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The future of our thermal comfort: a commentary on developments in electronic textiles to regulate body temperature

Ashleigh Naysmith[a] *

[a]Technical Textile Research Centre, Department of Fashion and Textiles, University of Huddersfield, Queensgate, HD1 3DH

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ABSTRACT

This commentary examines the potential for electronic textiles (e-textiles) to form part of the solution to improved thermal comfort for individuals whilst reducing the high energy consumption of heating and cooling systems. The article begins by introducing factors that influence thermal comfort for individuals and the weaknesses of the current thermal management systems. The commentary presents e-textiles as a promising solution to these challenges by demonstrating an option that can provide the individual with enhanced thermal comfort without reliance on centralised heating systems, and crucially, does so in a manner that minimises the need for individuals to change their behaviour. The article concludes with a view of groundbreaking research that is pushing the boundaries of current e-textile technological capabilities.

Introduction

September 2022. The cost of living and, acutely, the cost of fuel and energy has increased inordinately within the UK (The Bank of England, 2022). Campaigns such as *heat the human not the home* are gaining traction as people look for more affordable methods to maintain a comfortable body temperature (Monro, 2023). There is a pressing need for innovation in strategies to maintain thermal comfort (Friends of the Earth & the Marmot Review Team, 2022). Thermoregulating electronic textiles (e-textiles) are an emerging technology with the potential to fill this gap. This commentary gives a brief overview of human thermoregulation and a discussion on some of the core challenges within thermal comfort management, particularly within the UK and Europe, such as the environmental impact of building heating systems and the effects of fuel poverty. The commentary highlights emerging e-textile technologies as a potential solution to these challenges, focusing on two important obstacles to their market readiness; comfort and integration into a circular economy, which are addressed by contemporary research.

Thermal comfort and the human

Since the Mid-Pleistocene, humans have used clothing to aid thermal homeostasis (the biological mechanisms that keep the body at an optimal temperature) and manage thermal comfort (Gilligan, 2010). The vacillating temperatures through diurnal rhythms and shifting seasons have led to a reliance on additional behavioural, or technological, solutions since the first human sought shade in a cave and struck wood to create fire.

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Maintaining an optimal body temperature is critical for human health, well-being, and productivity. At its most extreme, inadequate thermoregulation is fatal. If the human core body temperature increases or decreases by 1°C, physiological responses such as shivering or sweating initiate (Figure 1.) Further increase or decrease of the core body temperature leads to increasingly severe health consequences such as brain damage, organ failure, and death (Song, 2011). At lower levels of thermal discomfort negative effects on mental and physical performance, and well-being can be observed. Optimum productivity is achieved by individuals working in a comfortable environment (Castaldo et al., 2018; Morris et al., 2020; Song, 2011). Accordingly, thermal discomfort negatively impacts individuals, but also businesses that suffer the economic impacts of decreased worker productivity. A comfortable thermal environment is a necessity to mitigate these effects.

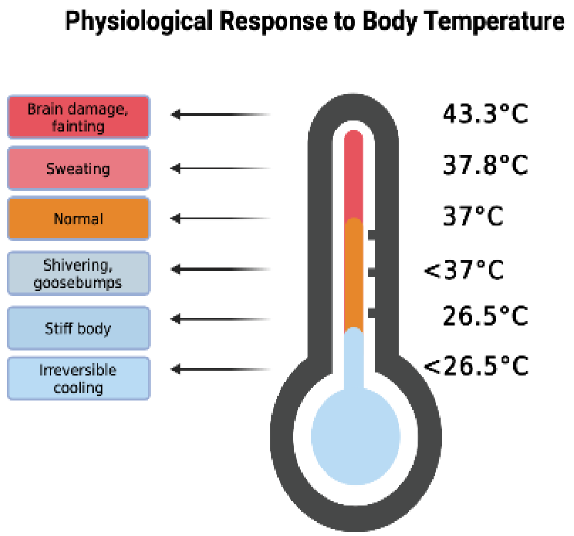

Figure 1: Physiological responses to temperature.

