Overlock-Stitched Stretch Sensors: Characterization and Effect of Fabric Property

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ABSTRACT

The comfort of wearable sensors is often limited by the materials and construction methods of sensors. Here, we present a textile-based stretch sensor that is formed using a common industrial sewing machine, in an overlock formation. Swapping a single thread in the stitch for a conductive thread renders the stitch responsive to stretch through opening and closing short circuits in the looped structure of the exposed conductor. However, the sensor response is influenced by the mechanical properties of the textile to which it is stitched. We explore the influence of fiber content (with an emphasis on elastomeric fiber content) on the baseline drift, response range, and hysteresis of the stitched sensor. Results show that the sensor provides a reliable and repeatable response, with a linear region that spans from the relaxed position to between 18 and 29% elongation. Average drift of about 0.5 Ohm and hysteresis of about 1 Ohm were measured. Effects of fiber content were observed, but do not show clear relationships to percentage of elastomer content.

Keywords: wearable technology, e-textiles, smart clothing, textile sensor, stitched sensor, stretch sensor

Introduction

Wearable body sensing is crucial to many computational applications, including pervasive computing, human-computer interface, and ambulatory medical monitoring. However, many applications that rely on input from body sensors similarly rely on long-term wear of those sensors. Because of this requirement of long-term wear, it is often essential to prioritize the human factors of the wearable sensor equally with the performance of the sensor. Few body-sensing solutions exist which approximate the comfort and wearability of everyday clothing while offering accurate sensor response.

While textile structures can present significant benefits for wearability and comfort, they can also often introduce irregularities and unpredictability into the sensing process. Particularly, garment-integrated body sensing inherently introduces a gap between the target for sensing (the human body) and the sensing structure (the garment). Characterizing the variables of this gap is crucial to the acquisition of useful data. Therefore, it is important to explore textile-based sensors under a wide variety of conditions in order to understand the variables that will affect sensor performance in the field. These variables are numerous and

complex, and include things like varying temperature and humidity conditions of the human body, irregularities in positioning during movement and donning/doffing, and the numerous design variables that can influence the physical properties of "everyday" clothing.

Here, we introduce a novel stretch sensor fabricated using an industrial overlock machine. The resistance response of this sensor to stretching is characterized, and the effect that the textile substrate has on the performance of the sensor is explored. We compare the responses of sensors stitched on four different textiles, two with elastomer content and two without. Because the sensor is created by leveraging an extremely common stitch formation (the overlock or serged stitch), it has significant benefits in terms of both wearability and manufacture.

Background

Wearable Stretch Sensing

Detecting and measuring elongations is useful for a variety of body-sensing applications. Most directly, it can be used to detect changes in the dimension of body parts, such as to detect breathing (Guo et al., 2011; Rovira et al., 2011), (Huang, Tang, & Shen, 2006) or swelling/edema. Less directly, it can be used to correlate changes in surface dimension to joint movements (Giorgino, Tormene, Lorussi, De Rossi, & Quaglini, 2009; Munro, Campbell, Wallace, & Steele, 2008; C. Mattmann, Amft, Harms, Troster, & Clemens, 2007). In that manner, it can be used for rehabilitation, activity recognition, or gaming, among other applications. Further, however, stretch sensing is a mechanism by which the forces experienced by everyday clothing during movement can be detected (Corinne Mattmann, Kirstein, & Tröster, 2005) without the need for additional, less wearable devices.

Textile Stretch Sensing

While there are many varieties of stretch sensors, this review will focus on stretch sensors integrated into textiles. In general most textile-based stretch sensors operate using one of three common approaches to detecting elongation. Piezoresistive, piezoelectric, and electro-active materials (De Rossi, Santa, & Mazzoldi, 1997; Huang, Shen, Tang, & Chang, 2008) change resistance or generate a small current when deformed, due inherent material properties. Suspending diffused conductive particles in a stretchable substrate causes the particles to move farther apart during stretch, increasing the resistance of the system (Lorussi, Rocchia, Scilingo, Tognetti, & Rossi, 2004). Electro-active materials and diffused conductive particles can be coated onto a textile material by surface application (such as painting or screen printing), or by coating through immersion. Finally, approaches similar to the one used here implement an un-insulated conductor of specific resistance per unit length in a looped formation (Bickerton, 2003; Paradiso, Loriga, & Taccini, 2005). The looped-conductor method is most often implemented through knitting. In this application, a conductive thread is used in place of a standard thread, and knitted into the textile structure. The knit forms rows of connected loops. When stretched parallel to the row of loops, these loops are pulled out of contact and the shorted portion of the loop decreases in length. This results in an increase in the electrical length from one side to the other, with a corresponding increase in resistance. When the knit is relaxed, the loops return to their original shape, shortening the electrical distance.

