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Deterioration of Textile vs. Electronic Components Over Time in Athletic Wearable Devices

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Abstract

Textile and electronic components are critical elements of most wearable technologies (wearables); both components deteriorate at different rates depending on factors of use, care, and user handling. The differences in mechanical performance characteristics (MPC) (i.e., abrasion, elongation, and bursting strength) of these components create a challenge for researchers and product designers to develop user-centric and economical wearables. For example, athletic wearables made of nylon/spandex knit blends exhibit drastically different MPC from minimal fiber content changes (1-10%). However, the wearable's end-use remains constant. This article presents ideas and methods for testing MPC and how to evaluate results for different end-use cases. Designing for end-user activities also highlights these performance differences because specific, end-uses drive textiles design, which may or may not be the wearable design's end-use. Three American Society for Testing and Materials (ASTM) test methods were used to test MPC of athletic fabrics and soft robotic sensors (SRS) to determine the abrasion resistance, elongation, and bursting strength of these components and two-tail t-test comparisons were performed on the results. The SRS's durability is less than the textiles they are integrated into, and with no standards for MPC testing on SRS, it can be unclear how long a sensor will last. Such methods need to be developed so product developers can find efficient combinations of fibers and electronic components to ensure user-centric functionality, wearer comfort, extended product longevity, and overall consumer satisfaction.

Keywords: Mechanical Properties Testing, Mechanical Performance Characteristics, Soft Robotic Sensors, Wearables, Wearable Devices

1. Introduction

When designing wearables for athletics, the textile components should be carefully considered to ensure user comfort and the wearable's proper function. In a sock fitted with soft robotic sensors to collect ankle joint kinematic data, it is required that sensors be pre-strained while the foot is in a neutral position so that minimal changes in movement can be detected [1]. The sock itself must then be strong and tight enough against the participant to prevent slippage against the sensors' pull so that the wearable will perform properly. When testing for user-comfort, friction against the skin and the fabric is of concern to determine the rate at which fabric will abrade. During athletic movements, the skin naturally stretches by 10-50%, and clothing needs to mimic and recover from that stretch, and it is beneficial to know the breaking point of textiles to ensure wearer protection over time [2] [3]. Researchers chose three ASTM test methods to determine the MPC of fabrics and SRS related to the previously mentioned concerns. Test fabrics included knitted fabrics marketed for use in athletics.

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2. Materials & Methods

Materials

Fabrics Selected: Primarily, athletic clothing is made from knitted fabrics, comprised of interlocking loops. All samples used in this study are weft knits consisting of wales and courses, pictured in Figure 1. Wales are the vertical columns of interlocking stitches (a), and courses are the horizontal rows of stitches (b).

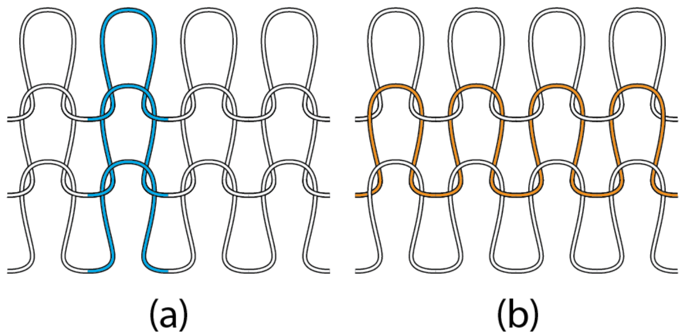

Figure 1. (a) Diagram of warp knit fabric wales. (b) Diagram of warp knit fabric courses.

Further definitions of textile terms used in this paper are listed in Table 1.

Table 1. Textile Terms

Term	Definition
Single-Knit	A fabric knitted on a single needle machine. Less body, substance, and stability when compared to double knit. [4]
Double-Knit	A fabric knitted with a double stitch on a double needle frame to provide double thickness. Excellent strength. [4]
Wales	Chain of loops in a knit fabric that run in the lengthwise direction. [4]
Courses	Chain of loops in a knit fabric that run in the horizontal direction. [4]
Jersey	A plain knitted cloth, in contrast to a rib-knit fabric. [4]
1x1 Rib	A knit fabric that has lines of wales on both sides of a fabric. Very elastic. [4]
Mesh	Any fabric knitted or woven with an open texture, fine or coarse. [4]
Modal	A distinct viscose rayon fiber genre. Satisfies a minimum value of tenacity in the wet stage at 5% elongation [5].
Lycra	A type of synthetic fabric used for tight-fitting garments [6].

