# Machine Embroidery Enclosure for Stretchable Fiber Optic Respiration Sensor

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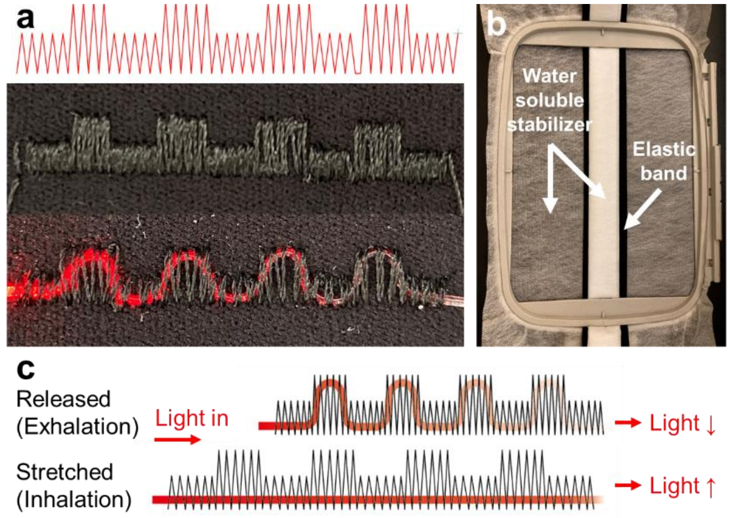
Keywords: Stretchable fiber optic, Machine embroidery, Respiration

***Background*** Respiratory pattern is one of the basic and crucial indicators of the physiological and emotional status of a person (AL-Khalidi et al., 2011; Boiten et al., 1994). Daily tracking of the respiratory pattern has become important along with the expanding home healthcare market, increasing interest in psychological wellness, and the recent pandemic. Yet, conventional devices are not adequate outside of the medical environment and recently introduced face-covering devices may not be useful when a mask is not required. Body-worn type devices tracking chest movements can be more versatile and relevant for daily activities such as sports or sleeping. Chest circumference changes ~4 cm in normal breathing and ~8 cm in deep breathing (Agostoni et al., 1965; Binks et al., 2007). Sensors detecting strain, pressure, or acceleration changes of/around the chest can infer the wearer's respiratory pattern, but the latter two – pressure or acceleration – can be easily exposed to noises from other body movements (Chen et al., 2020).

Strain sensors tracking chest circumference changes are mostly electrical sensors measuring resistance or capacitance. They can be susceptible to changes in humidity and temperature, and electrical insulation for the sensor reliability can introduce tactile discomfort, limited elasticity, and low breathability as part of clothing. Stretchable fiber optics can be an alternative, as it is thin, sensitive to mechanical inputs, and stable against changes in humidity, temperature, electromagnetic field, and chemical condition (Lee, 2003), while flexible and extensible, unlike conventional fiber optics. Methods such as weaving, knitting, embroidering, or gluing can embed the fiber optic onto textiles, but none of them provided both protection and control of the movements of the fiber, which is essential for the respiration sensor (Gong et al., 2019). Therefore, the purpose of this study is to create an enclosure for the stretchable fiber optic respiration sensor using machine embroidery, for durable and reliable respiration monitoring.

***Design*** A channel with four rectangular rooms was fabricated in zigzag stitches on an elastic band as shown in Figure 1a, using a computerized embroidery machine (PE700, Brother), a nylon thread, and a water-soluble stabilizer. The zigzag stitch corresponded to the strain of the elastic band, and there was no needle penetration in the middle of the shape to allow free movements of the fiber optic within the embroidery. Four rectangular rooms accommodated the excessive length of the fiber optic when the band is released. The water-soluble stabilizer under the elastic band helped the machine embroidery, while the multilayered stabilizers on the band loosened the embroidery by being dissolved in the water (Figure 1b). When the elastic band is stretched (i.e., the wearer inhales), the fiber optic becomes straight and transmits stronger light to the other side, while the curved fiber optic in the released band (exhalation phase) reduces the light intensity (Figure 3c). All the embroidery factors – number of the water-soluble stabilizer layers on top of the band, stitch spacing (density of the embroidery), number/size/shape of the rooms in the embroidery, and thickness of the embroidery thread – affect the sensing capability of the fiber optic respiration sensor.

