



## Machine-Stitched E-textile Stretch Sensors

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**Abstract:** Truly wearable sensing poses challenges in many areas. To be successful, wearable sensors must preserve wearer comfort while providing accurate sensor data. Further, for widespread commercial production they must also be compatible with soft goods manufacturing. Here, we present a method of fabricating stretch sensors using common apparel sewing machinery. The response of sensors made using industrial coverstitch (two varieties) and overlock machines are compared, and the sensor response of a bottom-thread coverstitch is characterized in depth. Three conductive thread structures are compared in the bottom-thread coverstitch sensor. Results show a consistent and repeatable response for 4- and 5-ply threads, while 2-ply thread displayed more noise and less repeatability. Finally, this sensor is applied in a spinal goniometry application in three garment structures, and sensor performance is compared to motion capture data. The fabrication approach is promising for wearable sensing applications due to its manufacturability and comfort. *Copyright © 2016 IFSA Publishing, S. L.*

**Keywords:** Wearable technology, Wearable sensing, e-textiles, Stretch sensor, Smart clothing.

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### 1. Introduction

One of the key challenges of mass-producing e-textiles and garment-integrated technologies is the large differences in fabrication processes between hard goods (circuit boards, enclosures) and soft goods (textiles, apparel). To date, many efforts to merge the two have concentrated on translating the fabrication of hard goods to accommodate soft goods: for example, snapping a hard unit onto a garment, adhering hard components to the surface of a textile, encapsulating hard goods on the surface of a textile, or printing electronic components (traces, sensors) onto the textile surface. Similarly, electronic sensors/actuators are typically thought of as discrete components, pre-fabricated and applied to the garment system during assembly or post-assembly.

One drawback to the focus on adapting techniques from hard goods to soft goods fabrication is the requirement that the soft goods manufacturer adapt

their processes (in some cases, dramatically). Unfortunately, apparel production in particular is a low-margin, short-cycle business that is typically resistant to change (often because significant change would require a loss of productivity that may not be sustainable for the individual business owner: for further discussion, see [1]). However, apparel production is rich with complex machinery and processes that hold under-explored potential for fabrication of wearable technology and which (appropriately applied) may reduce the impact on existing fabrication processes.

Here, we explore the potential of two of the most common industrial sewing machines to produce stretch sensors with minimal impact on production processes. We discuss the sensors produced by the industrial coverstitch machine (in two configurations) and the industrial overlock machine, and concentrate in detail on characterizing the sensor produced by the bottom cover thread of the coverstitch machine, the

most versatile of the three sensors. In all three cases, these machines produce repeatable, responsive sensors that present an interesting alternative to pre-fabricated strain sensors and to other methods of integrating a stretch response into apparel. Most importantly, they leverage extremely common cut-and-sew fabrication processes. To illustrate the viability of these sensors in practice, the bottom-thread sensor is applied in a spinal goniometry example, using three different garment forms. Sensor performance is compared to that of a standard optical motion-capture system.

## 2. Background

There exist many methods for integrating stretch-sensing abilities into a textile substrate. These approaches in general take the form of one of three central methods that lend dynamic electrical properties to a textile structure. The first is the use of electrically active materials such as piezo-electric films or electro-active polymers. These materials inherently respond to deformation by generating a small electric potential [2–4]. The second method is by embedding suspended conductive particles (such as carbon) in a substrate, which is then formed into a fiber or applied as a coating. Such an approach results in changes in the proximity of suspended particles as the substrate is stretched: bringing particles closer together reduces the resistance of the material, while bringing them farther apart increases the resistance [3, 5, 6]. The third approach to creating an electrical stretch response in a fabric structure is the method we implement here: manipulating the geometry of a looped conductor. In this approach, an un-insulated conductor with specific resistance per unit length is manipulated into a looped structure, which changes in some way as the structure is stretched and relaxed. A common use of this approach is seen in knitted stretch sensing, wherein the conductor forms an integral part of the knit structure and loops are formed through the structure of the knit stitch [6–10]. As the knit is stretched, loops slide over one another, shorting certain parts of the looped structure and opening other parts. Similarly, loops may deform, causing the short to shift along the length of the conductor. As such, this shortening and lengthening of loops, and shifting of loops into and out of contact create a change in the electrical length of the conductor, and correspondingly, its resistance. The change in resistance can then be correlated with the amount of stretch the substrate or structure experiences.

These approaches all have different benefits and challenges. Application of a suspended-particles approach such as a carbon-loaded rubber may require that the sensor be applied to the surface of the garment in something like a screen-printing process, and may add bulk or stiffness to the garment. Knitting a looped-conductor sensor may require that the sensor position be established before the textile goods are fabricated, limiting the flexibility in sensor placement and orientation. We find significant benefits to stitched

techniques that leverage existing CMT (cut-make-trim) apparel production processes, in their flexibility, adaptability, ease of customization, and minimal impact on production. Here, we present the theory of operation of three different stitched sensors, fabricated using industrial overlock and coverstitch machinery. We focus on the experimental testing of one of these sensors (the bottom-thread coverstitched sensor) and characterize the resistance response of this sensor to repeated stretching.

### 2.1. Stitched Stretch Sensors

Many industrial sewing machines create a looped thread structure. Among these are most types of overlock and coverstitch machines, which use one or more looper threads to create various stitch structures. The two stitch classes we will focus on here are ISO class 602 and 514, a two-needle bottom and top cover stitch and a 4-thread mock safety overlock stitch, respectively [11]. The stitches formed by these machines are depicted in Figs. 1 and 2.

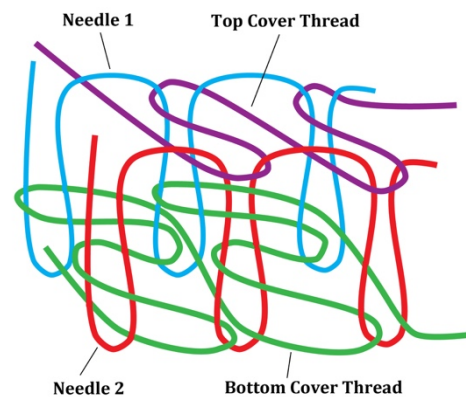


Fig. 1. ISO 602 top- and bottom-cover stitch.