One of the drawbacks of a knitted stretch sensor is that it generally follows the wales and courses (x and y axis) of the knit structure. It is difficult to create a free-form sensor pattern when the sensor is knitted directly into the textile. Similarly, for cut-and-sewn garment-integrated applications the requirement that the sensor be laid in as the textile is created makes planning and design far more difficult, and prevents the

sensor from being freely positioned on the surface of the garment after fabrication.

Stitched Stretch Sensors

Our method leverages the looped structures created by common sewing machinery. In previous work we have explored the industrial coverstitch machine (Author, 2012; Author, 2013), and here we describe sensors created using an industrial overlock machine.

There are many types of overlock machines, which use two, three, four, or five threads to create a variety of stitches, mainly used to bind the cut edge of a textile and in some cases to stitch a seam simultaneously. Stitched stretch sensors can be made using three, four, or five threads, in stitch classes 504, 512, 514, or 516 (ISO, 2013). Here, we focus on a sensor implemented using a class 514 four-thread overlock stitch, which is depicted in Figure 1 below. This stitch is applied to the edge of a textile or used to form a seam while simultaneously binding the edge. The machine also trims the edge of the fabric (to the left of the stitch depicted in Figure 1), so it cannot be applied to the middle of a piece.
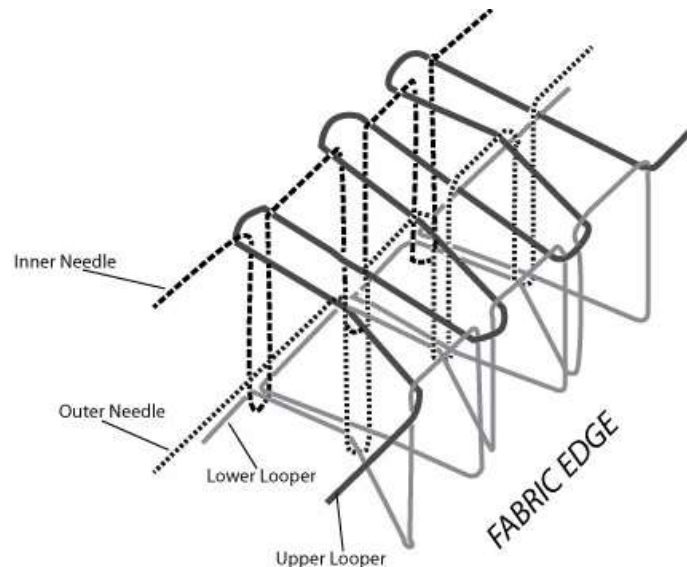

Figure 1. ISO 514 Overlock stitch structure

While the stitch structure creates the sensing mechanism, the sensor response relies heavily on the physical characteristics of the textile substrate to which it is stitched. For example, if the textile has poor recovery characteristics (has a tendency to "stretch out" rather than return to its original shape in the absence of a load), the sensor response will in theory follow that physical behavior, and fail to return to a baseline level. Here, we explore the relationship between the physical characteristics of the fabric substrate and the response of the stitched sensor.

Method

Either of the two looper threads (upper or lower) illustrated in Figure 1 can be used to create a sensor, but the electrical and mechanical action of the two looper threads may differ slightly depending on the machine set-up and thread tension. The upper looper thread was used to create our experimental samples. Each sample was a total of nine inches long, stitched along the direction of each textile with the greatest stretch ratio (elongated length/relaxed length). Example stitched sensors are depicted in Figure 2, in the relaxed (a) and stretched (b) position.

(a)

(b)

Figure 2. Example stitched sensors - (a) relaxed and (b) stretched

The conductive thread used here was Shieldex 235/34oz silver-coated nylon, rated at 50 Ohms/meter. Sensors were stitched on five different fabric substrates: 100% polyester jersey knit, 60% cotton/40% polyester jersey knit, 94% cotton/6% spandex jersey knit, 90% polyester/10% spandex jersey knit and 82% nylon/18% spandex jersey knit. Each of these textiles uses the same knit structure, with variations in fiber content. Three of the textiles were intentionally included for their elastomeric (spandex) content, which has a significant effect on elongation and recovery properties of the textile (Kadolph, 2010).