It is well established that the human connection with the thermal environment interweaves with multifarious factors including biological influences (such as metabolic rates), cultural effects, previous thermal experience, and socioeconomic impacts (Castaldo et al., 2018; Faruk et al., 2021; Nicol et al., 2012; Tabor et al., 2020). This implies that creating a thermal environment that is optimal for all individuals using a shared space is infeasible. Globally, many thermal comfort-building standards have been underpinned by Fanger's predicted mean vote (PMV) model since the 1960s (Hoof, 2008). The PMV model is based on healthy adults in North America and Western Europe. As stated above, even amongst healthy adults, individual differences in the perceptions of, and preferences in, thermal environments vary considerably (André et al., 2020; Fountain et al., 1996; Hoof et al., 2010). Those who fall outside this 'healthy adult' demographic, such as the elderly, are likely to be at a biological disadvantage when it comes to maintaining an optimal body temperature, putting them at higher risk of temperature-related illness (Anderson et al., 1996; Fu et al., 2016; Giamalaki & Kolokotsa, 2019). Correspondingly, current thermal comfort standards in building design are not appropriate to meet the thermal needs of significant proportions of the populations that rely upon them.

The Global North has developed an unhealthy dependency on building heating, ventilation, and cooling (HVAC) systems for the provision of thermal comfort. HVAC systems deplete resources from the National Grid at inexorable rates, contributing 16% to global energy consumption and thus the climate crisis (Cai et al., 2017; Ürge-Vorsatz et al., 2015). Recent trends in increased homeworking may increase this HVAC energy consumption, however, the environmental benefits such as reduced commuting may still lead to a net benefit for the environment (Wang et al., 2022). The detailed evaluation of this is outside the scope of this commentary.

Despite this behemothic burden on our environment, HVAC systems do not provide sufficient thermal comfort for large sections of society; either due to systematic implementation of thermal standards that are aimed at 'the average person' as established above, or for individuals that are unable to afford the cost of fuel, depressing them into fuel poverty. Fuel and energy poverty are enduring challenges worldwide that are consistently correlated to temperature-related morbidity and mortality (Morris et al., 2020; Nicol et al., 2012; Tham et al., 2020). Under the recent rising energy costs combined with increasingly erratic weather patterns, the pervasiveness of fuel poverty is increasing (Davillas et al., 2022). In 2018, 7.3% of the EU population was subject to fuel poverty (Friends of the Earth & the Marmot Review Team, 2011). Research in England has shown that colder homes bring a 20% increase in the risk of 'excess winter deaths' (Friends of the Earth & the Marmot Review Team, 2011) and emphasised by Public Health England (2010): 'We could prevent many of the yearly excess winter deaths – 35,000 in 2008/09 – through warmer housing' (p. 5).

It is therefore established that thermal comfort is vital for human health, well-being, and economic productivity, but that contemporary systems for providing thermal comfort to humanity, clothing, and HVAC systems, are inadequate. Conventional clothing, i.e. commonly available garments composed of simple fibres and fabrics without enhancement to the textile's thermal properties (Figure 2), is insufficient to provide thermal comfort during moderate changes in temperature or circumstance. HVAC is both systematically biased towards an average person thus deficient for many individuals, and environmentally damaging. A solution is required that provides the individual with control over their thermal environment, but without the high energy consumption that leads to climate impacts and energy accessibility issues such as fuel poverty.

Emerging e-textile technologies

The e-textile market is forecast to increase by a compound annual growth rate (CAGR) of 18% by 2028 (Market Growth Reports, 2022). The state of the art within the field has demonstrated flexible low-cost e-textile sensors and actuators have applications within industries as diverse as structural monitoring in construction; health and medical monitoring; soft robotics; clothing for extreme environments, strain sensors, detection of biochemicals, and personal thermal management (PTM) (Mohan et al., 2020; Coppedè et al., 2014; Gomes et al., 2018; Han et al., 2018; Polanský et al., 2017; Promphet et al., 2020; Sekar et al., 2019; Sempionatto et al., 2019; Seyedin et al., 2018).

E-textiles can improve individual thermal comfort by significantly enhancing the thermal performance of conventional clothing (Cai et al., 2017; Hazarika et al., 2021; Lan et al., 2021; Pollard et al., 2019; Tabor et al., 2020; Tat et al., 2022). The worldwide cultural permeation of using clothing to aid thermoregulation could enable e-textiles to conform to this social norm and displace HVAC usage without requiring a substantial behaviour change.

Figure 2: Conventional clothing (Stocker, 2023)

E-textiles that enhance thermoregulation through temperature sensing and heating are commercially available but remain in niche markets, such as snow sports and motorcycling as demonstrated in Figure 3 and Figure 4 (Ralph Lauren, 2019; Motorrad, 2023; Odlo, n.d.). These technologies are expensive and often bulky with evident electronic components or external hardware which requires removal before washing and changes the aesthetic of the garment. This makes the e-textiles functional but conspicuous, and thus misaligned with traditional consumer clothing preferences of aesthetic appeal and comfort, and thus go against the grain when changing individual behaviour (Mintel, 2020; The Behavioural Insights Team, 2014). However, recent research is advancing PTM e-textiles closer to that exemplar e-textile that invisibly integrates thermal control into garments.