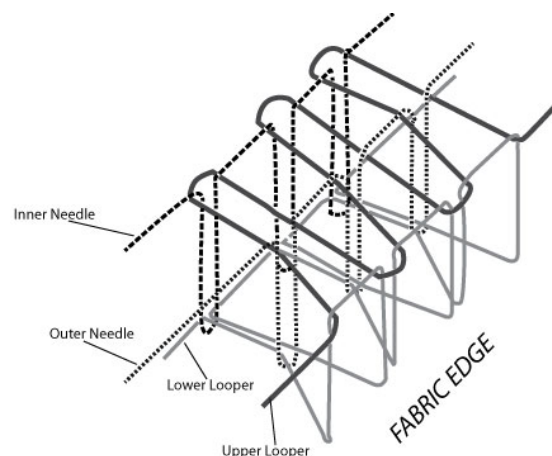


Fig. 2. ISO 514 4-thread overlock.

To create a stretch sensor from these two structures, it is necessary to replace one or more of the

looper threads with an un-insulated conductive thread. In the 602 coverstitch, this can be either the top or bottom cover thread (or both), and in the 514 overlock, either the upper or lower looper. It is important to note that the theory of operation described here can be extended to other looped stitch structures.

## 2.2. Theory of Operation: Top Cover Stretch Sensor

In the coverstitch, the top cover thread is brought back and forth between the two needle threads to form a sinusoidal pattern. It does not pass through the fabric, nor does it cross itself. In the relaxed position, loops of the sinusoidal curve are touching at either side of the stitch. However, as the fabric is stretched, these loops are pulled apart (as illustrated in Fig. 3).

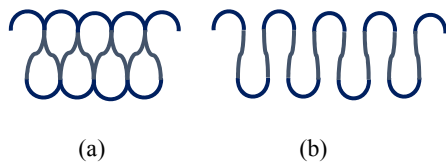


Fig. 3. Looped conductor in the relaxed (a) and stretched (b) positions.

Since the conductive yarn is resistive per unit length, when loops are shorted the sensor forms an anti-ladder topology of resistors, illustrated in Fig. 4a, with a lower total resistance. As the stitch is stretched, loops separate until all loops are separated (Fig. 4b) and the resistance increases until it reaches the resistance of the full length of conductive thread.

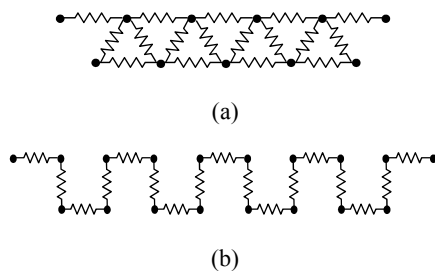


Fig. 4. Equivalent electrical model of top-cover sensor for all loops touching (a) and loops separating (b).

## 2.3. Theory of Operation: Bottom-Cover Stretch Sensor

The bottom cover thread, as seen in Fig. 1, takes a more complex geometry than the top cover thread. As it is pulled through the needle-thread loops to create a double-needle lockstitch, smaller loops of the bottom-cover thread are formed. For this thread, as the stitch is stretched, needle-loops are elongated and shorted,

shortening the length of what becomes a zig-zag pattern of the bottom cover thread, as illustrated in Fig. 5.

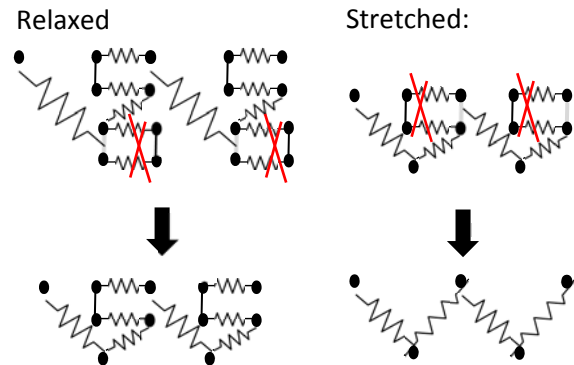


Fig. 5. Electrical equivalent model of bottom-cover stretch sensor in the relaxed and stretched positions.

This sensor, by contrast, reduces in resistance as it is stretched. Importantly, the top and bottom cover threads do not pass through the fabric, nor do they come into contact: they are electrically isolated by the fabric substrate. Therefore, it is possible to fabricate two sensors in one machine-stitched operation.

## 2.4. Theory of Operation: Overlocked Stretch Sensor

The upper and lower looper threads of the overlock stitch create a sinusoidal formation similar to the top-cover thread, but restrained by the outer needle thread. As the stitch is stretched, loops separate along the fabric edge, but are held together along the inner side of the stitch, as illustrated in Fig. 6. Therefore, as with the top-cover sensor, resistance increases as the stitch is stretched.

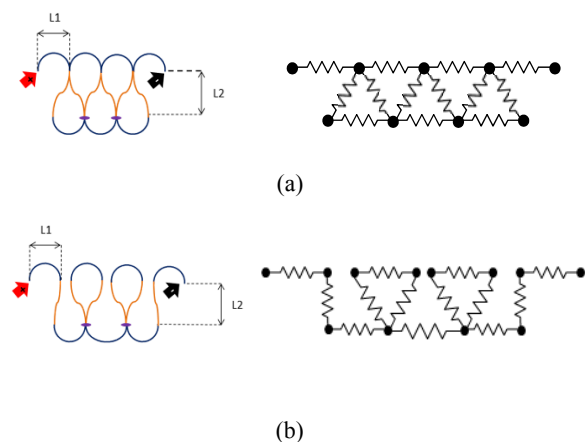


Fig. 6 Overlocked stitch conductor in the relaxed (a), and stretched (b) position, with equivalent electrical model.

### 3. Characterization: Bottom-Cover Stitched Sensor

The resistance response of the overlapped and top-cover stitched sensors have been reported elsewhere [12]. Here, we describe the response of the bottom-cover stitched sensor under controlled stretch conditions, and compare these results to the previously-characterized sensor formation methods.

#### 3.1. Sensor Fabrication

The stitch used here to create a stretch response is formed by the Juki MF-7723 high-speed, flat-bed coverstitch machine. The conductors used were all composed of Shieldex silver-coated nylon fibers. We tested these fibers in three thread structures: 177/17 dtex 2-ply sewing thread; 235/34 dtex 4-ply sewing thread; and a custom-fabricated 5-ply sewing thread.