Elongation Experiments

Sensors were stretched using an Instron tensile tester (used to measure elongation and load during each test), and the resistance of the conductive sensor was simultaneously measured using a BK Presion 2821E digital multi-meter (DMM). The experimental set-up is illustrated in Figure 3.

The functional length of the sensor in each test was reduced to five inches, due to two inches on each side of the sensor being restrained between the clamps of the Instron. Each sensor was stretched from its initial length of 5 in to a final length of 7 inches, (a total of 40% stretch) 18 times. Both top and bottom Instron clamp plates were isolated from the sensor with a layer of neoprene on each side to prevent the sensor from shorting over the length of the conductive plates. This adds a constant bias to the resistance measurements during the stretch, equal to the resistance between the plates for each pair. The Instron was used to record extension at sampling frequency of 10.0Hz, while the DMM measured the sensor resistance simultaneously at sampling frequency of 3.3 Hz, the fastest available rate of the DMM USB command interface. Data from the two instruments were subsequently aligned and overlapped using digital timestamps.

Figure 3. Experimental setup: sample mounted in Instron with DMM leads attached (top and bottom)

Recovery Experiments

Because recovery of the fabric substrate is an important factor in the performance of the stretch sensor, the recovery of each fabric was evaluated using a vertical hang test. Each fabric sample was measured, then loaded with the amount of weight corresponding to the load experienced in the Instron testing at 40% stretch. Fabric samples were pinned at the top end to a vertical surface, and left to hang freely. Weights were clipped to the bottom end using a 3" wide clip. Each sample hung weighted for 3 minutes, after which time the sample length was again measured. Increase in sample length was expressed as a percentage of the original length.

Data Analysis

To evaluate the characteristics of this sensor implementation with respect to fabric substrate, the following properties were measured: baseline resistance of the stitch in the relaxed position, range (peak-to-peak resistance) of the sensor response, hysteresis of the sensor response between elongation and relaxation components of the stretch cycle, and linear response range of the sensor response with respect to elongation.

Baseline resistance (or minimum of the resistance response) was measured at the trough of each elongation cycle (representing the minimum-load of each cycle).
Range of each sensor's resistance response was measured by computing the difference in resistance between the peak and trough of each elongation cycle.

Hysteresis of the sensor response was measured by computing the area between the extension curve and the recovery curve for each cycle, by using trapezoidal numerical integration. Further the difference in resistance response for a 10% elongation between the extension and recovery phase was calculated for each cycle, and averaged over all cycles for each test fabric.
The linear response range of each sensor with respect to elongation was computed by measuring the extension length corresponding to the peak and trough resistance.

For all measures, responses from the two tests of each sensor type were averaged. Because samples were all previously un-stretched, the first extension cycle for each sample is discarded as a "conditioning" sample.

Results

Sensor Theory of Operation

The overlocked sensor operates as a constrained version of the looped conductor method used in the top-thread coverstitched sensor, described in (Author, 2012). The variation on this method used in the overlocked sensor is illustrated in Figure 4. The conductive thread of the bottom looper passes through loops created by the inner needle thread. Adjacent loops of conductive thread are held in contact by this loop formed by the inner needle thread (see Figure 1), as illustrated in Figure 4 in the two extreme cases of completely relaxed stitch and fully stretched stitch.
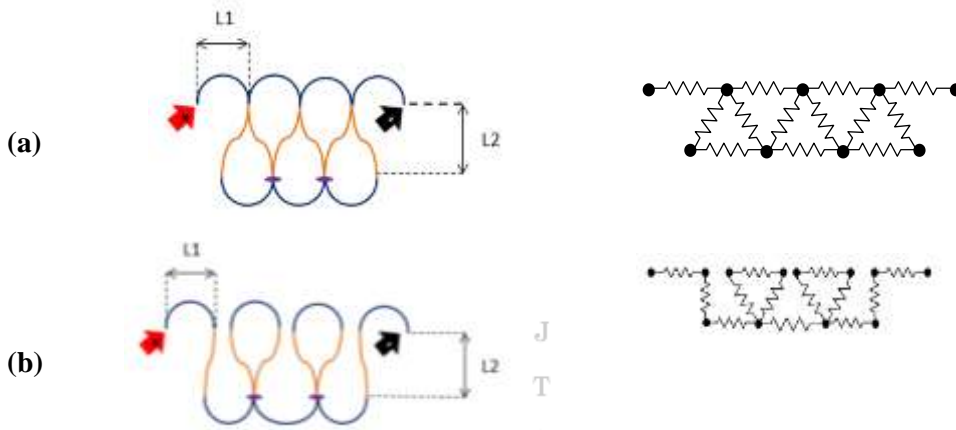