Figure 3: Example of thermoregulating ski jacket (Ralph Lauren, 2019)

Figure 4: Example of thermoregulating base layer (Odlo)

In the recent work of Wang et al. (2022), 2D titanium carbide nanomaterial known as MXene, was spray coated onto an aramid nonwoven fabric to create a textile-based heater that reached a temperature of 253°C under the application of 5V external voltage. Similarly, Zhang et al. (2022) have reported a Joule heater that reaches 121°C at 1.5V of input voltage based on a copper sulphide film with embedded copper sulphide nanospheres coated onto polyethylene terephthalate (PET) fabric using chemical deposition. These outstanding examples have harnessed the power of nanotechnology to induce excellent electrothermal performance and demonstrate technological advancements whereby heating functionality can be achieved with exceptionally low voltage input. This implies that minimal componentry will be required to power the e-textile, thus taking the technology a step closer to 'invisible integration' with greater comfort.

To date, advances in heating and temperature sensing e-textile developments far exceed that of advancements in cooling technologies. A publication from March 2022 has reported the development of a thermoelectric woven textile using bismuth antimony telluride/bismuth tellurium selenide alloy, polyimide, gallium-indium liquid metal and polydimethylsiloxane (PDMS) to create a textile that delivers solid-state cooling of 3.1°C (Y. Zheng et al., 2022). Whilst this technology is nascent and requires further development to integrate it into a truly intelligent garment, it takes the field a step closer to that holy grail of wearable thermoregulating e-textiles: a garment that senses the skin temperature, and then reacts by heating or cooling the individual to enable that perfect thermal balance.

Comfort

Comfort in clothing pivots upon four elements: Thermophysiological (heat/moisture balance); ergonomic (freedom of movement, stretch); skin sensorial (mechanical sensations such as soft vs stiff, smooth vs rough); psychological (style, trends, cultural or personal ideologies) (Meechals, as cited in Dolez & Vermeersch, 2018). Wearable e-textiles must provide comfort, in the broadest sense, to be viable alternatives to conventional clothing (Luo et al., 2020; Mokhtari et al., 2020; Yu et al., 2020; Zhang et al., 2017). Within current e-textile literature, thermophysiological comfort has been frequently analysed via assessment of water vapour transmission rate and air permeability (Luo et al., 2020; X. Zheng et al., 2022). Several studies have considered ergonomic factors such as stretch and stiffness (Ahmed et al., 2020; Dong et al., 2020) (Wang et al., 2021; Y. Zheng et al., 2022). However, few studies have yet examined skin sensorial and psychological comfort within the field of e-textiles. This leaves an unmistakable direction for further research, particularly in collaboration with industry and commerce to address psychological comfort.

A fundamental challenge in achieving comfort in e-textiles arises from joining technologies. Most current e-textiles require a connection between the soft, pliable, stretchable textile fabric, and a rigid non-textile component (Stanley et al., 2021). This connection typically relies upon joining technologies such as snap connectors, conductive pastes, or soldering. The result is a source of both discomfort for the user and weakness within the e-textile structure. The current technologies are satisfactory for the current commercial applications (e.g. snow sports and motorcycling) which highly value functional performance and bulky layers for protection. However, for e-textiles to reach their full potential, further development is needed to