One sensor was stitched for each thread. For the 4 and 5-ply sensors, 3" lengths were stretched. However, because of the much higher resistance of the 2-ply thread, only 1" could be tested with our equipment (a longer sensor exceeded the upper limit of the DMM.) All sensors were fabricated on a jersey-knit, elastomeric blend textile substrate, as shown in Fig. 7.



Fig. 7. 2-, 4-, and 5-ply (left to right) bottom-thread coverstitched sensors.

#### 3.2. Method

Sensors were stretched using an Instron tensile tester (used to measure elongation and load during each test), and the resistance response of the conductive sensor was captured using a BK Presion 2821E digital multi-meter (DMM). The experimental set-up is illustrated in Fig. 8.

Three separate experiments were performed on sensors of each thread type: the sensor tested was stretched from its initial functional length of 3 inches to a final length of 3.75 inches (a total of 25 % stretch) in the first experiment; to a final length of 4.05 inches (a total of 35 % stretch) in the second experiment; and to a final length of 4.50 inches (a total of 50 % stretch) in the last experiment. In each test, the sensors were stretched and relaxed 20 times in succession. It is

important to note that the actual measured length of each sensor was 7 in, since the section of the stitch between the two Instron clamp plates is restricted and unable to be stretched during the test. Each Instron plate is 2 in long, in the direction of the sensor. Both top and bottom 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 that was removed from the measurements during data analysis. The Instron data collection system was used to record extension at sampling frequency of 10.0 Hz, 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. Both Instron and DMM samples were collected with the corresponding machine time stamp. Data were aligned and Instron data were down-sampled to match the DMM data sampling rate using two digits of precision on the time stamps.

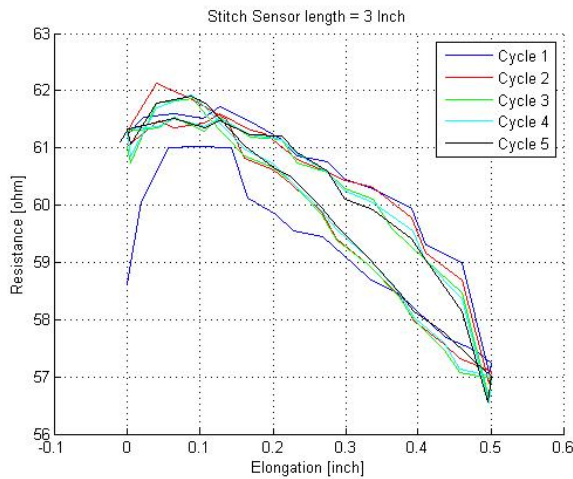


Fig. 8. Experimental setup: sample mounted in Instron with DMM leads attached (top and bottom).

#### 3.3. Data Analysis

For reference, the output response of a 4-ply 3 inch long bottom-cover stitched sensor for a 25 % stretch is illustrated in Fig. 9 for the first 5 stretch cycles.

Each stretch cycle contains an extension and a recovery phase. Sensors were not pre-conditioned: therefore, the very first extension is a conditioning cycle in which the fabric extends and does not fully recover (per the typical mechanics of elastomeric fabrics [13]). For this reason, the first cycle is not considered in the sensor average parameters discussed below.



**Fig. 9.** Bottom-cover stitched sensor resistance response curves, first 5 cycles.

For each cycle, sensor data was assessed for nominal and baseline resistance value at 0 extension, sensitivity, base and peak drift, peak-to-peak response, hysteresis area, and response to fabric bend regions in both extension and recovery phases. These values were averaged over all cycles to arrive at a mean response for each sensor.

- **Nominal resistance:** the nominal resistance represents the theoretical resistance we would expect for each inch of sensor in the relaxed position (no extension), and it was measured by rounding a coarse average value of ~10 consecutive measurements of 1-inch sections on different areas of the sensor;

- **Baseline resistance:** the baseline resistance was computed as the resistance in the relaxed position (no extension) of the second stretch cycle, after the first full extension;

- **Sensitivity:** the sensitivity is the ratio between the absolute maximum resistance change  $|\text{MAX}(R) - \text{MIN}(R)|$  and the amount of elongation, where R refers to the sensor output resistance at the maximum relative extension (i.e., 0.75" for a 25% stretch of a 3 inch sensor). Sensitivity is expressed as a change in Ohms per unit length of the sensor;

- **Average Base Drift:** the approximate derivative of the baseline resistance, base drift is calculated as the average difference between consecutive maxima in the sensor response, corresponding to minimum extension (or fully relaxed sensor);

- **Average Peak Drift:** peak-drift is calculated as the average difference between consecutive minima in the sensor response, corresponding to maximum extension;

- **Total Base Drift:** total base drift is defined as the difference between minimum and maximum values of the resistance value at minimum extension (or fully relaxed sensor);

- **Total Peak Drift:** total peak drift is defined as the difference between minimum and maximum values of the resistance value at maximum extension (or a fully stretched sensor);

- **Peak-to-peak response:** the peak-to-peak response is computed as the absolute difference between minimum and maximum values of the resistance in each cycle, averaged over all cycles;

- **Hysteresis area:** the hysteresis area is defined as the area comprised between extension and recovery curves of the same cycle, averaged over all cycles;

- **Bend region:** difference between the initial resistance value at minimum extension and the maximum resistance before resistance begins to decrease, averaged over all cycles.

### 3.4. Results

The bottom-cover stitched sensor was integrated on the same elastomeric fabric using three conductive threads with different structures (shown in Fig. 7). Table 1 shows the average sensor parameters for the three types of thread. Figs. 10-12 illustrate the response of each type of thread for each extension condition.