Researchers evaluated eight commonly sourced fabrics for use in athletics based on current fabrics in athletics and possible alternatives for current materials. The eight fabric's initial bursting strength performance determined the three samples selected for further evaluation based on the constant biaxial pressure exerted on athletic fabrics. The three chosen samples displayed favorable characteristics for product longevity while representing a range of fiber contents and fabric structures. Characteristics of these samples, including grams per square meter (GSM), are given in Table 2.

Table 2. Fabric Composition Information

Fabric	Fiber Content	GSM	Construction
Fabric A	57% Cotton, 38% Modal, 5% Spandex	159	Single-Knit, Jersey
Fabric B	79% Polyester, 21% Lycra	300	Double-Knit, 1x1 Rib
Fabric C	100% Polyester	156	Double-Knit, Mesh

Sensors: FlexSense sensors used in this study are made with conductive and carbon ink encapsulated in silicone. By comparing SRS's performance to possible support fabrics' performance, designers can better determine the life span of potential wearables. Fifteen sensors labeled 1-15 were tested with the above methods. However, not all test methods listed above were suitable in testing these sensors due to the shape, size, and silicone material of which the sensors are made. ASTM International testing methods for fabrics were adapted to evaluate the mechanical performance of SRS to compare to fabrics tested.

Test Methods

For research in athletic textiles, abrasion occurs during dynamic movements both between clothing and between clothing and the wearer's skin. ASTM D4966 – 12 (16) Standard Test Method for Abrasion Resistance of Textile Fabrics is used in this study and is suitable for determining end-use when testing various materials [7]. The Martindale Abrasion and Pilling Tester used in this method is appropriate for use with both woven and knitted materials of any fiber content [8, 9, 10]. Five test specimens of each material, both pre-and post-laundering, as well as five sensors, are tested to determine an average number of cycles before rupture. Textile specimens have a diameter of 38 mm and are tested with 12 kPa of pressure. In this study, a fabric is determined to be ruptured when it develops a hole, and a sensor is ruptured when the provided software registers the sensor with an error, as showing in Figure 2.

Figure 2. The error button displays red in the FlexSense software when there is an error with the sensor.

To evaluate the SRS using the Martindale abrasion tester per ASTM D4966 – 12, researchers custom-designed, and 3-D printed mounts to hold the sensors in a similar raised position against an abradant pad as seen in Figure 3. Special abradant pads were used with the sensors as it was expected that the woven abradant fabric would not affect the silicone. These specific pads used are the Advanced Testing Instruments, 54615 Trizact Pack, which stick on top of the woven abradant as pictured in Figure 4. When testing, a foam backing is used with the fabric per testing guidelines; however, when testing the SRS, this foam backing slipped out of the mount requiring specimens to be tested without it.

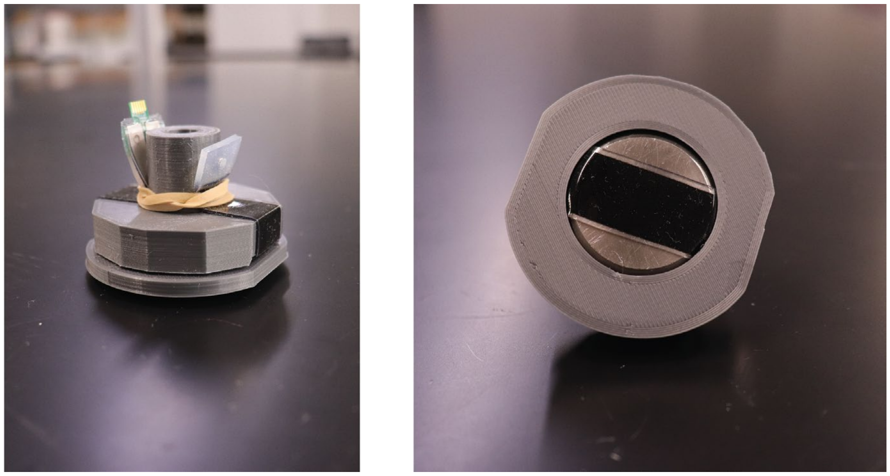

Figure 3. Custom design 3-D printed mount to test SRS on Martindale Abrasion tester. Mount utilizes the internal metal piece of standard fabric mounts.