Figure 4. Looped conductor in the relaxed (a) and stretched (b) position

When the overlocked sensor is relaxed, the equivalent electrical model is an anti-ladder configuration of resistors. When the sensor is stretched, the output resistance is given by a series of resistors. Because the overlocked sensor in the stretched position forms shorts on the inner needle side and closed loops on the fabric edge, and referring with n to the total number of inner and outer loop halves (n = 5 loops in Figure 4), and with $R1$ and $R2$ to the equivalent electric resistance corresponding to L1 and L2 in Figure 4, the total resistance is equal to

$$R_{total} = \left(\frac{n+1}{2} + 2\right) * R1 + 2 * R2$$

According with the convention used for measuring the total resistance R_{total}, we find that the overlocked sensor's R_{total} is smaller by a factor

$$\frac{n-1}{2} * (2 * R2 + R1)$$

compared to the total resistance of an equivalent Top-Thread Stitched Sensor (described in Author, 2012). The crossing thread holds together in contact adjacent edge-side loops during stretch. Theoretically, this determines isolated triangles that therefore are shorted from the series of resistors. Practically, the fabric through which the needle thread passes extends during the stretch and the needle thread loop loses some amount of contact between adjacent strands. How much the needle loop opens up depends on the elasticity of the fabric the sensor is integrated on, thus we can have fabrics with larger resistance increase during the stretch.
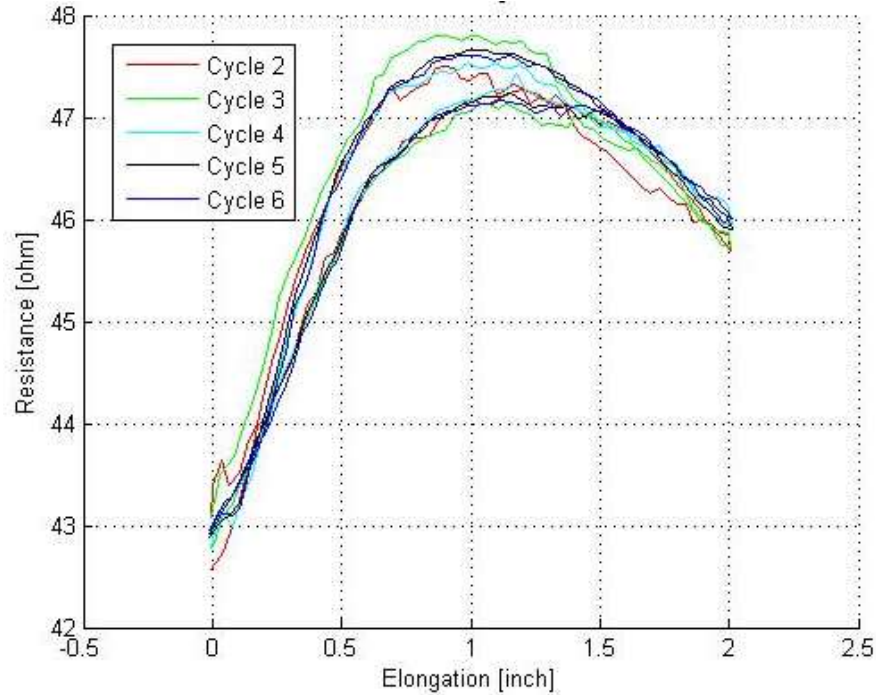
Figure 5. Example sensor resistance response to elongation of a cotton/spandex overlocked sensor, for 5 cycles

Experimental Results

An example plot of sensor resistance vs. elongation over 5 cycles for a cotton/spandex overlocked sensor is shown in Figure 5.

