E-Textiles Network

# E-Textiles for Healthy Ageing

**a roadmap to new research challenges**

**Produced by:**

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# Executive Summary

The UK government's industrial strategy objective for healthy ageing is "to ensure people can enjoy at least 5 extra healthy, independent years of life by 2035, while narrowing the gap between the experiences of the richest and poorest". Achieving this will improve each person's feeling of wellbeing, reduce healthcare costs and increase the ability of individuals to work and enjoy life. This report reflects on the definition of healthy ageing, the role of technology and personal health devices (PHDs) and, in particular, focuses on how electronic textiles (e-textiles or smart fabrics) can assist in achieving healthy ageing.

Healthy ageing is much more than just physical wellbeing, important though that is. In addition to common physical symptoms and conditions that are associated with ageing, technology can also assist in improving cognitive ability, social interaction and mood, prolonging independence and promoting healthy behaviour. There are many examples of PHDs being used to monitor physical wellbeing with the associated benefits of encouraging physical activity and maintaining physical function. The motivation for incorporating PHDs and electronic functionality into textiles in order to assist health ageing is clear. Textiles provide a comfortable ubiquitous platform that individuals are entirely familiar and comfortable with. The ability to hide the technology in garments can improve performance, remove stigma and improve compliance with technology amongst the ageing population.

Many age related requirements can be monitored or met with e-textile technology. However, it is not straightforward to include electronic and sensing capability in textiles and existing e-textile technology does not deliver practical solutions with the required levels of functionality. This report contains a comprehensive evaluation of the capability of existing technologies and approaches to address a wide range of age related challenges. This review is used to highlight the weaknesses and the associated research challenges that remain in order to realise practical e-textile solutions that assist individuals to achieve healthier ageing.

Research is required to improve the sensitivity, repeatability, durability, reproducibility and level of integration of the textile-based technologies enabling their use in long-term monitoring and support systems. Research topics can be grouped into materials, discrete sensor/device integration in textiles, garment/textile engineering and textile sensor/actuator structures. In order to efficiently address these research challenges, the range of disciplines involved in e-textiles research should be broadened to increase the involvement of materials scientists, chemists and instrumentation engineers. The research challenges can only effectively be met by interdisciplinary teams sharing expertise and methods and involving end users/stakeholders at an early stage in the research.

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# Introduction

The E-Textiles Network is an EPSRC funded network of predominantly UK based academic and industrial researchers and end-users of electronic textile (e-textile) technology. The aim of the network is to accelerate the development and adoption of e-textiles technology by facilitating focused research activities and disseminating results. The four main objectives are:

- To enable the university, textile industry and end-user communities to define the research challenges required to deliver the potential of e-textiles. The results of this will be evidenced in the medium to long term by new products.
- To catalyse the creation of new multidisciplinary teams required to address these challenges. The formation of collaborations will seek to support young academics in particular in establishing their research careers. This will be evidenced by a growth in funding applications in this area and the development of research leaders in the longer term.
- To facilitate the interaction and mobility of researchers. This is particularly important given the wide range of expertise and facilities required to design and manufacture e-textiles.
- To ensure that the advances in the science and the developments of the technology are more widely disseminated through an annual conference, regular workshops, training courses and media (e.g. newsletters, twitter, LinkedIn).

E-textiles can include a range of functionality such as sensing, signal processing, lighting, wireless data transmission and actuation. It has the potential to revolutionise the textiles industry, offering a new class of products across a range of application including medical, performance sports, automotive and fashion.

This report describes the outputs of the first workshop in the series, which was aimed at defining the research challenges in the area of e-textiles for Healthy Ageing. The Steering Board of the E-Textiles Network discussed a number of options for new and challenging areas of research and decided on healthy ageing for the first workshop. This theme was chosen due to the growing need for innovation in healthcare in an ageing population, as indicated in the Governments Grand Challenge[1]. The scope of the workshop included an overview of what is healthy ageing and sessions aimed to get people thinking about the practical challenges of addressing the topic and what this means in terms of research challenges to be met.

# Approach / methodology

## Who should read this?

This report is aimed at informing funding agencies (e.g. Research Councils and Innovate UK) of the new, challenging areas of e-textiles that should be addressed so as to help inform their programmes. It is also aimed at researchers from a broad set of disciplines interested

[1] https://www.ukri.org/innovation/industrial-strategy-challenge-fund/healthy-ageing/

in involvement in research that enables this new generation of e-textiles for healthy ageing applications. This report should inform them of the specific challenges to be met and the interdisciplinary skills required to do so. It is anticipated that this report will be the catalyst for a series of collaborative project proposals.