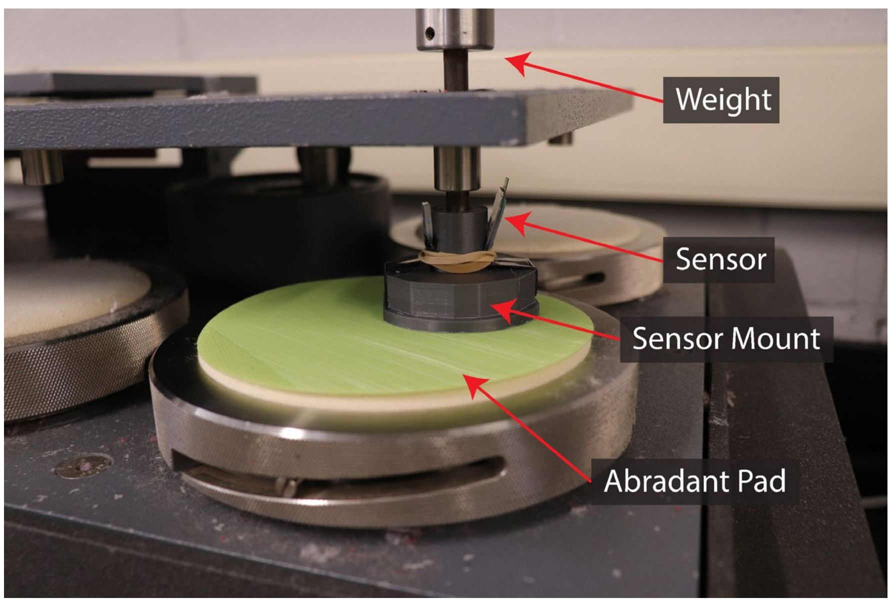

Figure 4. The green abradant pad sticks on top of the standard abradant fabric. The sensor is placed inside the senor mount and tested with a 12 kPa weight, like fabric samples.

Elongation of fabrics is a critical aspect in end-uses requiring high stretch, such as in athletic clothing and hosiery. ASTM D4964 – 96: Standard Test Method for Tension and Elongation of Elastic Fabrics tests elongation at specified loop tension for fabrics made of both natural and made-man fibers [11]. This method can be used to determine the overall tensile strength of the fabric and tensile strength in the horizontal or vertical directions separately [12,13]. Five samples are cut in the vertical (wale direction) and horizontal (course direction) for each fabric, totaling ten samples per fabric per laundering state. Vertical samples are those where the long end of the sample is parallel to fabric wales (Figure 5.a), and horizontal samples are those samples where the long end of the sample is perpendicular to fabric wales (Figure 5.b). Rectangular samples (350mm X 100mm) were sewn widthwise using two rows of single needle stitching so that the loop around the clamps measures 250mm in circumference. Specimens are tested at a constant rate of 500 mm/min on a Mark-10 tensile testing machine (CRE type) to a load of 100 N for three cycles. The last cycle is recorded and used for analysis.

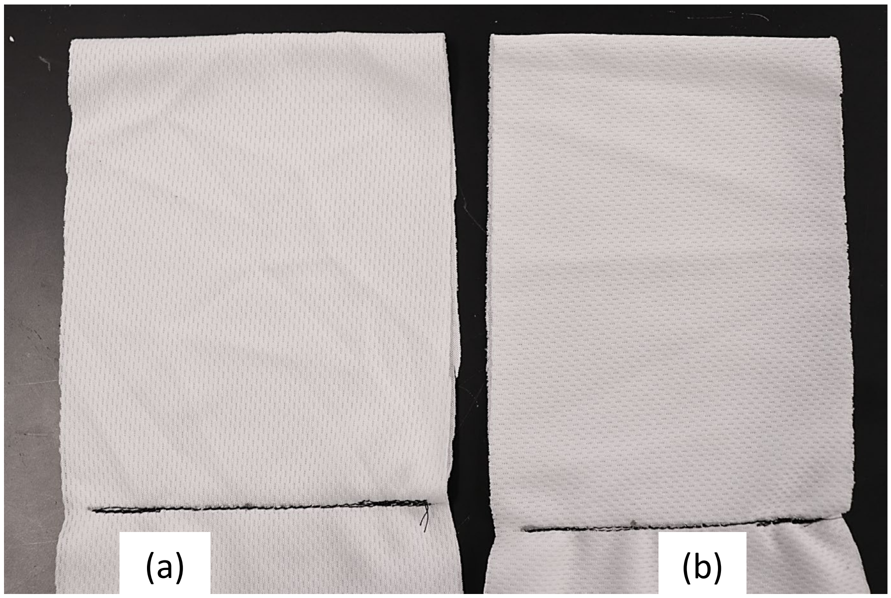

Figure 5. The green abradant pad sticks on top of the standard abradant fabric. The sensor is placed inside the senor mount and tested with a 12 kPa weight, like fabric samples.

