Liquid crystal thermochromic technology to prevent diabetic foot ulcers

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Key words
- Diabetes sock
- Diabetic foot ulcer
- Liquid crystal thermochromic technology
- Self-monitoring

Article points
1. There has been increased interest in the use of self-monitoring devices to improve prevention of DFU
2. The liquid crystal transitions through a gradient of colours to indicate the temperature change present on the sole of the foot, which can be extrapolated to represent a level of risk for ulcer formation
3. Embedded thermochromic colors in socks can help notify patient of excess heat and pressure in an area, and may be beneficial to reduce ulcer occurrences.

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There is increased interest in utilising technology to reduce the development of a diabetic foot ulcers. Diabetic foot ulcers have significant morbidity on an affected individual. This article presents novel data demonstrating the utility of applying thermochromic crystal paint and embedding it into a commonly available sock to indicate temperatures changes on the plantar surface of at-risk feet. The use of thermochromic paint is a relatively inexpensive, convenient and accessible alternative to currently available prevention methods in diabetic foot care. Through several experiments, the applied paint was noted to be durable, reproducible upon multiple pressure applications, while still indicating localised increased temperatures on any part of the sock. This has the benefit to warn an individual wearer that their feet may be at risk of developing a foot ulcer. The technology has some limitations that need to be addressed prior to broad commercialisation, but the technology is useful for this application.

The estimated global cost of treating diabetes mellitus (DM) in 2015 was $1.3 trillion, with diabetic foot complications estimated to constitute up to one-third of those costs (Bommer et al, 2018; Geiss et al, 2019). People with diabetes have a lifetime risk of developing a foot ulcer of 15%, and the risk of recurrence is approximately 40% at one-year (Armstrong et al, 2017). An estimated 14–24% of diabetic foot ulcers (DFU) lead to lower-extremity amputations, which result in permanent disability for these patients (Pemayun et al, 2015). A strong emphasis has been placed on the prevention of DFU given the significant psychological, physical, and financial burden that they cause. Despite this emphasis on prevention, recent evidence suggests that nontraumatic lower-extremity amputations are increasing after nearly two decades of decline (Geiss et al, 2019).

There has been interest in the use of self-monitoring devices to improve prevention of DFU. Several wearable and smart home objects are being designed to detect early signs of ulcer formation. It is well documented that one of the first measurable changes in an area at risk for ulcer development is a localised increase in temperature. Therefore, many new self-monitoring devices use temperature detection technologies to locate the high-risk areas. For example, an early cohort study of the 'smart bathmat', a remote foot-temperature tracking system, showed promise as a useful self-monitoring device for ulcer prevention (Frykberg et al, 2017; Podimetrics, 2021). Two single-blinded, randomised control trials in which neuropathic patients used 'personal thermometers' were also seen as useful prevention tools (Aan de Stegge et al, 2018).

Novice et al (2019) demonstrated patients with DM had a willingness to obtain wearable technology for prevention of DFU, and patients without DFUs were more motivated to do so (Novice et al, 2019). Our proposed ulcer preventing technology is a diabetic sock that provides a relatively inexpensive, convenient and accessible alternative to current methods, which can be costly and difficult to use. This diabetic sock uses liquid crystal technology to indicate a relative temperature change in the feet of patients with diabetic peripheral neuropathy through a colour changing, synthetic material. A study by LeSar et al (2017) concluded that the colour change detected by thermochromic liquid crystal (TLC) fabrics is comparable to that of thermal imaging with few minor differences.

Materials and methods

The thermochromic sock prototype is fabricated by altering the plantar surface of commercially available diabetic socks. The authors use TeeHee Socks (Las Vegas, NV, USA), which are made of a bamboo blend and engineered to address diabetic neuropathy symptoms. They are composed of 53% viscose from bamboo, 32% elastic, 12% nylon and 3% elastane. These socks are advertised to reduce foot irritation and to be comfortable for patients experiencing leg fatigue, swelling and dry skin. A layer of black paint followed by a layer of liquid crystal are evenly applied to the sole of the sock via airbrush at a pressure of 20 psi. Both the black backing paint and the chiral nematic sprayable liquid crystal are purchased from ThermometerSite. The black paint is a sprayable aqueous coating that is applied to the sock prior to the liquid crystals. It provides a non-reflective surface with good adhesion (LCRHallcrest, 1991; Button, 2015). This layer is then allowed to sit under ambient conditions for approximately 10 minutes. This initial layer enhances adhesion of the liquid crystal to the sock. A second layer of sprayable TLC in the form of a slurry is airbrushed on top of the black paint and dried in a likewise manner (LCR Hallcrest, 2019).