## Overall approach

A workshop was designed to help facilitate the definition of the new research challenges in the area of e-textiles for healthy ageing. Participants from a wide variety of disciplines, including healthy ageing, wearable technologies, medical sensing, e-textiles and manufacturing, were invited with representation from both academia and industry. The aim was to use the input of this group to understand the various developments (scientific and technological) that will be required in order to realise the defined vision and to help generate a series of specific research challenges that if addressed would move the field forward substantially.

The workshop agenda (see Appendix 1) was split into two parts with the first part exploring what is healthy ageing and an insight into how conventional electronics and sensors (as known as personal health devices) can assist healthy ageing. This led to a facilitated discussion in mixed groups on how technology in general can address the challenges associated with healthy ageing and identified if there were any drivers for e-textile solutions to particular challenges. The second part of the day focused on the practicalities of e-textiles and began with three talks exemplifying e-textile solutions and the technologies involved. The second discussion session then explored the current suitability of e-textiles to support these healthy ageing factors, identifying in particular the research and manufacturing challenges that exist. Presentations from both parts of the workshop can be found on the e-textiles network website: https://e-textiles-network.com/e-textiles-for-healthy-ageing-workshop/. The outcome of the group discussion was presented by a group representative and recorded as a starting point for defining the research challenges presented in this report. The workshop discussions have been augmented by a comprehensive literature review capturing the state of the art in technologies to assist healthy ageing and relevant e-textile developments.

## The roadmap

A roadmapping methodology was used to frame the discussion and ensure that the exploration of the gaps between current capability and future needs was thorough. In building the roadmap the task and structure was broken down into the following:

- Definition of a vision
- Exploration of the drivers
- Outlining of the potential applications and areas of impact
- Exploration of the technology developments that are due to occur over the relevant period
- Exploration of the underpinning science and engineering that will be needed

The timeline for the roadmaps was 10 years from the present (until 2029) with timing generally being defined as when something becomes mainstream rather than the first instance of someone working on the topic.

## Scope & limitations

This roadmapping exercise has been designed to specifically focus on the application of e-textiles for healthy ageing. The roadmap itself is not intended to represent an exhaustive development plan, as is the case with some industry or company specific roadmaps. Its chief purpose is to frame a structured discussion. In this way it is hoped that the result will be a comprehensive coverage of the needs and challenges that leads to the identification of the current gaps in capability and the research themes which would help to fill them.

# What is Healthy Ageing?

Currently one in 12 people in the UK are over 75 years old and this is expected to rise to one in 7 by 2040. This will place additional strain on the UK's health services and there is a clear motivation to help people to stay active and productive for longer as they age. The UK government's mission is "to ensure people can enjoy at least 5 extra healthy, independent years of life by 2035, while narrowing the gap between the experiences of the richest and poorest".[2]

But what is meant by the term healthy ageing and what factors should be considered? A variety of definitions of health has been presented including "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (World Health Organisation). An alternative definition by Friedman et al (2019)[3] states healthy ageing (or successful ageing; optimal aging; ageing well etc.) depends on our goals and cultural expectation, for example:

- Minimising costs of healthcare
- Enabling people to work for as long as possible
- Enabling people to feel as good as possible

A further definition from Rowe and Khan (1997)[4] can be presented graphically as shown in Figure 1.

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[2] https://www.ukri.org/innovation/industrial-strategy-challenge-fund/healthy-ageing/

[3] Friedman , S.M.. et al. (2019). Healthy aging: American Geriatrics Society white paper executive summary. Journal of the American Geriatrics Society, 67, 17-20

[4] Rowe, J.W. & Kahn, R.L. (1997). Successful aging. The Gerontologist, 37, 433-440.