**Figure 1.** (a) Structure and design of the insole, (b) Sensor arranged on the insole, (c) Test setting.

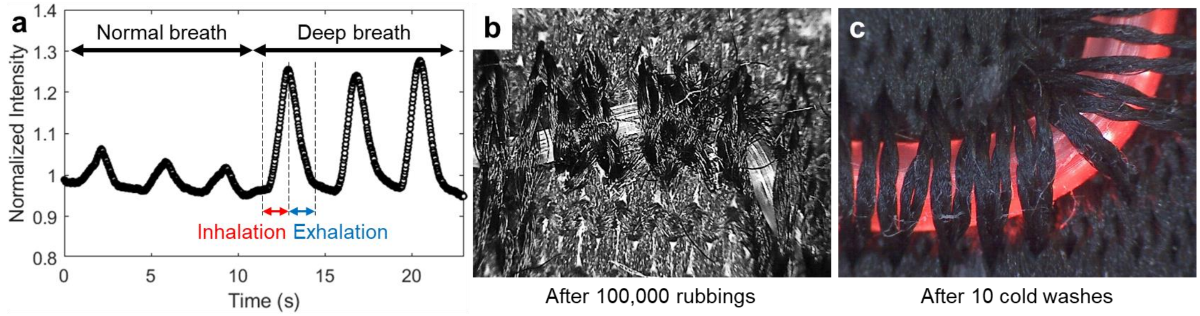



***Evaluation*** Sensitivity by the number of the water-soluble stabilizer layer and stitch spacing was investigated along with an abrasion test (ASTM 4966) and a laundry test (AATCC TM135-2018t). When there was no water-soluble stabilizer layer between the embroidery and the band, there was no light detected because the embroidery was too tight. The more layers and the larger stitch spacing, the more light was transmitted when the belt was in the released state. Based on the tests, four water-soluble stabilizer layers with stitch spacing of 0.6 mm demonstrated the highest and most reliable sensitivity to strains (Table 1). Figure 2a shows the results of preliminary tests that the fiber optic sensor was capable of detecting respiration patterns. Results of the abrasion test, in the evaluation of the impact of repetitive rubbing (90,000 cycles) among the elastic band, the stretchable fiber optic, and the embroidery, show no damage observed. The fiber optic sensor after 100,000 rubbings showed very minor damage (a few nylon fibers broken) as in Figure 2b. Lastly, 10 cold washes also didn't make any changes in the physical conditions, data quality, and sensitivity of the fiber optic sensor (Figure 2c).

**Table 1.** Sensitivity by the number of water-soluble stabilizer layers and stitch spacing

| Water-soluble stabilizer | No layer | | | | 4 layers | | | | 8 layers | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stitch spacing [mm] | 0.4 | 0.5 | 0.6 | 0.7 | 0.4 | 0.5 | 0.6 | 0.7 | 0.4 | 0.5 | 0.6 | 0.7 |
| Normalized light intensity: Released [%] | No light | | | 0 | 0 | 0 | 1.5 | 7.5 | 6.25 | 6.25 | 30 | 37.5 |
| Normalized light intensity: Stretched [%] | | | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

**Figure 2.** (a) Preliminary test result, (b) Abrasion test result, (c) Laundry test result.




***Discussion* and Conclusion** The machine embroidery enclosure in this study provided not only satisfactory protection but also a capability to control the sensitivity of the stretchable fiber optic respiration sensor. Further human participant tests will increase the reliability of the findings. This study only investigated the channel with four rectangles, but there are more opportunities to design unique enclosure shapes, potentially for other types of wearable sensors tracking strain changes. Follow-up studies need to investigate the potential and feasibility of using embroidery as flexible switches and the replacement of wires that can improve the tactile comfort and wearability of smart clothing.

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