The liquid crystal transitions through a gradient of colours to indicate the temperature change present on the sole of the foot, which can be extrapolated to represent a level of risk for ulcer formation. It is sensitive to temperature changes within the range of 25–30 ºC which results in a corresponding colour change (LCR Hallcrest, 1991; 2019). The distinguishable colour transitions are red at 25°C, green at 27°C, and blue at 30°C. In this orientation, blue is correlated with the highest risk. This gives the prototype a level of sensitivity that is comparable to other ulcer prevention devices, which look for a temperature asymmetry of ~2°C (Houghton et al, 2013). The final product would ideally have three sock options: low temperature (20–25°C), medium temperature (25–30°C) and high temperature (30-35°C). The colour gradients would be the same in all three versions with only the temperature ranges varying.

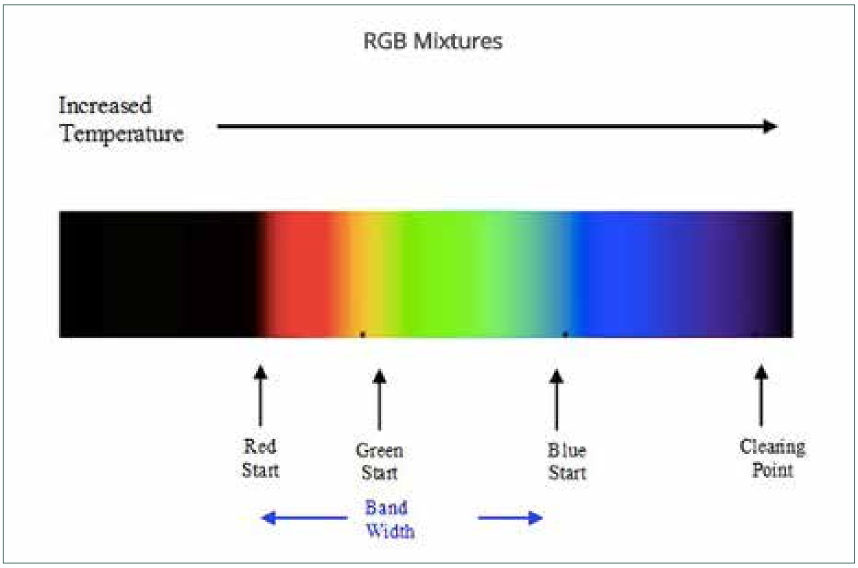

Figure 1: Colour transitions of thermochromic liquid crystal with increasing temperature (LCR Hallcrest, 2021).

Thus, it is recommended users consult with a podiatrist to identify their appropriate range based on the individual patient. In patients with diabetic peripheral neuropathy, mean pedal temperatures of 27.67°C, 28.58°C, 29.21°C and 29.88°C in the toes, forefoot, midfoot and rearfoot, respectively. Therefore, the 25–30°C strongly supports the range for which we have aimed (Schmidt et al, 2019; Yavuz, 2019).

Results

Liquid crystals exist between the solid and the liquid phases, with mechanical properties of a liquid and the optical properties of a solid (Button, 2015). The careful arrangement of molecules comprising liquid crystal cause colour to appear when it reflects incident white light. They produce the most vibrant colour when used with a non-reflective, totally absorbent background, such as black (LCR Hallcrest, 1991). Liquid crystal can be applied in numerous industries and is increasing being used in healthcare for its sensing capabilities (Button, 2015). The technology is also being introduced to the fashion world, creating liquid crystal-coated fibres that respond to external stimuli, such as temperature (Aan de Stegge et al, 2018; Guan et al, 2019). By using TLC technology at a basic level, our product improves lives by traversing both the healthcare and textile industries.

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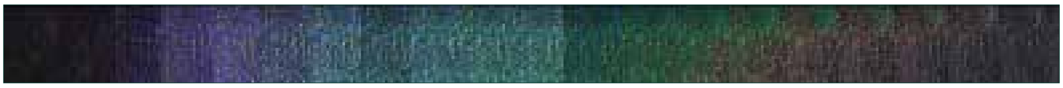

Figure 2: Colour transitions of a Hot Spot thermochromic sock over the span of approximately 20 minutes.

Figure 3: A Hot Spot sock a) before temperature change, b) with localised temperature change from the pressure of a hand, and c) completely colored due to heat from a hair dryer.