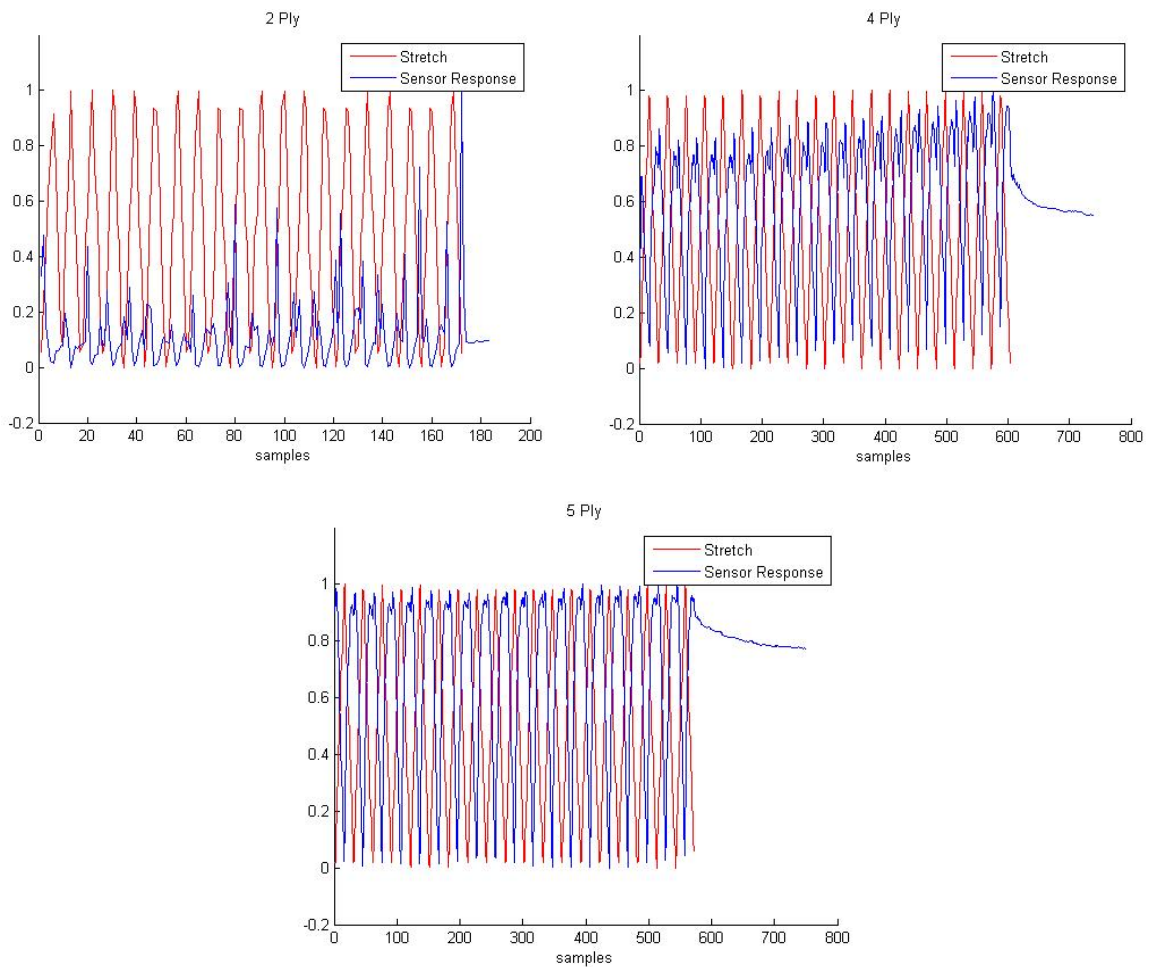
### 3.5. Discussion

The bottom-cover stitched sensor was tested with three different thread structures: 2 ply, 4 ply, and 5 ply. This particular thread is made by coating filaments of nylon with a silver coating. However, the nylon filaments are twisted into a 2-ply thread before they are coated with silver. These coated threads are then twisted into multi-ply threads. Because the filaments are coated as twisted 2-ply yarn, areas where the twisted plies are held closely together can experience "shadowing" effects, where the coating is less uniform [12]. These shadow areas have more resistance, due to the thinner and less uniform coating. However, when multiple threads are twisted together after coating it is more likely that the outer parts of the component threads are in contact in the multi-ply twist, improving the electrical contact between threads.

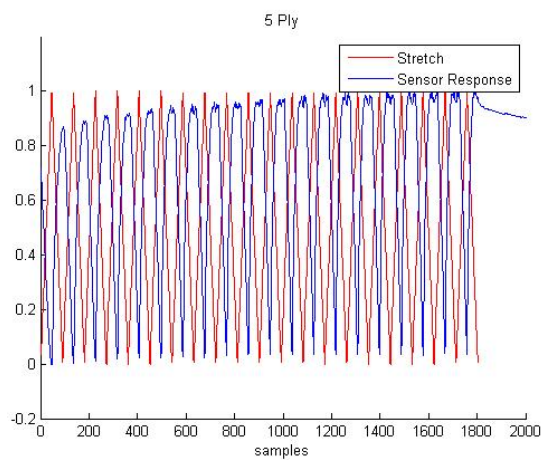
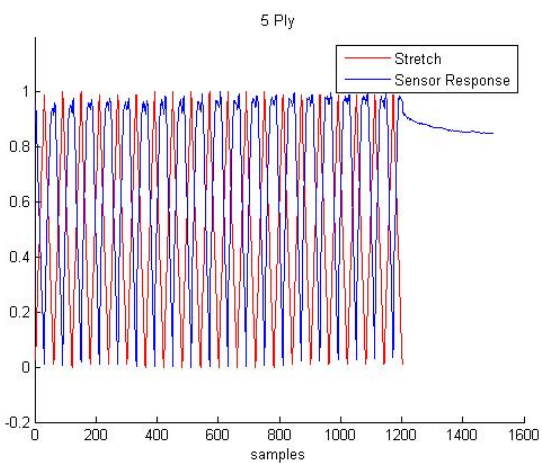
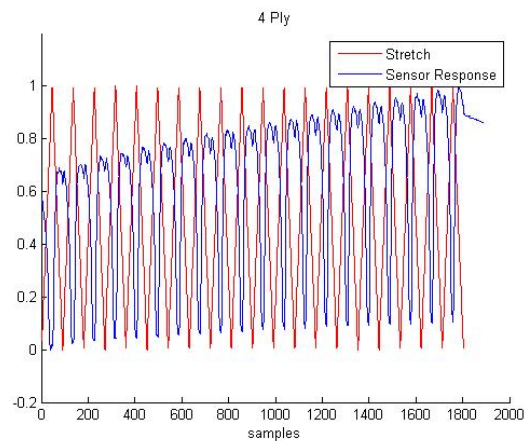
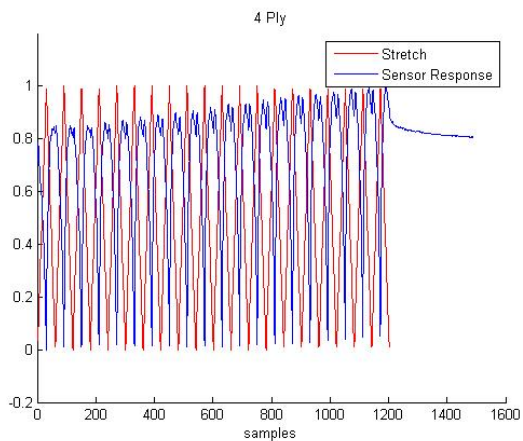
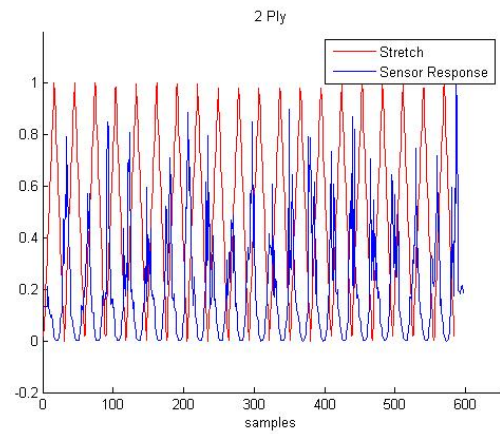
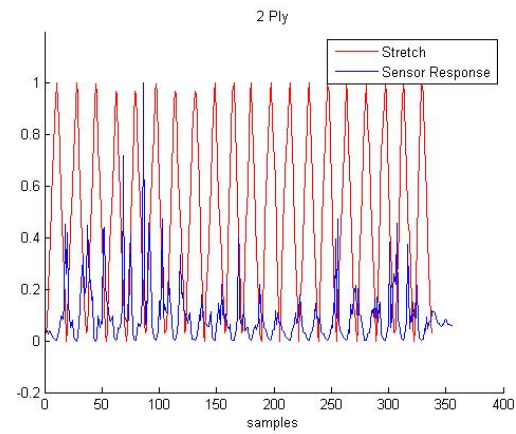
The larger the number of plies twisted together, the more conductive contact there is between the filaments in the yarn, and the more likely that external surfaces of different plies (areas that are unlikely to experience shadowing effects) are in contact. This also translates to a more reliable sensor response as the yarn is stressed by successive extension and recovery cycles. Comparing the long term repeatability parameters indicated in Table 1 between the three thread structures, in the 2 ply yarn we see an increase in drift of the sensor response, potentially due to a decrease in contact between filaments as "shadowed" areas of the coated filaments are shifted into contact (resulting in a decrease in electrical conductivity). The 5 Ply yarn sensor, by contrast, showed the smallest resistance drift. An example of output sensor resistance drift is shown in Fig.'s 10, 11, and 12 for the 2-, 4-, and 5-ply sensors, where the sensor response is aligned with the extension and recovery stretch phases in a normalized graph.