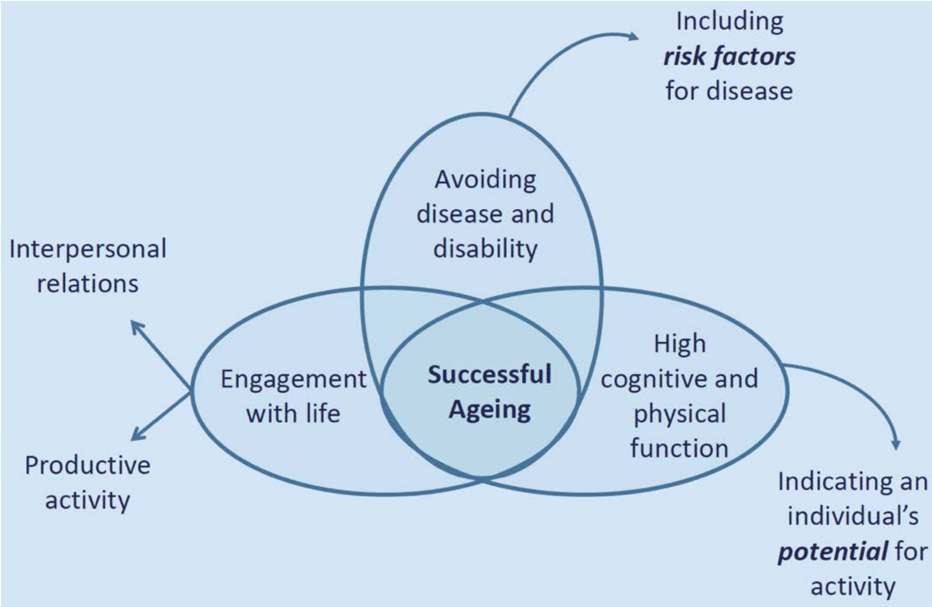


*Figure 1: Rowe and Khan definition of successful ageing*

Each of the three aspects of successful ageing as presented in Figure 1 are defined in more detail below.

## Avoiding Disease and Disability

A recent study by Lu et al[5] reviewed the literature covering measures of healthy ageing presented in epidemiological studies. Most common were self-reported chronic diseases, and other studies measured hypertension and cardiovascular risk factors, biomarkers of kidney and cardiovascular function, Body Mass Index (BMI), pain, vision, audition, and sleep. Age UK has published an almanac of disease profiles in later life presenting a reference on the frequency of major diseases, conditions and syndromes affecting older people in England[6]. This presented many common conditions that have been widely studied as shown in Table 1.

| | | | |
|---|---|---|---|
| **Cardiovascular diseases:** | Hypertension<br>Atrial Fibrillation<br>Coronary heart disease<br>Heart failure<br>Stroke | **Neuropsychiatric:** | Dementia<br>Depression<br>Epilepsy<br>Mental Health (Psychoses, schizophrenia, bipolar affective disorder) |
| **Respiratory:** | Asthma<br>Chronic obstructive pulmonary disease | **Edocrine:** | Diabetes<br>Hypothyroidism |

[5] Lu, W. et al. (2018). Domains and measurements of healthy aging in epidemiological studies: a review, The Gerontologist, https://doi.org/10.1093/geront/gny029
[6] https://www.ageuk.org.uk/Documents/EN-GB/For-professionals/Research/Age_UK_almanac_FINAL_9Oct15.pdf?dtrk=true

| | | | |
|---|---|---|---|
| **Chronic kidney disease** | Stages 3 to 5 | **Cancer in the previous 5 years** | Excluding non-melanoma skin cancer |
| **Additional common conditions:** | Anaemia<br>Osteoarthritis<br>Osteoporosis | **Additional syndromes:** | Falls<br>Fragility issues<br>Incontinence<br>Skin ulcers/pressure sores |

*Table 1: Diseases and common conditions and syndromes*

## High Cognitive and Physical Function

This includes measures of cognitive and physical ability as defined by Lara et al. (2013)[7] listed as follows:

- Episodic memory
- Cognitive processing speed
- Executive functions
- Grip strength
- Gait speed
- Standing balance test etc.

These can also be related to functional ability to perform activities associated with daily living such as bathing or using a telephone (Lawton and Broody, 1969[8])

## Engagement with Life

This can be broken down into two sub-categories. Interpersonal relations cover socio-emotional relations (e.g. kinship) and instrumental relations (e.g. co-operative and goal orientated). Measures for this can be used to prevent loneliness and assign provision of social support. Productive activity is a measure of an individual's contribution to society or their purpose in life as defined by Ryff and Keyes (1995)[9].

## Lay Perspectives

There are differences in the measured definitions of successful ageing compared with an individual's lay perspective. For example, Strawbridge et al (2002)[10] studied 867 adults aged 65-99 years of which 18.8% were rated as ageing successfully by Rowe & Khan criteria but 50.3% rated themselves as ageing successfully. Individuals perspective on ageing well is varied but successful ageing is more than physical health and psychosocial factors such as attitude were the most frequency mentioned component of successful ageing[11].

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[7] Lara, J. et al. (2013). Towards measurement of the Healthy Ageing Phenotype in lifestyle-based intervention studies. Maturitas, 76, 189-99.

[8] Lawton, M.P. & Broody, E.M. (1969). Assessment of older people: self-maintaining and instrumental activities of daily living. The Gerontologist, 9, 179-186

[9] Ryff, C.D. & Keyes, C.L.M. (1995) The structure of psychological well-being revisited. Journal of Personality and Social Psychology, 69, 719-727.

[10] Strawbridge et al. (2002). Successful aging and wellbeing: self-rated compared with Rowe and Khan. The Gerontologist, 42, 727-33.

[11] Cosco, T.D. et al. (2013). Lay perspectives of successful ageing: a systematic review and meta-ethnography. BMJ Open, 3, e002710.