The response shows a linear region in which the sensor's resistance increases with elongation, a saturation region in which the sensor's resistance ceases to increase with elongation, and a "compression" region, in which the sensor's resistance begins to decrease with elongation. The linear response and saturation are explained by the opening of shorts in the looped structure as illustrated in Figure 4. The "compression" region is explained by compressive forces applied to the conductive thread looper thread by the needle threads (dashed lines in Figure 1) as the stitch is elongated. The conductive thread is composed of multiple silver-coated nylon filaments twisted into a 4-ply structure. As the loops of needle thread tighten over the conductive looper thread, these filaments are brought into closer contact, shorting out more filaments and increasing the conductivity of the thread structure. Because the loop-separation response has been saturated, the compression effect is clearly seen in the overall resistance response.

The linear portion of the response is of most direct utility in sensing applications. For that purpose, the remainder of discussion will focus primarily on characterizing the linear response region.

Figure 6 shows the average baseline resistance trends for sensors stitched to each test fabric, over 17 cycles. These baseline resistances are adjusted to a common initial resistance, for ease of comparison.
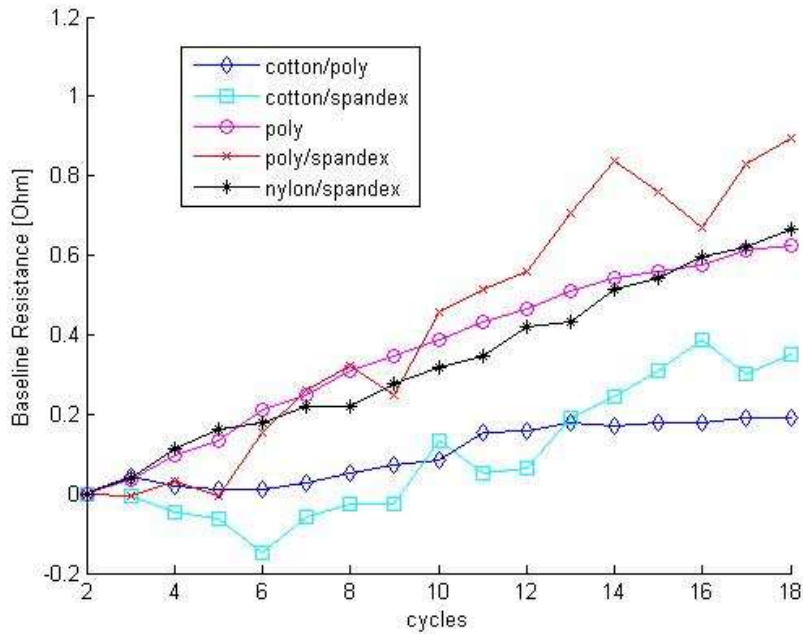
Figure 6. Adjusted baseline resistance per cycle for each test fabric

Table 1 shows the actual baseline resistance values averaged for each fabric type. Drift is calculated as the total difference between the maximum baseline (trough) value and the trough of elongation cycle 2.

Figure 7 shows the average peak-to-peak response range for sensors stitched to each fabric, normalized with respect to baseline resistance.