**Table 1.** Bottom-cover stitched sensor characterization: 2-ply, 4-ply, 5-ply.

Relative Stretch – yarn Ply's	Basic Parameters			Precision and Accuracy							
	Nominal R per unit length [ $\Omega$ /in]	Baseline R [ $\Omega$ /in]	Sensitivity S [ $\Omega$ /in]	Long Term Repeatability						Hysteresis Area [ $\Omega^*$ in]	Bend Region [ $\Omega$ ] @ Extension – Recovery
				Average Base Drift [ $\Omega$ ]	Average Peak Drift [ $\Omega$ ]	Total Base Drift [%]	Total Peak Drift [%]	Peak-to-Peak Mean [ $\Omega$ ]	Peak-to-Peak Var [ $\Omega$ ]		
25 % stretch – 2 Ply	2 K	1.48 K	0.47 K	24.92	4.92	95.75	6.44	0.8 K	0.29M	2.33 K	1.94 K – 1.25 K
25 % stretch – 4 Ply	16	16.88	5.52	0.02	0.02	1.34	1.47	4.16	0.02	12.63	1.14 – 0.73
25 % stretch – 5 Ply	8	9.59	3.78	0.01	0.02	0.72	1.93	3.79	0.03	9.12	0.30 – 0.15
35 % stretch – 2 Ply	2 K	3.3 K	7.34 K	76.33	2.02	112.3	5.70	1.3 K	0.43 M	7.09 K	1.47 K – 2.95 K
35 % stretch – 4 Ply	16	17.48	15.02	0.07	0.02	3.23	1.74	16.04	0.14	80.10	1.47 – 1.72
35 % stretch – 5 Ply	8	9.67	7.87	0.01	0.01	0.98	1.21	8.34	0.01	32.38	0.42 – 0.30
50 % stretch – 2 Ply	2 K	2.37 K	2.9 K	18.97	-0.43	197.69	134.88	3.3 K	2.7 M	25.4 K	2.99 K – 1.32 K
50 % stretch – 4 Ply	16	18.90	16.79	0.61	0.20	17.40	8.48	29.25	5.18	229.01	2.31 – 2.88
50 % stretch – 5 Ply	8	8.90	6.76	0.06	0.018	3.60	1.81	10.71	0.04	69.42	0.31 – 0.33



**Fig. 10.** Normalized 2, 4, 5 Ply Bottom-cover Stitched Sensor output aligned to stretch phases, 25 % stretch case.



**Fig. 11.** Normalized 2, 4, 5 Ply Bottom-cover Stitched Sensor output aligned to stretch phases, for 35 % stretch case.

**Fig. 12.** Normalized 2, 4, 5 Ply Bottom-cover Stitched Sensor output aligned to stretch phases, for 50 % stretch case.

The 2-ply sensor output has also a larger variability over consecutive cycles than both 4-ply and 5-ply sensors as can be seen from the Peak-to-Peak values, and the amount of noise in the sensor response (as seen in Fig. 10, 11, and 12). This again is likely due to the poor contact between fibers of the 2-ply yarn, as shadowed areas are moved into contact during extension. We conclude that the 2-ply thread is not as well-suited to this kind of sensing as the multi-ply threads.

By contrast, the 4-ply and 5-ply sensors showed consistent, repeatable, and reasonably comparable performance. The 4-ply sensor has double the nominal resistance of the 5-ply sensor. For each sensor, the baseline resistance shows consistent values with a small variability among the trials at 25 %, 35 %, and 50 % due to the cumulative effect of deforming the fabric repeatedly.