## Interventions and technologies to support healthy ageing

It is clear that healthy ageing concerns more than just physical wellbeing and given the very broad range of factors that contribute to the overall concept of healthy ageing, there is a correspondingly broad range of objectives by which interventions and technologies can support healthy ageing. These include measures to:

- Avoid disease & disability
- Reduce risk factors
- Maintain cognitive ability
- Increase functional ability
- Promote independence
- Reduce isolation
- Promote acceptance of age-related change
- Increase health behaviours
- Promote positive mood and attitude

## Workshop Part 1 – Healthy ageing and wearable devices in general

The initial part of the workshop explored interventions and technologies in general that would support healthy ageing. Initially the discussion focused on particular aspects of ageing that can be supported through wearable technologies in general. The drivers for developing textile embodiments and their associated constraints were then discussed to identify where e-textiles solutions could offer advantages and benefits beyond existing conventional sensor and electronics technologies. At this stage the workshop did not explore e-textile solutions in detail and the research challenges and associated feasibility of these are presented in part 2.

### Wearable technologies

Personal health devices (PHDs) are defined as devices equipped with one or more sensors for monitoring physiological signals or activity levels. These are typically autonomous wireless devices and are therefore constrained in terms of the energy and processing power available, and they are typically, but not exclusively, wearable devices. Several examples of wearable devices exist that use conventional commercial off the shelf (COTS) electronic and sensor components applied as, for example, wrist or lanyard-based systems. The EPSRC IRC project SPHERE[12] developed a wrist mounted 6 axis inertial measurement unit for activity sensing[13]. Multiple inertial sensors distributed around an individual improve the accuracy of activity classification but require time synchronisation and orientation calibration. Such sensors can be wirelessly connected forming a Wireless Body Area Network (WBAN) or Body Sensor Network (BSN) typically using Zigbee or Bluetooth Low Energy (LE) communications protocols and can be readily incorporated into part of a larger smart home environment. Other examples of PHDs include pulse oximeters, blood pressure monitors, weighing scales, blood glucose meters, thermometers and fall detection sensors. Such sensors are an integral part of ambient assisted living systems and are an important source of data for health informatics.

### Current and future applications of devices to support healthy ageing

The workshop identified the following ageing related challenges where technology and wearable PHDs could be used to support individuals. These have been divided into two tables with Table 2 covering non-physical (e.g. cognitive) health related challenges and Table 3 covering physical health and functional ability related challenges. Examples of existing technologies or underpinning research are referenced where possible.

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[12] https://www.irc-sphere.ac.uk/

[13] Fafoutis, et al. (2017). Designing wearable sensing platforms for healthcare in a residential environment. EAI Endorsed Transactions on Pervasive Health and Technology, 3 (12), 153063.

| Non-physical health challenge | Technology | Drivers for e-textile solution | Constraints for e-textiles |
|---|---|---|---|
| Age related mental illnesses e.g. Alzheimer's disease. | GPS and inertial tracking devices [1]. Supporting personal memory recall using wearable cameras [2]. Cognitive training apps [3] and help with time keeping and reminders. Assessment and monitoring using ambient and wearable sensors and cameras [4]. Communications aids [5]. | Interactive textiles that incorporate a range of GPS and inertial sensor tracking devices in garments. Integrate textile speakers to enable audible prompts that aid memory recall. | Personalised solutions difficult to scale. Technical challenges around textile speakers. Need to integrate into a larger system e.g. appliance monitoring sensors. |
| Compliance with prescriptions | Smartphone medication adherence applications (adherence apps) [6], sensors on medicine packaging [7], activity recognition detecting cap twisting and hand to mouth movements [8]. | Actuators/sounders in clothing to prompt users. Incorporate drug delivery into garments (replace a patch). Wearable inertial sensors in clothing to improve compliance. | Need to be personalised as the prescription varies. |
| Improving emotions and mood/emotion detection | ICT systems that provide training for inducing positive moods and entertainment through improved interactions (e.g. email, chat, friends' forums, photos, videos and music) [9] and communication technologies e.g. voice assistants. Monitor using Electroencephalography (EEG) and through facial recognition [10]. Exercise reduces risk of depression [11]. | Wearable e-textiles can provide haptic feedback (e.g. hug shirt [12]). Clothing implemented voice assistant would be with user at all times.<br><br>Wearable comfortable EEG implementation Invisible - EEG electrodes can be hidden in hat /headband. Convenient – quick to put-on and take-off | Insufficient processing power in wearable component – need to interface to smartphone.<br><br>Accuracy and repeatability of EEG readings, electrodes position and motion artefacts. Require close fitting hat/ headband. |
| Monitoring sleep quality | Wearable activity monitors, smartphone apps, baby monitors, embedded sensors in mattresses [13]. Heart rate and respiration sensor for sleep analysis [14]. | E-textiles would provide a convenient, comfortable platform for hidden wearable sensors and facilitate combination of multiple sensors e.g. breathing, ECG, movement. Enable sensors to be integrated into bed linen. | Sufficient processing power required for data analysis and pattern recognition. |
| Monitoring household and indoor activities. | Wearable inertial sensors for activity monitoring, classification [15] and location tracking [16]. | E-textiles would provide a convenient, comfortable platform for inertial and location sensors embedded in clothing. | Processing power required for accurate inertial based location sensing. |