Table 1. Average baseline and drift resistance values (Ohms) by fabric type

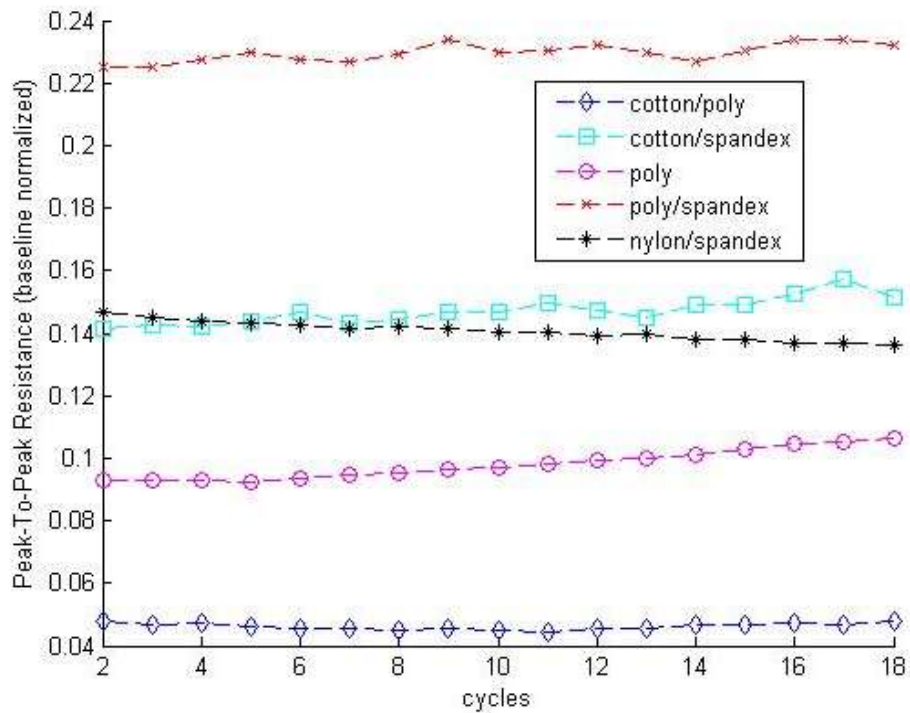|	Cotton/ Poly	Cotton/ Spandex	Poly	Poly/ Spandex	Nylon/ Spandex
Baseline resistance @cycle 2	55.33	43.16	42.96	57.77	42.88
Total Drift	0.19	0.35	0.62	0.90	0.67
Av. Drift	0.01	0.02	0.04	0.06	0.04

Figure 7. Normalized peak-to-peak response range for each test fabric

Figure 8 shows the average extension values that correspond to the maximum resistance value for sensors of each fabric type in each extension cycle (illustrating the elongation distance that corresponds to this maximum resistance, the limit of the linear region of the sensor response) and Table 2 shows the averages and standard deviations of these values over all cycles. After this maximum resistance elongation length, the sensor response shifts to the compression response seen in Figure 5.

Figure 9 shows trends in hysteresis for sensors stitched to each test fabric. Table 3 shows the hysteresis error defined as the difference between the sensors' output in the extension and recovery phases at 10% of the total elongation input.
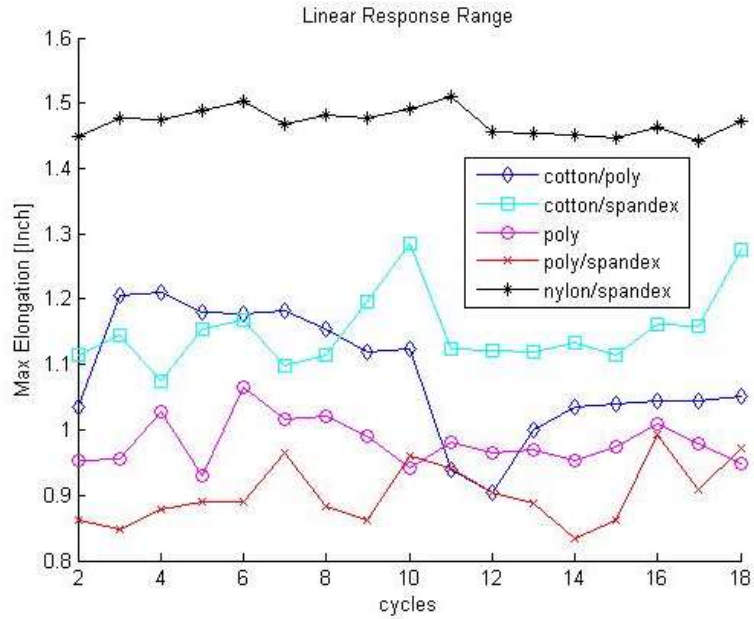
Figure 8. Sensor linear response range: average elongation lengths at maximum resistance for each elongation cycle, by fabric type

Table 2. Average extension lengths (inches) corresponding to maximum resistance response for each fabric type