Both sensor types show a larger sensitivity increase between 25 % and 35 % stretch than between

35 % and 50 %. If the sensor response were perfectly linear, sensitivity would be consistent regardless of the amount of extension. Instead, we observe a larger change between 25 % and 35 % stretch than between 35 % and 50 %. However, because the bending region is encompassed in the beginning of the stretch period, it comprises a relatively larger portion of the 25 % stretch response than the 50 % stretch response.

The 5-ply sensor has better long term repeatability properties than the other two threads, exhibiting smaller drift and smaller variance. However, the 4-ply sensor showed similar performance, especially for 25 % and 35 % stretch, and both sensors show drift on the order of less than 4 % for 25 % and 35 % stretch. Increasing the amount of stretch in both the 4-ply and 5-ply sensors correlates with a predictable increase in the peak to peak mean responses, while average drifts stay about the same, except in the case of the 4-ply sensor (that shows a larger increase, particularly at 50 % stretch). The 4-ply shows increase of both total drift and peak to peak variance with increase in extension; the 5-ply shows a smaller increase compared to the 4-ply of the total base drift with the extension, while the total peak drift and peak to peak variance oscillate around closer values for 25 %, 35 %, and 50 % stretch. The hysteresis between the extension and recovery curves increases as the stretch increases for both types of threads. This is consistent with the behavior of elastomeric fabrics.

In all our tests the fabric was never pre-conditioned (pre-stretched). As can be seen in Fig. 9, the very first cycle exhibited different behavior than subsequent cycles, and was removed from data analysis. However, this difference is due to incomplete recovery of the fabric following extension: in essence, the fabric gets longer following the first stretch. Therefore, following the first cycle the fabric was never completely straight in the relaxed position, but was slightly bent between the plates due to the excess length. As can be seen in Fig. 9, this results in a slight increase in resistance at the peak (maxima) of the response curve (the fully-relaxed position). We attribute this increase in resistance as a response of the sensor to bending (as established in [14], this sensor is also sensitive to

bending as well as stretching.) This bend region is fairly stable for all sensor types across degrees of stretch, consistent with it being primarily an effect of the mechanics of the textile substrate.

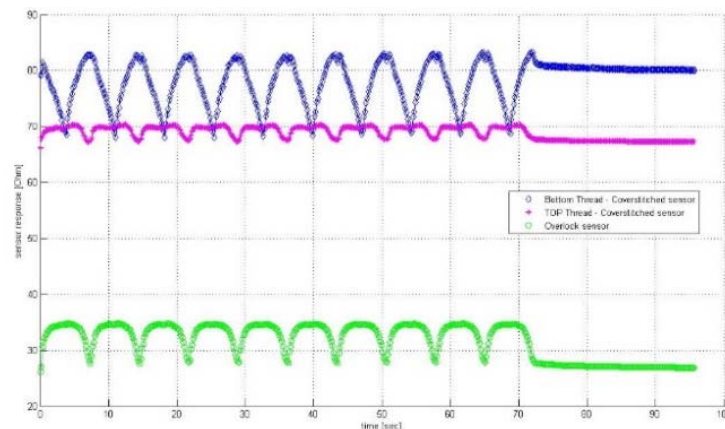
Finally, while it appears that the 5-ply thread exhibits the best sensor behavior, there are other practical considerations that affect the choice of thread for fabricating sensors. For example, the 4-ply thread is commonly used, easily available, and relatively low cost while the 5-ply thread must be custom-fabricated and is higher-priced. While this factor is feasibly overcome, the 5-ply yarn is also thicker and bulkier than the 4-ply yarn, as seen in Fig. 7. This has two key consequences: it is more difficult to handle in the machine, and it creates a bulkier, more noticeable appearance in the finished stitch. Therefore, given the similarity in performance parameters between the 4- and 5-ply threads, the 4-ply thread is for us the preferred choice.

#### 4. Comparison: Stitched Sensors

The previous section focused in depth on characterizing the bottom-thread coverstitched stretch sensor. However, the three methods discussed earlier create alternative sensors with different properties. Here, we compare and contrast performance and fabrication variables among the three alternatives (top- and bottom-thread coverstitched stretch sensors, and overlapped stretch sensors).

##### 4.1. Sensor Response

Fig. 13 shows the responses of 3" top-cover, bottom-cover, and overlapped sensors for a 25 % elongation, all fabricated using the 4-ply thread. As can be seen in that figure, the bottom-cover thread creates a sensor with a response inverse to that of the top-cover and overlapped sensors (per the theory of operation outlined earlier). The response of the bottom-cover thread is also not subject to saturation in the same manner as the top-cover and overlapped sensors.



**Fig. 13.** Sensor responses for 4-ply bottom-thread coverstitched sensor, top-thread coverstitched sensor, and overlapped sensor, at 25 % elongation.

## **4.2. Fabrication**

The most significant difference between the coverstitch and overlocked sensors is that the overlock stitch can only be formed at the edge of a piece (either as an edge-finish on a single layer or as a seam joining two layers together). This limits the flexibility of the sensor placement. Further, while it is possible to overlock a sensor for only part of an edge or seam, it is less straightforward to do so (as the machine typically must start from an edge, or else it must “drive” on and off of the edge forming something like an on-ramp and off-ramp mid-seam, as seen in Fig. 14). It is possible that a section of sensor could be overlocked over a standard overlocked seam (non-conductive), but the seam structure would affect the extension properties of the fabric (and consequently, the sensor response).

By contrast, the coverstitch can be placed anywhere on the garment surface, and can be stopped and started mid-piece. This increases the flexibility of sensor placement and dimensions significantly.

Further, the coverstitch structure maintains the top and bottom cover threads exclusively on opposite sides of the fabric. Because of this, both the top- and bottom-cover sensor can be fabricated in one operation, and remain electrically isolated by the fabric. This facilitates an even broader range of applications, including using the differential between the sensor responses to detect fabric bends (for example, see [15]).

## **4.3. Interconnects and Sensor Placement**

While the coverstitch and overlock machines create fully-formed sensors, these sensors must be integrated into a circuit in order for their responses to be detected. Depending on the application, it may be necessary to attach leads to a stitched sensor in order to connect it to a larger circuit. There are many ways to achieve this (many of which similarly preserve cut-and-sew operations and require minimal changes to current practice), including stitching straight stitches (or zig-zag stitches, to permit extension) that join the ends of the sensor to the circuit, or leaving thread tails on either end of the stitch that can be attached to appropriate connectors (such as snaps). Further, it may be possible to isolate the extensible portion of the stitch by stitching a non-extensible material (such as fabric, woven tape, or interfacing) into areas that should not be allowed to extend. In this manner, a conductive thread may pass the entire length of a seam or from edge to edge of a garment piece without responding to extensions along the entire stitch length.