| | | | |
|---|---|---|---|
| | Sensors on power points for appliance monitoring [17,18]. Sensors in furniture/carpet [19]. | Pressure sensors integrated into furniture textiles/carpets. | |
| Physical isolation/loneliness | Wearable sensors for location monitoring and detecting if they are speaking [20]. | Invisible, comfortable and ubiquitous sensors for tracking and location sensing and breathing sensors or microphone for detecting speech. | Wireless communication/signal processing when outside the home vs in the home.<br>Complex electronics required to identify speech accurately. |

*Table 2: Societal challenges associated with healthy ageing*

| **Physical Challenge** | **Technology** | **Drivers for e-textile solution** | **Constraints for e-textiles** |
|---|---|---|---|
| Rehabilitation from injury or condition (e.g. stroke), limited mobility | Functional electrical stimulation (FES) [21]. Assistive physiotherapy, sensors and robotics [22]. | Electrodes for FES can be located on textiles for wearable comfortable solutions leading to improved compliance with exercises and rehab. Integrated inertial sensors in textiles/clothing can monitor exercise progress and be linked to gaming. Soft robotics can potentially be implemented in textiles assisting mobility through garments. | Individuality (may require personalised solutions)<br>Assisting mobility (soft robotics) requires high levels of actuation.<br>Implementations typically require tight fitting clothes. |
| Poor circulation and muscle atrophy | Assistive technologies for exercise to improve function e.g. FES [23]. Encouraging exercise through sensors, tracking and gamification [24], [25]. Resistance training followed by heating [26]. Compression garments [27]. | Textiles provide comfortable wearable textile electrodes for FES, heart rate monitoring and pulse oximetry. Inertial sensors integrated in textiles and clothing can monitor activity and technique to improve function and enable gamification. Heating functionality built into clothing - target specific locations to increase circulation and aid muscle growth. | Accurate positioning of electrodes and blood flow sensors. |
| Incontinence (detection and monitoring) | Disposable sensors for assessment applications (identifying care plans) [28]. Implantable bladder sensors (pressure). Electrical stimulation for management of overactive bladder [29]. | Textile based moisture activated batteries or sensors can enable underwear to sense incontinence and provide an alert. More comfortable external textile-based electrodes can be used for electrical stimulation to | Electrical stimulation requires tight fitting garment. |

| | | | |
|---|---|---|---|
| | | exercise muscles and improve control. | |
| Cardio health monitoring | Wearable health devices with heart rate sensors (e.g. smartwatches, chest straps) [30]. | Textile ECG electrodes on garments provides unobtrusive and comfortable interface. Convenient – quick to put on. | Quality of data needs to be sufficient to detect ECG waveform. |
| Managing bedsores | Specialised wound dressing e.g. containing silver, negative pressure wound therapy [31]. Pressure modulating mattresses/beds/ overlays that relieve pressure [32]. Pressure sensing arrays on support surfaces [33]. | Smart bandages with antibacterial properties (UV germicidal irradiation) and pressure and temperature monitoring capabilities. Pressure sensing sheets, clothing or integrated into mattress upholstery. | Cost constraints for disposable bandages. Bedding undergoes harsh washing cycles. |
| Managing Glucose | Analysis of blood (finger-prick test). Flash glucose sensor (wirelessly addressable sensor placed on skin surface) [34] and continuous glucose monitoring (battery powered wireless system with implanted sensor) [35]. Monitoring through sweat [36] and tears [37]. | Wearable, comfortable and less unsightly remote monitor for implanted continuous glucose sensor.<br><br>Textiles provide convenient platform for sweat based glucose sensor. | Alignment of transmitter over skin mounted and implanted glucose sensor important. Textile based glucose sensors in their infancy. |
| Early warning of falls/fall detection | Monitor balance through gait [38], inertial sensors [39] and foot-based sensors [40]. Predicting falls from visual data (e.g. Kinect) [41]. Fall detection using inertial sensors [42] and floor-based sensors [43]. | Clothing based inertial sensors for comfort and ease of use. Balance monitoring through pressure sensors in shoe insoles or socks. Carpet based floor sensor arrays. | The impact of mounting inertial sensors in loose clothing is not understood.<br>Accurate textile pressure sensors required.<br>Low cost carpet based distributed sensor arrays in infancy. |
| Monitoring breathing and encouraging breathing exercises | Controlled slow breathing and breathing technique can affect a range of physiological parameters (e.g. heart rate, blood flow dynamics) that are associated with health and longevity [44]. | Clothing based sensors can conveniently monitor breathing rate and type of breathing (e.g. shallow vs deep). | Optimum sensing approach for textile-based solutions not known. Influence of garment type on sensor performance not understood. |