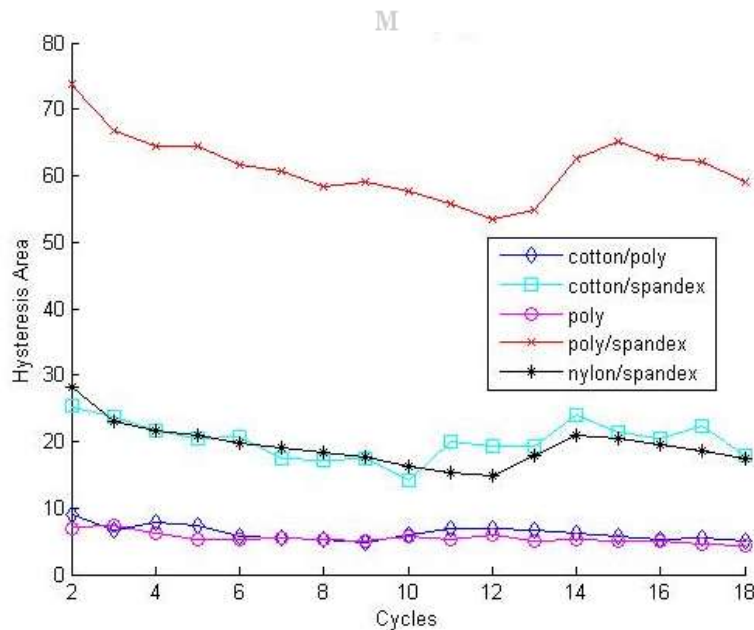|	Cotton/ Poly	Cotton/ Spandex	Poly	Poly/ Spandex	Nylon/ Spandex
Mean	1.02	1.15	0.98	0.90	1.47
SD	0.07	0.08	0.05	0.07	0.05

Figure 9. Hysteresis magnitude for each test fabric

Table 3. Hysteresis (Ohms) at 10% elongation

Hysteresis	Cotton/ Poly	Cotton/ Spandex	Poly	Poly/ Spandex	Nylon/ Spandex
@10% Elongation	0.35	1.15	0.19	3.04	0.82

Table 4. Percent elongation for each fabric following recovery test

Cotton/ Poly	Cotton/ Spandex	Poly	Poly/ Spandex	Nylon/ Spandex
3.41%	3.33%	2.11%	2.11%	3.23%

Finally, Table 4 shows the percent elongation of each sample following the recovery test.

Discussion

The initial portion of the typical sensor response shown in Figure 5 displays the linear behavior predicted by the theoretical model described in Section 4.1. However, the model in Section 4.1 would assume that once all outer-edge loops have come out of contact, the sensor's resistance response would saturate and cease to change. In Figure 5 we observe a saturation effect at the peak of the sensor resistance response, followed by a decrease in resistance as the fabric substrate continues to extend. This effect could be a result of the needle thread loops beginning to apply pressure to the filaments of the conductive thread as the slack in the needle threads is fully taken up during extension. As the needle loops compress the conductive thread, filaments of the thread are brought into closer contact, reducing the resistance of the thread itself.

The linear region as measured in Table 2 represents 18-29% stretch, depending on the fabric. For the purposes of using a stitched, textile-based sensor such as this to measure elongations in dimensions of the human body (such as breathing or joint bends), it is unlikely that the sensor will ever exceed the linear range. For example, most in-vivo measures of skin stretch are limited to about 30% stretch (Sohn, 2012), and measures of

clothing elongation during movement peak around 20% for skin-tight garments (C. Mattmann et al., 2007). However, for applications where the textile will be subject to much larger extensions, the compression region may in fact serve as the active range of the sensor. We have not yet evaluated the response characteristics of the compression region.

The peak-to-peak response of the sensor is small (between 2 and 14 Ohms), but stable (as seen in Figure 7). With appropriate amplification, this signal is a feasible method to detect elongations. Peak-to-peak response span showed much less change than baseline resistance during the test cycle, as observed in Figure 7. The poly/spandex sensors showed the highest sensitivity of response, with an average response range of 22.97% of its baseline resistance. The three elastomeric fabrics showed the highest overall sensitivities, with the non-elastomeric fabrics showing a narrower, less sensitive response span.

The baseline resistance response in Figure 6 shows some evidence of drift for all fabrics, which is most dramatic in the poly, poly/spandex, and cotton/poly fabrics. The presence of an elastomer was hypothesized to reduce the amount of baseline drift in the sensor, since the elastomer would improve the ability of the fabric to recover from extension, increasing the likelihood that the fabric substrate would return to its original