## **5. Application: Spinal Posture Sensing**

Detection of spinal flexion and curvature is of interest to many wearable monitoring systems, from general-purpose activity recognition to medical

conditions like kyphosis. As with many wearable sensing applications, soft, comfortable sensors are beneficial in improving the wearing experience and increasing user willingness to use a monitoring system. In this study, we compare the ability of three different garment styles to effectively capture spinal flexion in the sagittal plane through embedded textile stretch sensors. For our healthy adult volunteers, we find that the leotard garment that provides a point of counter-force at the base of the spine shows a marked increase in sensor accuracy with an average  $r$ -sq of 0.85 as compared to a marker-based optical motion capture system.

## **5.1. Background**

The position and movement of the body, when effectively measured and monitored, can be used in many ways. For consumer applications, spinal positions and movements can be an essential part of activity-recognition algorithms. For the everyday computer user, spinal posture is a significant factor in longer-term musculoskeletal disorders. For clinical use, measuring spinal curvature over time can help in the monitoring and treatment of disorders such as thoracic kyphosis (hunchback) without requiring expensive office visits or potentially harmful diagnostics like x-rays. While non-invasive methods of monitoring spinal curvature exist in therapeutic settings, such as goniometry or flexicurve measurement, these methods are rarely feasible for long-term, continuous monitoring.

A garment-integrated method of measuring and monitoring spinal curvature would be useful in facilitating long-term, pervasive monitoring of activity as well as the progression of musculoskeletal disorders. Here, we assess a comfortable, textile-based sensor that has not yet been evaluated for sagittal spinal posture in terms of its accuracy and reliability for measuring spinal curvature.

Spinal posture has been previously measured in garments using a variety of techniques. There are several devices in the academic literature [13, 14] as well as consumer market [15] that use inertial sensors like gyroscopes and accelerometers to detect changes in spine orientation and movement, and from that to deduce posture. Mattmann et al. [16] evaluated textile-integrated strain gauges made from conductive rubber filaments to map a wide range of spinal postures, including sagittal bends. Walsh et al. used marker-based motion capture [17] and Dunne et al. used optical bend sensors [18] to measure spinal curvature.

Here, we apply the previously-discussed stitched sensor structure to the spine. Garment mechanics during body movement have been previously shown to have an effect on the accuracy of sensor measurement, particularly in garment structures where body movements result in elongation of certain body dimensions and garments can consequently “ride up”, or slide upwards on the body as the body dimension elongates and subsequently contracts during

movements. Stretch garments may alleviate this effect, as they are capable of accommodating the body's elongation by stretching. However, it is unclear if this elongation is sufficient to counteract the forces on the garment that may result in riding up or sensor buckling.

In this evaluation, we assess three different garment structures. The vest structure is the shortest garment, which requires the least amount of body coverage, ending around the L3 vertebra (the natural waist). The shirt structure is a long-sleeved t-shirt, extending to the full hip (close to the sacrum). The leotard passes between the legs, securing the garment around the vertical girth of the torso as well as the horizontal circumference.

### 5.3. Method

#### Sensor and Garments

A stretch sensor constructed following the bottom-thread coverstitched sensor method was stitched to the dorsal side of each garment, aligned with the spine. Each sensor was insulated with 3 M 7012 stitchless bonding film following the procedure in [19].

Three test garments were evaluated. These garments vary in body coverage and attachment, and are depicted in Fig. 14.



Fig. 14. Test garments, dorsal view: vest, shirt and leotard.

#### Test Method

Garments were evaluated as worn by 10 participants (1 male). Participant chest and waist circumferences are depicted in Fig. 15.

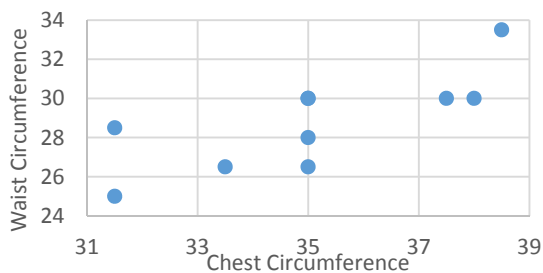


Fig. 15. Participant chest and waist circumference measures.

Each garment was tested in the same manner. Three reflective motion capture markers were placed along the sensor length at specific distances beginning at the center-back neck, following the measures articulated in Table 2.

Table 2. Marker spacing.

	Marker 1	Marker 2	Marker 3
Vest	0	8.5 cm	18.5 cm
Shirt	0	18 cm	23.5 cm
Leotard	0	18 cm	23.5 cm

The participant donned each garment sequentially. A digital multi-meter (DMM, BK Precision 2821E) was used to collect the resistance of the stitched sensor over time, while a Vicon Nexus motion capture system was used to calculate a reference spinal angle from the three markers. At the beginning of each trial, the participant stood upright for approximately 2 seconds, before an artificial disturbance was introduced by moving the bottom marker and folding the sensor, in order that the two datasets might be aligned later. The participant stood upright for approximately 2 more seconds following the disturbance, and subsequently commenced the flexion sequence.

For a series of 5 repetitions, the participant flexed their spine in the sagittal plane to its maximum flexion, and then returned upright. Participants were instructed to "roll" or curve their spine as much as possible rather than flexing from the hip, in order to induce the maximum degree of kyphosis into the spine. At the end of the series of flexion repetitions, the participant returned upright for approximately 2 seconds.

#### Data analysis

As the two systems sample at different frequencies, Vicon data were first down-sampled to match the DMM frequency. Vicon and DMM data were then aligned manually by synchronizing the artificial disturbance. The disturbance was then removed from the dataset, at the mid-point of the upright period following the disturbance. In a few cases, missing data from the full-flexion portion of the participants' movement due to markers passing out of view of the Vicon system were removed.

The trimmed data were then compared by linear regression. R-sq values for each participant in each garment were calculated, and subsequently averaged over all participants. Standard deviations for the mean r-sq values were calculated.

### 5.4. Results

Mean r-sq and standard deviations for the three garments are shown in Fig. 16. Two Vicon captures for the vest were corrupted and were not included in the analysis.