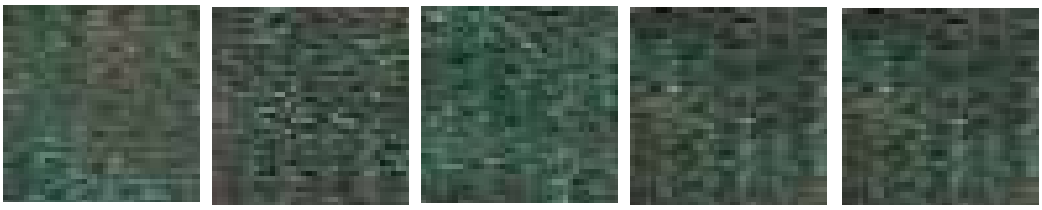

Figure 4: Colour appearance on a Hot Spot thermochromic sock with different application periods between black backing and liquid crystal.

The Hot Spot Sock LLC prototype (Ann Arbor, MI, USA) is a bamboo blend diabetic sock that was airbrushed with a black acrylic base paint and an aqueous solution of TLC. This prototype was tested using a heat lamp attached to a thermostat controller capable of emitting predetermined temperatures. The TLC goes through a gradient of colours, beginning at black below the temperature range, transitioning from red to green to blue, and returning to black above the temperature range as seen in *Figure 1* (LCR Hallcrest, 2021).

Figure 2 uses images of the physical sock to show the comparable colour spectrum available. The same area was imaged numerous times across a span of 20 minutes to show how the prototype transitions from blue to red as the sock cooled down. The relationship between applied heat to the sock and the time for the sock to fade to black (baseline) were inversely related. When the heat source was applied to the sock for a longer duration, the subsequent colour change lasted longer, and took more time for the sock to fade back to black.

The thermochromic socks also change colour when pressure is applied. Simply pressing on the sock with a finger creates a local change in temperature, resulting in a coloured spot on the otherwise black sock. This spot performs the same way as when the sock is exposed to a heat source, fading through the gradient back to black. *Figure 3* shows three versions of the prototype. The all black sock is the baseline indicating under ambient temperature and pressure the base of the sock remains black (*Figure 3a*). The middle sock (*Figure 3b*) has a patch of colour change due to pressure imposed by pressing on the material with the palm of a hand. Lastly, *Figure 3c* depicts how the liquid crystal transitions from blue to green and finally to red. A hair dryer was used to induce colour change across the whole sock. When the heat from the dryer was removed, the centre of the sock remained at a higher temperature, as indicated by the dark blue coloring, whereas the toe and heel regions cooled faster and faded to red quickly.

The time between applications of the black base and the liquid crystal was varied to determine which process would optimise the intensity of colour change. *Figure 4* shows five different sock samples with varied time between application of the black backing and the liquid crystal. As seen in the image, all five swatches are the same colour following the same exposure from a heat lamp. It can be concluded that the time between applications of each coat did not affect the vibrancy of the liquid crystal. For all future experiments, the authors decided to apply the liquid crystal 5 minutes after the black backing to reduce wait time.

Conclusion

Previous studies have shown that one of the first indications of ulcer development is a localised increase in temperature in the area at risk for ulcer development (Armstrong et al, 2017). Presently, it has been shown that a difference in temperature greater than 2°C is statistically significant and places the patient in a high-risk category for ulcer development. This relationship has been validated in a number of trials through a variety of temperature-sensing tools (Armstrong et al, 2007; Houghton et al, 2013). The risk of ulceration can be reduced by monitoring the temperature of patients' feet and alerting them to areas at risk for ulcer development (Yavuz et al, 2019).

Furthermore, it has been shown that when patients are provided with tools to measure their foot temperature at home, self-monitoring for potential 'hot spot' areas, they have a statistically significant decrease in incidence of foot ulcers as compared to the current standard of care described above (Rothenberg et al, 2020).

While TLC technology has proven useful, it is not without limitations. Based on feedback from participants in ongoing trials, it was determined that improvements need to be made to both the longevity and durability of the socks. Possible ways to improve the longevity of the colour change include adding an overcoat as a third layer. Low durability may be a result of liquid crystal degradation over time or the liquid crystal wearing off with subsequent wears. With no wear, the thermochromic technology remains active for over a year. Possible enhancements for the sock include a more vivid and longer lasting colour change so that consumers notice an obvious deviation from the black background. A preliminary idea was to reverse the colour spectrum so that red would represent the highest temperature change and blue would represent the coolest temperatures. Although this range is more intuitive, liquid crystals with this colour spectrum are not commercially available. The black backing paint used underneath the liquid crystal is washable and runs off of the sock when wet. Users may be concerned about not being able to wash their socks, but they do not have to be worn long to be effective. Our technology shows great potential, but several advancements are required before they are sold commercially. ■

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