length following extension and not affect the physical length (and therefore resistance) of the stitched sensor. This improvement in recovery properties due to elastomeric content was indeed observed in the recovery test results shown in Table 4 (although the recovery percentage is not perfectly correlated with percentage of elastomer content, which may indicate further interaction of effects of fiber/thread structure). However, while we observe the nylon and cotton fabrics with elastomer content exhibiting less drift, the polyester/elastomer blend introduces more drift than the pure-cotton fabric. Further, the percentage of elastomer content also did not show a direct relationship to the amount of drift observed. It was hypothesized that increased elastomer content would reduce the amount of drift in the sensor response. In the observed response, the poly/spandex blend (10% spandex) showed more than four times as much drift as the cotton/spandex blend (6% spandex). This could be due to differences in the frictional properties of the non-elastomer fibers, or the structure of the fine threads of the textile structure. However, it is important to note that in all fabrics, the amount of drift is very small (on the order of less than one Ohm); therefore the differences are quite small.

Figure 8 shows the relationship between fabrics in magnitude of the linear response range (in resistance), and Table 2 articulates the average elongation at maximum resistance for each test fabric. As seen in these figures, the fabrics exhibiting the largest response range (e.g. poly/spandex) did not also have the largest extension at that maximum response. The poly/spandex peak resistance response was measured at the smallest elongation. This could be related to the ability of elastomeric fabrics to stretch within-fibers (rather than between-loops), allowing parts of the stitch structure such as the small gap between sides of the needle-loops to extend, separating parts of the conductive thread loops that are held together by the needle-loops. However, this pattern is not consistent for all elastomeric fabrics –

indeed, the nylon/spandex fabric shows the longest elongation at maximum resistance response, and the cotton/spandex blend shows a mid-range response.

A stronger relationship to elastomeric fiber content is seen in Figure 9 and Table 3, where the three elastomeric fabrics showed the most hysteresis in their responses. This is consistent with observed hysteresis effects in load/elongation relationships for elastomeric fabrics (Ben Abdessalem, Ben Abdelkader, Mokhtar, & Elmarzougui, 2009). Again here, however, there was no clear relationship between the amount of elastomeric content and the amount of observed hysteresis, but the hysteresis errors are for the most part in the range of one Ohm, and thus can be considered to be fairly small.

The results observed here that pertain to the effects of fabric substrate characteristics on sensor response indicate that although there are clear effects of elastomeric content in influencing sensor response range and hysteresis, it would appear that more variables are at play that affect the drift of the stitched sensor response, and other complicating variables may affect the relationship between elastomeric content and mechanical variables. While the experiment presented here controlled for knit structure, it did not precisely control for or vary fiber content, thread structure, or knit gauge in an incremental fashion, which may be necessary to fully evaluate the effects of these variables on stitched sensor response. Further, the experimental methodology employed (using the Instron tensile tester) measures elongation in terms of the distance between the instrument's heads, rather than the actual length of the sample being tested. Because the stitch geometry is strongly affected by changes in length of the fabric substrate, a hanging elongation test as performed here is important in understanding the effects of the recovery properties of the textile.

Conclusions

Textile-based sensors can provide considerable comfort benefits to wearable sensing, but are often difficult to construct and manufacture in a manner that preserves the mechanical properties of the textile. Leveraging the structure created by a machine such as the industrial overlock machine can minimize the effects on both comfort and manufacture. As observed here, a commonly-used industrial stitch can produce an inexpensive, reliable stretch sensor simply through the replacement of one standard sewing thread with a conductive thread. The sensor's response is a linear increase in resistance within the bounds of extensions commonly experienced through body movements, but saturates between 18 and 29% elongation, after which point the sensor experiences a compression response that results in a decrease in resistance.

However, textile-based sensors are subject to variability in mechanical properties due to mechanical variations in the textile substrate to which the sensor is coupled. As seen here, sensor properties are influenced by textile variables such as fiber content, but may also be influenced by knit structure and thread properties. In this case, many of the variations in baseline drift, magnitude of the sensor's linear response, and hysteresis effects are relatively small, and for some applications may not pose significant problems. For applications that require more precision, a better understanding of these variables and/or a calibration step specific to the individual sensor is needed.

In stretch sensing, elastomeric fiber content was hypothesized to have a significant effect on sensor performance. Specifically, the benefits of improved textile recovery were hypothesized to improve sensor properties such as baseline drift. However, while effects of elastomeric content were observed in these experiments, clear influences of amount of elastomeric content were not observed, and were likely influenced by complicating variables such as thread properties and fiber blends. Further investigation is needed to

characterize the effects of these variables on the sensor response.

Acknowledgements

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