Fig. 17 shows the garment resistance response and Vicon reference measure from the trial closest to the mean r-sq for each garment.

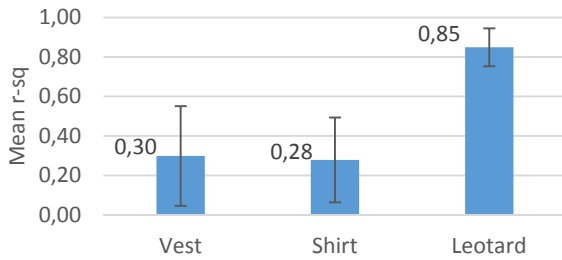
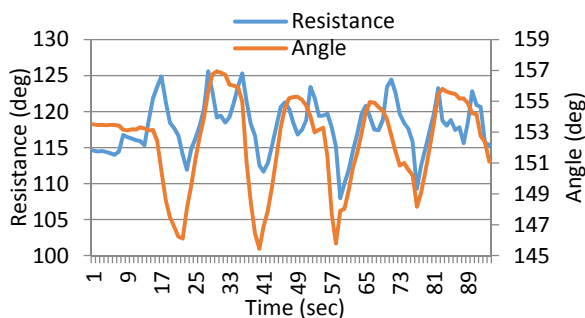
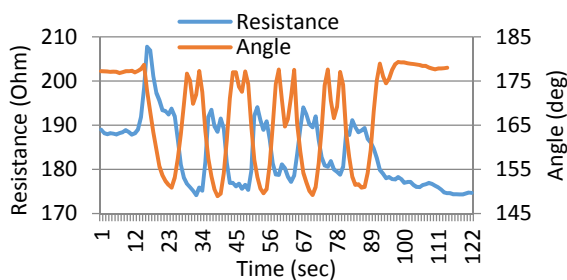


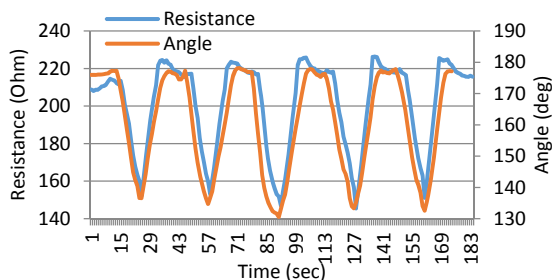
Fig. 16. Mean r-sq and standard deviation by garment type.



(a) Vest: r-sq = 0.26



(b) Shirt: r-sq=0.34



(c) Leotard: r-sq=0.88

Fig. 17. Representative sensor responses closest to the mean r-sq value for each garment.

## 5.5. Discussion

As seen in Figs. 16 and 17, there was a dramatic difference in the mean r-sq values for the various

garment types. The shirt and vest prototypes both showed far worse correlation with the Vicon reference angle than the leotard garment. Further, as seen in Fig. 17, the vest and shirt sensor responses often showed an almost opposite response than the leotard: the leotard was in-phase with the Vicon angle, while the shirt and vest were often nearly out of phase.

This behavior can be explained to some extent by the nature of the sensor response. While the stretch response for this sensor is typically in-phase with joint flexion angles (as the joint is flexed, the sensor resistance drops), the shirt and vest garment sensor responses may actually represent a drop in resistance due to the multi-fold bending that happens when the garment rides up on the body during full extension but does not slide back during extension, instead buckling into s-curve wrinkles (similar behavior was observed in the sensor described in [18]). While sinusoidal curves in the optical fiber bend sensor in [18] had a negligible net effect due to convex and concave curves cancelling each other out, in this sensor convex and concave curves sum to a net greater effect on sensor resistance. Therefore, during the extension phase of these garments that are not secured between the legs, the buckling behavior results in a net decrease in resistance due to the multi-fold bending that occurs.

While the fold response of this sensor has been shown to be useful in loose-fitting garments worn over the knee [20, 21] it is apparent that for tight-fitting, extensible torso garments it is necessary to secure the garment between the legs in order to provide enough counter-force to effectively extend the textile (and therefore, the integrated sensor). Looser-fitting garments may provide an effective bending response, however.

The secured leotard garment showed a correlation with the marker-based motion capture angle that is similar to other textile-integrated sensors used for wearable goniometry, and is likely a viable alternative that provides benefits in terms of smooth surface profile and next-to-skin comfort.

## 6. Conclusion

We find there is significant potential for adapting common industrial sewing machines to the needs of wearable technology and e-textiles, while minimizing the changes required of current practice. As discussed here, two of the most common sewing machines (the coverstitch and overlock machines) have the ability to produce reliable, repeatable, sensitive sensors. Each machine produces sensors with slightly different characteristics: the overlock and top-thread coverstitch sensors are sensitive to small amounts of extension, but saturate at 5-10 % (top-thread coverstitch) and 20-25 % (overlock) elongation. By contrast, the bottom-thread coverstitch sensor does not saturate, but displays an inverse response (decreasing in resistance as it is stretched). The top- and bottom-thread coverstitched sensors can be fabricated in one operation, and remain electrically isolated, and are

further able to be placed on the surface of the garment in any location. The overlapped sensor must be formed at the edge of a piece or seam.

Here, three options for conductive thread were compared in the bottom-thread coverstitched sensor. We find that a multi-ply thread is essential for reliable sensor response, but that the marginally improved accuracy and repeatability of the 5-ply thread may not outweigh its drawbacks in bulk. The Shieldex threads we used in these experiments are by no means the only option for conductive thread, and different fiber/thread structures may exhibit different properties in sensor response. Further, as a stretch sensor the fabric substrate for the stitch has a significant impact on the sensor response in addition to factors like the thread type and stitch structure. In [16] we present the results of an experiment evaluating the impact of fabric type on the response of the overlock sensor.

Variables of implementation are often crucial to the ultimate success of a wearable sensing garment. Here, we investigate the relative effects of garment style on accuracy of the coverstitched sensor in a garment-integrated spinal posture sensing application.

From the results discussed here, stitched sensors such as this should be implemented with a counterforce in the vertical direction if their stretch response is to be leveraged, and bending effects avoided. To facilitate a spinal bend measurement using the sensor's bending response, which would not require a counterforce in the vertical direction, a looser-fitting garment with a low coefficient of friction with the body may be effective.

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