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Effect of natural dyes on the sensitivity of knitted strain sensors

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Background. E-textiles, or electronic textiles, represent cutting-edge innovations at the intersection of textiles and electronics, offering versatile solutions for wearable technologies. The modification of textiles with conductive materials imparts conductivity to the textiles and they act as a piezo-resistance sensor under the influence of mechanical stimuli, such as strain and pressure. In recent years, the advancements in knitting machinery have allowed knitted strain sensors to move wearable technologies beyond handheld or pocket devices, to be fully integrated into the fabric of smart garments (Afsarimanesh et al., 2020; Souri et al., 2020). Knitted strain sensors can continuously capture a wide range of body motions, with applications in personalized healthcare, sports performance, soft robotics, and beyond (Alam et al., 2022; Zhang et al., 2018). Because e-textiles are expected to detect signals while maintaining contact with the wearer's body, their constituent materials should be nontoxic, compatible, and adaptable to diverse external deformations such as human body movements (Moon & Chae, 2024). However, given the rampant use of synthetic fibers in smart garments, along with their not eco-friendly coloration processes, there is a clear unmet need for a sustainable product design, the use of eco-friendly materials along with sustainable manufacturing processes (Dulal et al., 2022). Several studies explored the use of natural fibers and natural dyes for e-textiles, but the focus was on woven fabrications and color attributes rather than sensor performance (Moon & Chase, 2024; Xu et al., 2020).

Within the realm of wearable technologies for patient rehabilitation, soft gloves with incorporated strain sensors for wrist flexion monitoring have been proposed as an aid to the physiotherapists assisting stroke patients with their hand rehabilitation exercises (Li et al., 2019). The sensing mechanism of knitted sensors embedded into gloves depends on the knitting structure, fabrication approach, stretchability, and the sensing yarns used (Atalay & Kennon, 2014; Alam et al., 2022). Most of the reported strain sensor testing methods only involve unidirectional fabric tensile tests, but in actual applications, when sensors are on a knitted glove, the fabric is subject to complex multidirectional stretching (Reddy et al., 2019; Foroughi et al., 2016). Therefore, the purpose of this study was to investigate how natural dyes affect the sensing performance of a knitted strain sensor seamlessly integrated into a fingerless glove, aimed at detecting wrist flexing motions through the change in electrical resistance when the fabric is stretched on a hand.

Materials and methods. A weft knitting flatbed Silver Reed SK 840 standard gauge knitting machine was used to knit gloves using six different yarns (sizes between 41- 4,000 ypp) of various fibers: (1) 50%wool 50%acrylic, (2) 100% bamboo, (3) 62%rayon 38% linen, (4)100% baby alpaca, (5) 40%cotton 35%bamboo 25% linen, and (6)100% cotton. All yarns were greige/natural color. The sensor strip was knitted by adding a commercial silver-coated nylon yarn (X-Static yarn 40 dtex 12f, resistance of 12.5 Ω/cm) in the rows aligning with the middle finger, to capture the maximum strain. The stitch structure used was plain knitting, with incorporated 3D shaping for a tight fit of the glove around the wrist, and attachment to the middle finger (Fig.1). Three sets of six gloves (one of each fiber) were knitted and assembled, one set was kept as "greige" (control set), and the other two sets were dyed using ingredients from www.juliesinden.com.

Fig. 1. Knitted glove design and strain sensor testing positions.

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Two natural powder dyes were tested: (1) osage sawdust extract (yellow color), and (2) logwood chips extract (purple color). The gloves were first treated with mordant to ensure colorfastness. Gallnut bath was used for gloves made of plant fiber yarns (#2,3,5 and #6) for 120 minutes (ph=4.78). All gloves were then treated with alum bath, for 120 minutes (ph= 3.18, 210°F). The gloves made of animal fiber yarns (#1 and #4), were only treated with alum bath for 120 minutes (ph=3.82, 210°F). The extracts were prepared according to vendor instructions. A set of six gloves was dyed with osage extract for 120 minutes (ph= 6.47), and another set was dyed with logwood extract for 120 minutes (ph=7.08). All gloves were put through a regular laundering process of rinsing in a Whirlpool machine for 20 minutes at low temperature, followed by a drying cycle for 40 minutes at low temperature. The control set was subjected to washing and drying.

The 18 gloves were tested on the right hand of a healthy volunteering participant. A Kikuhime device (TT Meditrade, 2023) was used to ensure glove pressure on the wrist was constant between the gloves (3mmHg). A 34460A digital multimeter (Keysight, 2023) was connected to the ends of the sensor on each glove, and Keysight BenchVue software was used to record the resistance data. Measurements for unloaded sensor were made with gloves flat on a table, and for the loaded sensor the participant's hand was in the last two positions shown in Fig. 1. The flexing of the wrist was repeated 10 times, with 5 seconds in between each flexing (Fig. 2).

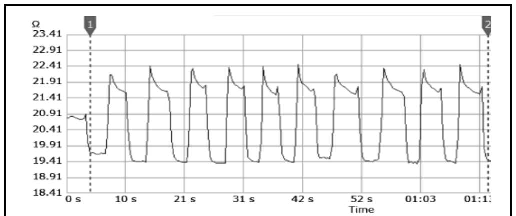

Fig. 2. Sensor resistance by time for bamboo glove, logwood dye (10 wrist flexes).

The sensitivity of a strain sensor is quantified by the gauge factor (GF), which is defined as GF=(ΔR/R0)/ε, where ΔR/R0 is the change of resistance, R_0 is the resistance of the sensor under zero strain, and ε is the applied strain (Liu et al., 2018). SPSS software was used to evaluate the effect of dye and fiber factors on GF as dependent variable.

Results and significance. The course strain of all samples during wrist flexing ranged between 4-12%, (M=8.2, SD= 2.6) resulting in a fairly low mean GF for all samples, only 1.9 (SD=1.15). However, Fig. 3 shows the increased effect of both dyes on GF means for all samples, relative to the control samples, except for those made of yarn #4 (baby alpaca). This is due to the fact that the wool fibers relaxed during dyeing, resulting in an increased strain for the dyed samples, unlike the other samples, which decreased their strain with dyeing. The osage extract dye had a lower effect on GF than the logwood dye except for the glove made of 100% bamboo yarn, when it recorded the highest GF of all samples (4.82).

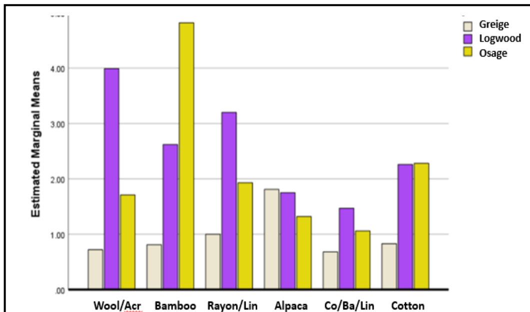

Fig. 3. Estimated marginal means of GF.

These results show that natural dyes improve the knit sensor performance by affecting its strain, except for the sensors made using 100% baby alpaca fibers. The fiber composition clearly influences the sensitivity after dyeing, and osage dye is less effective than the logwood dye, except for the sensors made with 100% bamboo yarn. Given the different pre-treatments applied to the yarns used in this study, that also affect the strain of the resulting fabric, more studies are needed to elucidate the effect of other variables on GF. This work advances the interdisciplinary scholarship of the authors, that are focused on improving the sustainability of functional apparel with applications in healthcare and sportwear. Further investigations will be pursued evaluating natural dyed sensor performance over several cycles of laundering.

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