During elongation testing, sensors were not tested as looped specimens but as strip specimens. Of note is that the sensors did not meet the 250 x 100mm size requirements directed by ASTM D4964 and were unable to meet the 100 N tensile force test of the fabrics. An additional modification for SRS performance testing specific to ASTM D4964 – 96 included a custom-designed and 3-D printed spacer for the Mark-10 tester pictured in Figure 6. This spacer ensured that any electronic components were not damaged by pressure from the clamps. To compensate for these differences' researchers tested the sensors to the max elongation of the tested pre- and post-laundered fabrics, which was a total elongation of 200mm. Sensors were stretched to this length over three cycles for the five sensors tested to calculate the average force at this elongation.

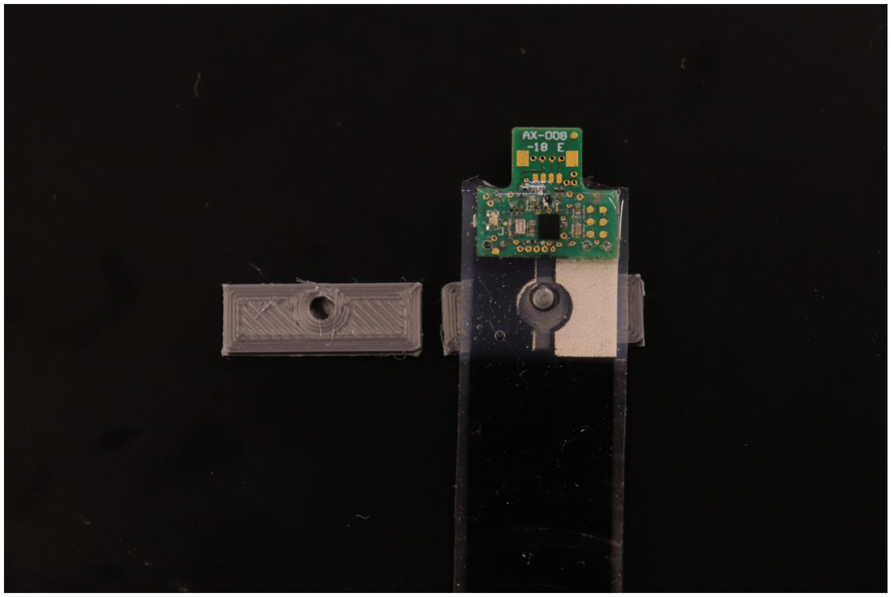

Figure 6. Custom spacer created for testing SRS in a Mark-10 Tensile testing machine. The spacer takes advantage of mounting holes in the sensors to ensure the spacer does not slip during testing.

In textiles where strength is essential in more than one direction, burst testing can simultaneously give information about strength in warp and weft directions. For this study, the James Heal TruBurst 4 Pneumatic bursting tester was used according to specifications in ASTM D3786 – 18: Bursting Strength of Textile Fabrics [14]. Five specimens of each fabric in each laundering state are cut with a circular cutter of 140mm diameter and tested, so the burst is within 20+/-5 seconds of the start of the test. Pounds per square inch (PSI) at burst is recorded, and bursting strength is calculated by subtracting diaphragm pressure from this value. Diaphragm pressure is the PSI value at the height of burst (rounded to the nearest whole number) for the specimen and is calculated without any specimens loaded into the machine.

The bursting method used in this study was suitable for testing the SRS with the modification that the sensors were placed over the metal plate in the bursting tester instead of underneath (see Figure 7). This change was made to accommodate the sensor's circuitry, which the metal plate's high force would damage. The sensor also does not entirely cover the diaphragm opening and is placed as close to the middle of the opening as possible during testing.