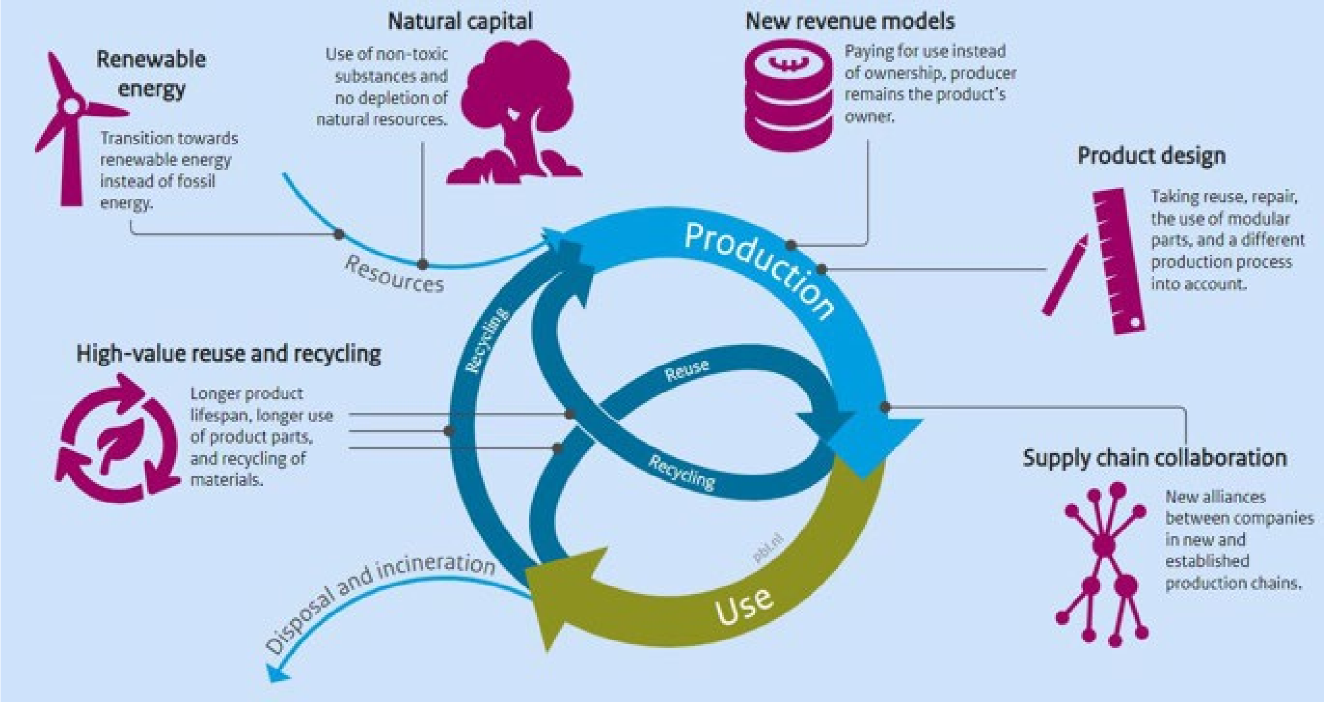

Figure 5: Elements of a circular economy (PBL Netherlands Environmental Assessment Agency, 2019)

invisibly integrate the joining technologies. Recent research has sought novel materials such as nanomaterial paste or (encapsulated) liquid metal, and strategies, such as 3D printing and ultrasonic nanosoldering for creating connections points (Du et al., 2017; Seoane et al., 2019; Simegnaw et al., 2021; Suarez et al., 2017).

Durability and integration into a circular economy

The textile industry is a source of substantial environmental impact with an array of energy and water consumption, greenhouse gas emissions, waste effluents, and significant quantities of textiles culminating in landfill (Gong et al., 2022; Luo et al., 2022). E-textiles pose a particular challenge within sustainable practices since, within current technologies and recycling logistics, e-textiles are complex if not impossible to recycle and are not biodegradable.

Durability is the *pièce de résistance* of the textile circular economy. The more durable a garment is (both physically and emotionally), the longer it survives in the use phase (Figure 5). Numerous studies have examined aspects of e-textile durability, such as washability, abrasion resistance and performance degradation over time (Afroj et al., 2020; Atakan et al., 2019; Gong et al., 2022; Uzun et al., 2019). Recent research has demonstrated a culmination of previous works through the development of a nanocomposite-based heating e-textile that has successfully undergone durability testing including UV light exposure, washing, temperature extremes, and bend testing (Hazarika et al., 2022). This extensive analysis lays a foundation for future developments of truly durable e-textiles. Notwithstanding, it can be anticipated that even the most durable garment will eventually degrade beyond use. In this scenario, the seminal paper by Gong et al. (2022) leads the way in the development of decidedly environmentally friendly e-textiles by using biobased polylactic acid (PLA) and gallium indium alloy to create an e-textile that is durable (abrasion and wash tested), biocompatible, and can be separated and recycled in a closed loop.

Conclusion

Thermoregulation is vital for survival; thermal comfort is vital for health and productivity. Current solutions for attaining thermal comfort are rapidly depleting both natural resources, and individual microeconomic resources. This combination creates an apt juncture to instigate change, as society seeks ways to attain thermal comfort with minimal energy consumption. This transition, although difficult, could be eased with the development and use of thermoregulating e-textiles. E-textile research has made key advancements in the past five years towards the 'invisible integration' of electrothermal performance in textiles. Further research on cooling technologies, alongside continuing work to improve both comfort and durability is ongoing.

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