*Table 3: Physical health and functional ability related challenges associated with healthy ageing*

## Wearable technology: the motivation for e-textiles

It is clear textile implementations of sensors, electrodes and soft robotics have a large range of potential applications in supporting healthy ageing. A single development such as textile based inertial sensors benefit a range of physical and non-physical challenges including the sensing of motion for the identification of household activities and taking of medicines, the provision of feedback during exercise or rehabilitation, fall prevention and detection and encouragement of exercise through activity monitoring and gamification. The importance of encouraging physical activity in achieving healthy ageing should not be underestimated. Exercise maintains physical and cognitive function and reduces the risk of many of the challenges identified above. For example, remaining physically active helps maintain cardio health, reduce the risk of fall, improve mood and reduce the risk of depression and dementia [45].

Similarly, textile-based electrodes also address a number of the societal and physical challenges identified above. This includes EEG monitoring for mood detection, ECG electrodes for monitoring exercise, cardio health and sleep, and FES electrodes for assisting rehabilitation and strengthening muscles to reduce muscle atrophy and prevent incontinence.

The benefits offered by e-textile implementation depend upon the application and the solution but there are a number of common advantages:

- Textile/clothing-based solutions provide a comfortable and familiar platform to users.
- E-textiles would enable unobtrusive and ubiquitous deployment sensors in clothing and furnishings.
- The integration in clothing will improve compliance (users might forget to use the conventional technology, but they always remember to get dressed).
- The unobtrusive nature of the technology will avoid any perceived stigma associated with wearing devices.
- Multiple sensors can be incorporated into a single platform (e.g. item of clothing) rather than requiring users to wear a number of separate devices.
- Information or alerts can be provided through the textile providing real time feedback to the user in a single platform.
- Textiles are the most common material that people interact with through, for example, clothing, soft toys, home furnishings and bed linen, and therefore providing an attractive platform for a range of applications.
- Ease of use and increased compliance can provide more data to better inform preventative interventions [46].

Certain constraints apply to e-textile implementations and some of these are universal and apply to all the applications identified in tables 2 and 3. For example, e-textiles are reliant on conventional primary or secondary batteries and these are bulky, rigid and incompatible with the feel of the textile. For long-term monitoring applications, batteries require user intervention to replace or recharge and limit the level of integration since they must be removed prior to washing. Embedding sensing functionality can be achieved by coating a textile with smart or functional material [47], or embedding miniature MEMS sensors in the yarns [48] or fabric [49]. These approaches are not straightforward given the structure of the fabric, its fibrous nature and lack of consistency even along the same textile roll. The use of a textile substrate for coating-based approaches places constraints on the processing of the active film (e.g. processing temperature) which can limit the functionality of the active materials. Sensors must be reliably connected to signal processing electronics and power sources and embedding these technologies in an unobtrusive manner is not straightforward. The influence of the textile or clothing on the accuracy of the sensor data is unknown and will require calibration e.g. the data gathered from inertial sensors on garments will depend upon how tight fitting the clothing is. Electronic and sensing technologies incorporated during the manufacture of the textile must survive the associated manufacturing process (e.g. weaving, knitting, surface finishing) and e-textile processes must be compatible with mass manufacture. During use, textiles routinely experience harsh physical conditions (e.g. physical wear, bending and flexing, exposure to liquids) and ensuring solutions are robust and reliable is a significant challenge. E-textiles based applications must consider safety considerations and the implications of data management and associated ethics/privacy issues must also be addressed. Ultimately, some e-textile applications may need to meet regulations that apply to medical devices.

Addressing these will enable e-textile technology to provide a user-friendly acceptable platform for assisting healthy ageing that address many of the limitation of existing conventional solutions [50]. The following section focuses on these constraints in more detail and identifies the specific research challenges that remain.