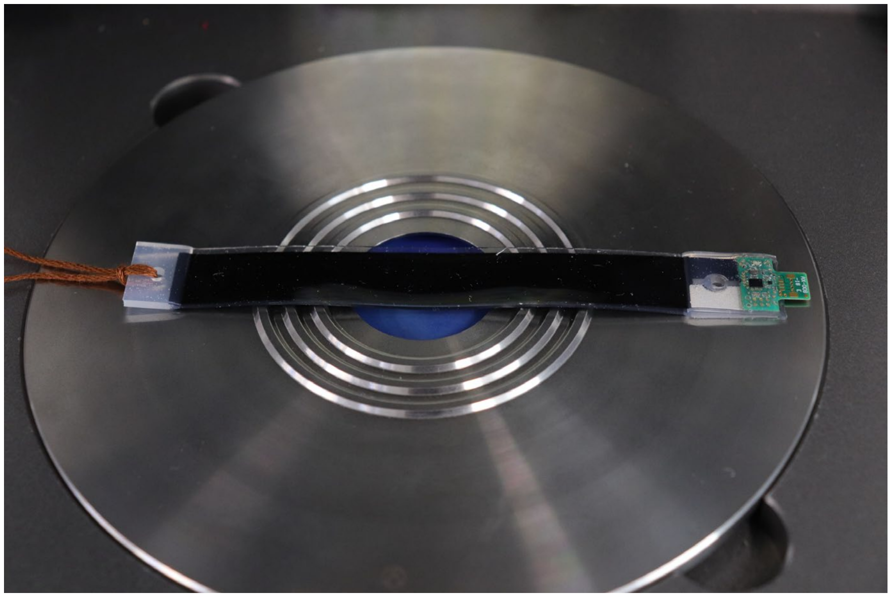

Figure 7. Sensors were placed over the metal plate of the bursting tester to accommodate circuitry.

All tests were performed in conditions of ASTM D1776: Practice for Conditioning of Textiles, which is 21 ± 1◦ C and 65 ± 2 % relative humidity [15]. Laundered specimens were washed according to preparation instructions in the American Association of Textile Chemists and Colorists (AATCC) 135-2015: Dimensional Changes of Fabrics after Home Laundering test method [16]. The SRS in this study were not tested for launderability as it was thought that the silicone would not have a significant change in MPC after one wash. The copper traces of the SRS are left exposed and would be damaged during laundering leaving the SRS unable to give an output. It is assumed traces of any SRS would be insulated in a wearable, preventing damage during laundering.

3. Results & Discussion

The average number of cycles before rupturing for Fabrics A, B, and C is shown in Table 3, along with p-values of two-tail t-test comparisons. Fabric A had a significant decrease in performance after laundering. As did Fabric C, note that the double-knit structure of Fabric C required two values to be recorded for each sample. The first value is the average number of cycles to cause a hole for the first layer of the fabric, and the second value is the average number of cycles to cause a hole in the second layer.

Table 3. ASTM D4966 – 12 (16) Abrasion Data for fabric specimens. Specimens denoted (*) had two sets of rupture averages recorded due to the fabric's double-knit structure. The first value listed is for the rupture of the first layer, the second value given is the rupture of the second layer.

Fabric	**Measure**	**Mean Pre-launder (SD)**	**Mean Post-launder (SD)**	**P-Value**
Fabric A	Number of Cycles to Hole	23,600 (800)	14,000 (1,673)	<.001
Fabric B	Number of Cycles to Hole	100,000+	100,000+	----

Fabric C	Number of Cycles to Hole *	71,000 (6,708), 104,000 (7,348)	29,800 (2,857), 56,800 (3,600)	<.001, <.001

Due to time constraints, Fabric B was not tested to rupture but instead only run for 100,000 cycles in pre-and post-laundered states. Figure 8 shows what the post-launder and pre-launder samples look like after 100,000 cycles compared to an untested pre-laundered swatch. The post-laundered swatch only had one layer of the fabric abraded away after the 100,000 cycles; during testing, specimens never developed holes, and abrasion only had a brushing effect on the fabric. The pre-laundered fabric is behaving similarly to post-laundered fabric specimens but will take a much larger number of cycles to reach the same results.

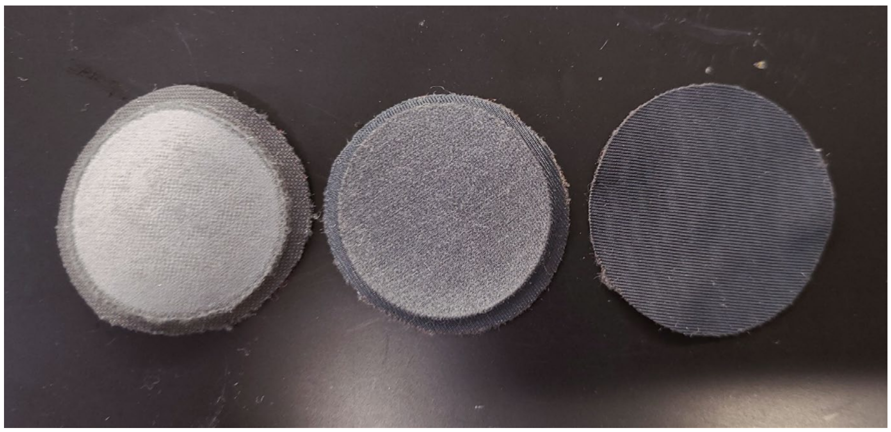

Figure 8. Far left is a post-laundered sample after 100,000 abrasion cycles, the middle is a pre-laundered sample after 100,000 abrasion cycles, and the far right is an untested pre-laundered fabric swatch.

