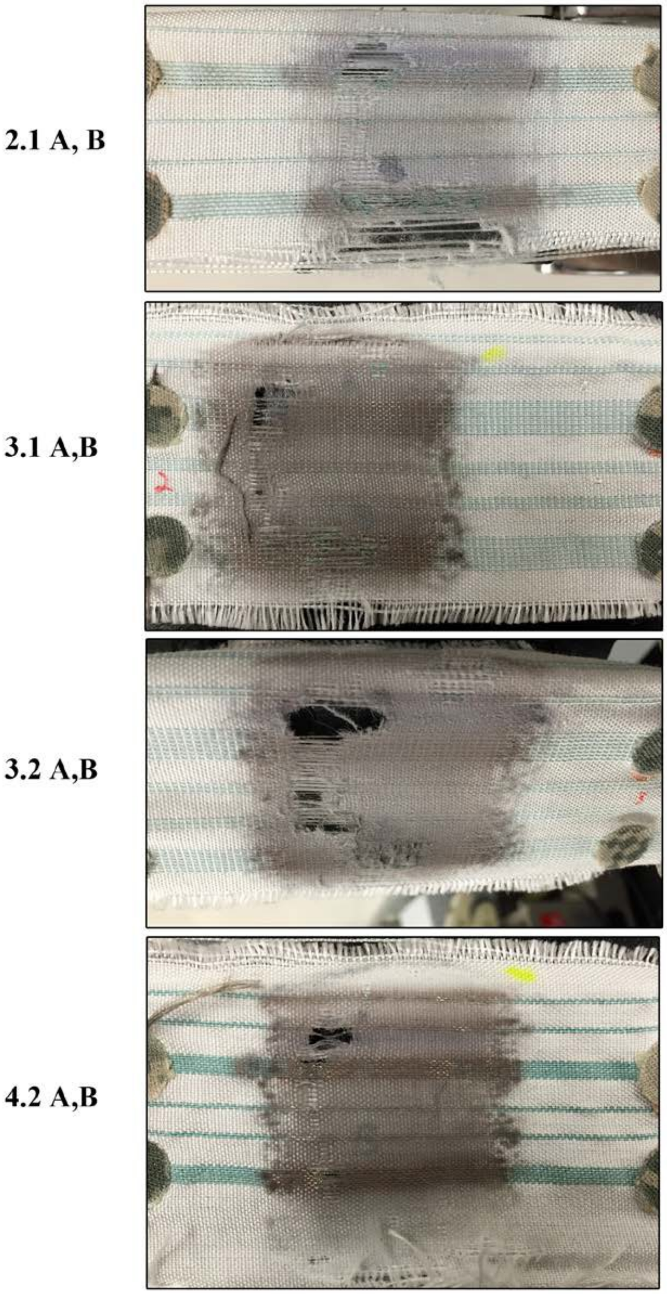


Figure 7. Wyzenbeek Test Sample Photos: Network A is top trace and Network B is bottom trace in pictured test sample. The onset of failure occurred at different cycles of abrasion testing. A possible explanation for the variation in the number of abrasion cycles is based on the formation factors, e-yarn type and number of e- yarns in the trace.

It was observed that failure occurs first with sample 2.1 (NEY, 6 e-yarns per trace) at ~1,200 abrasion cycles. Second to fail was 4.2A (UEY, 8 e-yarns per trace) at ~ 2,000 abrasion cycles. 4.2B was omitted from analysis due to sample preparation issues that rendered the electrical resistance of the network to be inaccurate due to connectivity issues between the sample and DAQ. The remaining samples 3.1 and 3.2 share the same specs (NEY, 8 e-yarns per trace). Failure for these samples occurred within a range from ~4,400 to ~7,000 abrasion cycles.

Sample 2.1 (NEY, 6) failed first because it had 6 e-yarns in trace, which likely means that the load is concentrated in the same area of the woven trace, making it more susceptible to abrasion. For this reason, the trace carried more load over less e-yarns resulting in a fast failure. From Figure 7 it can be observed that network A and B of sample 2.1 shared the same level of abrasion. A possible explanation for this could be that even tension was applied to both traces during the test set up.

Failure of 4.2A (UEY, 8) occurred ~2,400 abrasion cycles before that of 3.2A (NEY, 8). This shows that by only increasing the number of e-yarns from 6 to 8 will not drastically improve the abrasion resistance; the yarn type is also an important factor. Sample 4.2 has UEY yarn, which has less textile yarn wrapped around the conductive core, making it more susceptible to abrasion. Even though the abrasion load is more evenly distributed across a trace with 8 e-yarns, less protection on the conductive core will result is a faster failure.

The best preforming fabric was EIOTV 3, from which samples 3.1 and 3.2 were cut. This fabric has NEY yarn with 8 e-yarns per trace. NEY yarns have more textile yarn wrapped around the conductive core wires, making it less susceptible to abrasion. Thus, a conductive trace with 8 of the more protected e-yarn had the best abrasion resistance. Variation on the number of cycles to reach failure between samples 3.1 and 3.2 can be explained by possible inconsistencies with sample preparation steps.

In summary, all samples performed to standard from the Martindale test method. This implies that the samples exhibit good abrasion resistance to everyday wear that occurs between the e-textile and the test standard wool abradant. For the Wyzenbeek test method, the samples exhibited a more varied response. This implies that the samples would have varied abrasion resistance against environmental terrain, such as sand.

The e-textile construction that provides the best abrasion resistance performance is based on results from Martindale and Wyzenbeek testing. All samples remained unchanged from Martindale testing, so the best performing fabric from Wyzenbeek testing, EIOTV 3, is the most suitable to support abrasion resistance.

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Conclusion

The observations on abrasion testing found that the e-textile construction that best supports abrasion resistance is EIOTV 3. All samples remained unchanged from Martindale testing, which implies they exhibit good abrasion resistance to everyday wear that occurs between the e-textile and itself. Wyzenbeek testing exhibited a more varied response, which implies samples would have varied abrasion resistance against environmental terrain, such as sand.

Due to the fact that all samples remained unchanged from Martindale testing the best performing fabric was determined from Wyzenbeek testing. It should be noted that fabric EIOTV 3 has a poor weldability rating, which adversely impacted electrical resistance at high RH (Bogan, Seyam, and Slade, submitted to 2016), For EIOTV 3 to perform best with abrasion testing, it can be assumed that the weld point at lower RH does not compromise the electrical integrity of the network.

This study along with the previously published study on the effect of temperature and RH drew definitive conclusions on the impact of environmental conditions and abrasion resistance on the electrical integrity of e-textiles. The conclusions point to a need for added reliability and consistency of electrical networks within e-textiles, especially those subjected to terrain environment. The serviceability of an e-textile is largely reliant on the consistent performance of these connections and systems they reside in (the formation factors of e-textiles). Electrical integrity, as the precursor for all e-textile functions, will continue to require thorough research as the industry matures.

Acknowledgement
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