## Workshop Part 2 – Healthy ageing and e-textiles

The second part of the workshop explored e-textiles technologies that will be able to support healthy ageing in the future. The discussion focused on the technical constraints and challenges identified in part 1 and identified the fundamental scientific research and technical developments required to advance e-textiles to where they can deliver a practical solution. This work has been augmented by a literature review to highlight the current state of the art in each aspect. The following table lists each e-textile technology and which aspect of healthy ageing it relates to. For each of these, the existing technology readiness level (TRL[14]) of e-textile implementations and time to achieve a viable e-textile product is estimated. The table also includes an example of the current state of the art and the research and development required to reach TRL 9 is identified.

| E-textile technology | Application in healthy ageing | Existing TRL | Time to product[1] | Current state of the art and research required |
|---|---|---|---|---|
| Inertial sensors (e.g. accelerometer) | Inertial tracking, activity monitoring, monitoring physiotherapy exercises, gamification to encourage physical activity, fall prevention/ detection, monitoring sleep quality, compliance with prescriptions. | 5 | short | Existing textile-based activity monitoring uses a variety of strain sensing techniques (see below) rather than inertial sensors [51]. Accelerometers can be mounted on to a textile using the Lilypad platform (sewn on rigid PCBs) [52]. Improved integration in the fabric itself has been achieved in the EPSRC funded FETT project [53] (not yet published). Research required includes achieving full inertial measurement using incorporating magnetometers and gyroscopes, understanding how the textile embodiment effects performance and the impact this has on activity classification. |

[14] https://epsrc.ukri.org/research/ourportfolio/themes/healthcaretechnologies/strategy/toolkit/landscape/

| | | | | |
|---|---|---|---|---|
| Fabric electrodes for biosignal sensing (ECG, EMG, EEG) and stimulation (FES) | ECG - heart rate for activity tracking, cardio health monitoring and sleep analysis. EMG – muscle activity during physiotherapy. EEG - brain signal monitoring for mood detection.<br>FES: assistive physiotherapy for rehabilitation and improved function, bladder control. | 4-9 | Medium | Fabric-based dry electrodes have been demonstrated for ECG [54], EEG [55] EMG [56] and FES [47]. At present all associated signal processing and control aspects are performed off the textile which increases the number of electrical connections required, reduces portability and ease of use. Further research is required to: 1. Improve dry electrode/skin contact and reduce resistance without using gel/water. 2. Incorporate the electrodes into user friendly garments and reduce the requirement for such tight-fitting clothing. 3. Improve the reliable integration of electronics in textiles. |
| Textile pulse oximetry | Non-invasive monitoring of oxygen saturation of a patient's blood. | 3 | Long | Conventional fingertip or earlobe-based pulse oximetry sensors are common place. Polymer fibre optics embroidered into a textile [57] and fabric embedded LEDs and photodiodes [58] have demonstrated the feasibility of textile implementations. Neither approach has been developed into a practical solution. Further work is required to ensure robust and reliable operation and studies are required to validate performance. |
| Strain gauges: piezoresistive (measure strain through a change in resistance) or capacitive (change in capacitance) | Activity monitoring and classification or monitoring breathing by measuring strain or bending in a textile/garment. | 3-6 | Medium | Existing solutions include screen printed resistive material with sewn conductive thread contacts [59], knitted resistive sensors [60] and multilayer capacitive assembly using conductive textiles and dielectric layers [61]. Further work required on cyclical stability of sensors and minimising drift, sensor placement vs activity type, activity classification and sensor fusion (combining data with output from other senor types). |
| Temperature sensors (e.g. thermistor - change in resistance with temperature) | General health monitoring and feedback control in heated garment applications (e.g. improving circulation). | 4-9 | Short | Discrete temperature sensors have been embedded into textiles. Commercialised products exist (e.g. Siren smart socks for diabetic foot temperature monitoring). Thermistors have been integrated with complete circuits in the FETT project [62]. Applications specific challenges remain. |
| Moisture sensors | Incontinence application. | 3-6 | Long | Disposable urine activated battery can be used to provide a self-powered system detecting urinations [63]. Carbon nanotube-based filament sensors can be fabricated as a yarn – change resistance with moisture [64]. Existing lab-based demos need to be |

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| | | | | developed for the application, cost reducing and manufacturing challenges remain, sensor robustness and reliability need to be established. |
| Textile pressure sensors | Managing bed sores, foot-based balance monitoring for fall prevention, compression garments. | 3-9 | | Resistive based approaches including dielectric coated conductive yarns have demonstrated good performance in terms of sensitivity and stability [65]. Similar concept has been commercialised by Texis [66]. Other sensor types e.g. carbon nano tube coated fabrics [67], piezoresistive textiles [68] demonstrated in the lab but less developed. Remaining challenges include improving stability and longevity, scaling up for large area production and ensuring washability. |
| Fabric based glucose sensors | Managing glucose levels using discrete monitors for flash and implanted sensors and new sweat based glucose sensors. | 2-5 | Short - long | Electronics for remote monitoring of flash and implanted sensors can be integrated and hidden in clothing. Flexible circuits and packaging technology developed in FETT project is applicable [53] – this requires development and testing in the intended environment.<br>Sweat based glucose sensors would be well suited to a textile platform but whilst the feasibility of using sweat has been demonstrated [36], a fabric-based glucose sensor has yet to be demonstrated. Research into textile compatible electrochemical sensor for glucose monitoring and associated electronics, packaging and validation is required. |
| Actuators | Assisting mobility and providing haptic feedback. | 2-3 | Long | Fibre based twisted and coiled soft actuators based on Spandex can contract by 45% when heated to 130°C (resistive heating) [69]. Electrostatic actuation demonstrated with woven soft PVC fabric sandwiched between two electrodes suitable for generating vibrations [70]. Pneumatic actuators (artificial muscles) have been demonstrated in a power-assist suit [71] and orthotic device [72]. Pneumatic exoskeleton suits are commercially available but these are not integrated in a textile. Research challenges include overcoming the high-power consumption of thermal actuators, formulating materials and soft robotic structures that maximise strain whilst minimising energy consumption. Developing soft fibres, yarns and fabric structures that maximise the |