Comparison between Fabric A and Fabric C (first layer) for pre-and post-laundered samples show statistical significance, as seen in Table 4. Comparisons were not made using Fabric B as testing data was incomplete.

Table 4. ASTM D4964 – 96 Abrasion T-Test data between the different fabric of the same laundering state. Means not shown are the same as those listed in Table 3 for fabric type and laundering states. Values in bold are not statistically significant.

Laundering State	**V1**	**V2**	**Measure**	**P-Value (Between V1 and V2)**
Pre-launder	Fabric A	Fabric C (first layer)	Number of Cycles to Hole	<.001
Post-launder	Fabric A	Fabric C (first layer)	Number of Cycles to Hole	<.001

Abrasion testing of the SRS revealed that on the Trizact abradant, an average of 72 (SD = 23) cycles was enough to break the sensors. However, these results' standard deviation is quite large, with the smallest number of cycles to sensor break being 40 cycles, with the largest number of cycles to break being 110. Such differences might be attributed to conditions during manufacturing and highlight the need for SRS standard test methods.

Results of average elongation with standard deviation for ASTM D4964 – 96 are shown in Tables 5. Fabric B performed the best with an average elongation of over 155 mm in both horizontal and vertical directions in pre-and post-laundered samples. Note also that Fabric B is the only specimen in which performance improved after laundering (with significance), indicating that this fabric might have a finish that reduces stretch, but that is removed when laundering. Fabric A performed better in Horizontal samples, but the difference in distance traveled is not significant between laundering stages. Fabric C performs the worst of the three fabrics. One cause of this performance could be that Fabric C is 100% Polyester. Significant changes in travel distance occurred in almost all samples between laundering states. Standard deviations of results are worse for post-laundered specimens, and this could be due to characteristic changes during laundering, such as removing fabric finishes related to stability.

Table 5. ASTM D4964 – 96 Elongation T-Test data between pre-and post-laundered samples of the same fabric. Values in bold are not statistically significant.

Fabric	**Sample Orientation**	**Measure**	**Mean Pre-launder (SD)**	**Mean Post-launder (SD)**	**P-Value**
Fabric A	Horizontal	Distance Traveled (mm)	**180.416 (2.20)**	**154.404 (22.77)**	**.085**
	Vertical	Distance Traveled (mm)	118.58 (1.93)	109.852 (2.93)	.002
Fabric B	Horizontal	Distance Traveled (mm)	175.268 (3.79)	191.552 (8.75)	.019
	Vertical	Distance Traveled (mm)	155.948 (1.96)	175.576 (5.92)	<.001
Fabric C	Horizontal	Distance Traveled (mm)	138.11 (4.52)	90.260 (17.72)	.004
	Vertical	Distance Traveled (mm)	41.808 (3.61)	29.944 (3.00)	<.001

Comparisons between fabrics of the same laundering state are listed in Table 6.

Table 6. ASTM D4964 – 96 Elongation T-Test data between the fabric of the same laundering state. Means not shown are the same as those listed in Table 3 for fabric type and laundering states. Values in bold are not statistically significant.

Laundering State, Sample Type	**V1**	**V2**	**Measure**	**P-Value (Between V1 and V2)**
Pre-launder, Vertical	Fabric A	Fabric B	Distance Traveled (mm)	<.001
	Fabric A	Fabric C	Distance Traveled (mm)	<.001
	Fabric B	Fabric C	Distance Traveled (mm)	<.001
Pre-launder, Horizontal	Fabric A	Fabric B	Distance Traveled (mm)	<.001
	Fabric A	Fabric C	Distance Traveled (mm)	<.001
	Fabric B	Fabric C	Distance Traveled (mm)	<.001
Post-Launder, Vertical	Fabric A	Fabric B	Distance Traveled (mm)	<.001
	Fabric A	Fabric C	Distance Traveled (mm)	<.001
	Fabric B	Fabric C	Bursting strength (psi)	<.001
Post-Launder, Horizontal	Fabric A	Fabric B	Distance Traveled (mm)	.029

	Fabric A	Fabric C	Distance Traveled (mm)	.002
	Fabric B	Fabric C	Distance Traveled (mm)	<.001

Testing on the sensors revealed that less force is needed to stretch the sensors than is needed to stretch the fabrics over the same distance. Tensile testing of the sensors showed that over a 200mm travel, the sensors only reached a load of 14.5 N, and at a tension of 35.5 N (a 400 mm travel), the sensors reached their breaking point. A wearable device utilizing both SRS and fabric components is unlikely to experience elongation over 200mm due to limitations of common human body movements. However, this test shows the ability of silicone SRS to stretch beyond that of fabric components. It would be desired to know how many stretches over a short distance a fabric or sensor could handle before breaking in further testing. This testing would be more applicable to real-world scenarios such as the repeated donning and doffing of a sock.

As shown in Table 7, Bursting strength data reveals the strongest of the specimens to be Fabric C, which outperforms other samples before and after laundering. It should be noted that the pre-laundered specimens for Fabric C reached the maximum psi of the equipment without breaking, and calculated bursting strength for these samples uses an estimated 124 average psi equivalent to the max of the machine. The actual value of the average psi would need to be found using a test method such as ASTM D3787 Bursting Strength of Textiles—Constant-Rate-of-Traverse (CRT) Ball Burst Test, which is suitable for fabrics that outperform the machinery of ASTM D3786 and is suitable for use industrial textile testing [14, 17]. Performance of Fabric A appears to have increased after laundering; however, differences in bursting strength between pre-and post-laundering samples are also not statistically significant. The difference in distance travel is statistically significant for Fabric A, and this decrease suggests that while the fabric retained its strength, its elasticity was reduced after laundering. Results are echoed by the results of the elongation testing, primarily in the horizontal samples. Looking at Fabric B's results, the strength needed to travel 28 mm to fill the dome before laundering is greater than the strength needed after laundering, and the difference is significant. These numbers support elongation testing results and the theory of a stabilizing finish being removed during laundering.

Table 7. ASTM D3786 – 18 Bursting T-Test data between pre-and post-laundered samples of the same fabric, specimens denoted (*) filled the dome during testing, specimens denoted (**) did not burst or fill the dome but reached the max psi of the testing equipment. Values in bold are not statistically significant.

Fabric	**Measure**	**Mean Pre-launder (SD)**	**Mean Post-launder (SD)**	**P-Value**
Fabric A	**Bursting Strength (psi)**	**48.182 (1.56)**	**50.018 (2.75)**	**0.289**
	Distance Traveled (mm)	27.38 (0.08)	19.58 (1.08)	<.001
Fabric B	Bursting Strength (psi)	89.556 (0.89)	51.092 (2.57)	<.001
	Distance Traveled (mm)	28 (0)*	28 (0)*	----
Fabric C	Bursting Strength (psi)	107.98 (0.21)**	103.38 (1.87)**	.004
	Distance Traveled (mm)	13.72 (0.28)	12.38 (0.18)	<.001

Comparing fabrics of the same laundering state proved to be statistically significant in all but one scenario in comparing post-laundered bursting strength of Fabrics A and B. This result could conclude that Fabric C performs better after laundering since the comparison between Fabric A and C and Fabrics B and C are both significant. Results of comparisons can be seen in Table 8.

Table 8. ASTM D3786 – 18 Bursting T-Test data between fabrics of the same laundering state. Means not shown are the same as those listed in Table 3 for fabric type and laundering states. Values in bold are not statistically significant.

Laundering State	V1	V2	Measure	P-Value (Between V1 and V2)
Pre-launder	Fabric A	Fabric B	Bursting strength (psi)	<.001
			Distance Traveled (mm)	<.001
	Fabric A	Fabric C	Bursting strength (psi)	<.001
			Distance Traveled (mm)	<.001
	Fabric B	Fabric C	Bursting strength (psi)	<.001
			Distance Traveled (mm)	<.001
Post-Launder	Fabric A	Fabric B	**Bursting strength (psi)**	**.584**
			Distance Traveled (mm)	<.001
	Fabric A	Fabric C	Bursting strength (psi)	<.001
			Distance Traveled (mm)	<.001
	Fabric B	Fabric C	Bursting strength (psi)	<.001
			Distance Traveled (mm)	<.001

Results of burst testing on the SRS showed less pressure to fill the dome than is need for fabric specimens, and like Fabric C, it would be useful to test the SRS with ASTM D3787. Mean as the standard deviation of bursting strength and travel distance for the SRS can be seen in Table 9.

Table 9. ASTM D3786 – 18 Bursting mean and standard deviation for sensor specimens.

Specimen Type	Measure	Mean (SD)
Sensor	Bursting strength (psi)	7.454 (.097)
	Distance Traveled (mm)	28 (0)

The SRS filled the dome during testing in the same way as Fabric B; however, when compared using a Two-Sample t-test, the differences in bursting strength were deemed statistically significant.

It has been observed that double-knit fabrics have a higher tensile resistance than single-knit fabrics when fabricated with a spun, non-stretch yarn, as is the case for Fabric C [18]. This result is not observed in Fabric B since it is fabricated with stretch-yarns, allowing for an elevated overall stretch for the fabric. Higher tensile resistance would not be desirable in a form-fitting athletic garment such as a sock, making Fabric A and Fabric B better choices for an athletic wearable than Fabric C. It can also be assumed that in a sock, there is less stretch in the vertical (wale) direction than in the horizontal (course) direction, meaning the performance of the vertical samples would not be as important as those of the horizontal direction.

Fabric A is the only one composed of some Cotton percentage performs worse than the other fabrics in bursting strength. Cotton could contribute to poor performance as previous research has seen that an increased ratio of cotton in fabric yarns caused a decrease in bursting strength [19]. However, Fabric A's performance could also be attributed to its single-knit structure, and more testing would be needed to determine the true cause of its performance in bursting strength.

4. Future Work

Some work done in association with this research included preliminary testing of the FlexSense SRS regarding its electrical properties. Provided software outputs sensor data as percent elongation where a neutral unstretched state of a sensor would read a 0% value. Measurements were taken in a neutral position of sensors 11-15, used for burst testing, before testing, immediately after testing, ten minutes after testing, and one hour after testing. The purpose was to determine if there was a significant change in the sensors' output after experiencing the test and the sensor's recovery over time. Outputs were also measured during testing for sensors 14 and 15. A graph of this data for sensor 14 is shown in Figure 9. The sensor stops giving output above a specific elongation; however, this does not break the sensor. It can provide output again once the elongation is reduced.

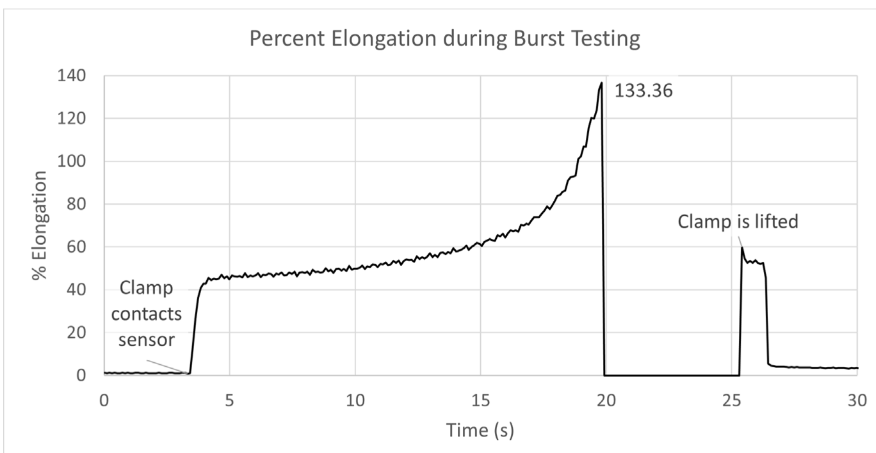

Figure 9. Output in % elongation of FlexSense SRS during burst testing for sensor specimen #14.

To further investigate the durability of the materials comprising the stretch sensor and the stability of the signal produced by the sensor, high-cycle fatigue (HCF) data, defined as > 10,000 loading/unloading or stretch/relaxation cycles [20], could be collected under orthopedic loading conditions. Under displacement control, the sensors stretched over a displacement that corresponds to a specified sensor output could be used to determine joint angles. An example of this would be a range from 10° of plantarflexion to 50° of plantarflexion in a 450 pF to 650 pF sensor output range [21]. Simultaneous with the fatigue testing, the capacitance produced during the cycling could also be recorded. The sensors ' fatigue life can be predicted by capturing both the sensor's mechanical and electrical properties. When coupled with the fabric test results, it will provide a complete picture of the sensors' performance during daily living activities.

The results of this research and the modifications to textile testing standards to accommodate SRS shows the need for a set of methods specific to SRS that can be used to test their MPC. Not only should MPC of SRS be tested before use in any wearable products, but such standards would be beneficial in the manufacturing of the SRS to ensure consistency in the product. There is the possibility that the combination of fabrics with SRS could improve the performance of the sensors over time [22], allowing products to last longer without the need for sensor replacement. Further studies on MPC of SRS combined with textile components would be a valuable insight into estimating product life-spans and ensuring correct information is given to the customers.

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