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| | | | | strain achieved in electroactive actuators. Pneumatic actuation is capable of high forces but is poorly integrated into textiles and bulky. Research is required to improve integration, reduce size and engineer actuators and garments such that forces are coupled effectively. |
| Fabric speakers | Enabling audible communication with users for memory prompts and other assisting technologies. | 2-4 | Medium-long | Active materials have been used to generate sound from textiles. A ferroelectret actuator (thin foam-based material driven by applied voltage) has been sandwiched between fabrics to make a music playing flag [73]. Piezoelectric materials such as PVDF have also been used [74]. Current driven printed conductive spirals on textile have been combined with a permanent magnet to generate sound [75]. Research required to increase the actuating force of the active materials whilst retaining compatibility with fabrics, improve coupling between the actuating materials and the textile and investigate the influence of garment design on speaker performance. |
| Monitoring breathing | Measuring sleep quality, assist with breathing exercises and improving technique, detecting speech (social interaction). | 2-4 | Long | Breathing rate and volume can be determined by a number of methods: measuring local strain resistive sensors on the skin [76] and on textiles [77]. Strain sensitive fibre optic sensors have been glued to a textile [78]. Other novel sensing techniques demonstrate include RF frequency [79], change in capacitance (e.g. capaciflector [80]). Inertial sensors and magnetometers can be used [81] but have yet to be demonstrated implemented in a textile.<br>The fabric-based sensing techniques demonstrated are all in the early stages of development and require further work to improve integration and achieve reliable operation over a long-term basis. Performance also needs to be benchmarked against existing systems. |
| Integrated location sensing | Identifying an individual's location and movements both within the home and outside. | Textile based systems 4 | Medium | Rigid electronics modules that use a combination of GPS and inertial sensors to track the performance of elite athletes are commercially available. These are typically inserted into a pocket in the clothing at the top of the back [82]. |

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| | | | | Research is required to improve the integration of the technology into the clothing, such that it is invisible both to the user and externally. Textile GPS antennas have been widely researched but no textile-based GPS/inertial system has been demonstrated. Flexible electronics and packaging approaches such as that developed in the FETT project [62] need to be applied in this application and benchmarked. |
| Antibacterial textiles | Smart bandages | 1-4 | Medium-long | Antimicrobial fabrics and associated finishing products are commercialised and used, for example, in medical environments [83] and bandages. Research challenges remain in improving the environmental friendliness of passive fabrics and preventing the migration of silver nano particles that reduces efficacy. Wound treatment can be improved with using smart bandages that include active functionality such as sensing and controlled drug release [84]. Incorporating ultraviolet emitting sources into a bandage can also actively kill bacteria but this has not yet been demonstrated. |

*Table 4: Technical breakthroughs and scientific research challenges required for e-textiles*

*[1] Time to product defined as short/medium/long term which corresponds to 1-3 years/4-6 years/ 7+ years respectively*

## E-textiles technology development for heathy ageing applications

The technologies listed in table 4 address the e-textile solutions identified in tables 2 and 3 with the exception of the heating functionality intended to improve circulation and aid recovery from certain injuries. Heated clothing is already widely commercialised based upon resistive heating (for example Blaze Wear [85]) and there are no significant research challenges remaining. The TRL quoted does depend on both the technologies and applications. The range of TRLs quoted for each e-textile technology also reflects the multiple potential solutions being explored.

For the technologies listed in table 4, there are a wide range of major challenges required to advance the e-textile embodiments to a point at which they offer a practical solution and potentially a commercially viable product. In general, research is required to improve the sensitivity, repeatability, durability, reproducibility and level of integration of the textile-based technologies enabling their use in long-term monitoring and support systems. The research topics relating to these challenges can be grouped into the following categories:

1. **Materials research** - Materials and their performance in textiles—There have been a wide range of functional materials been used in healthcare care applications including fabric-based dry electrodes for monitoring, diagnosis and treatment; flexible stretchable resistive and piezoelectric materials for sensors; electroactive polymer for actuators (e.g., artificial muscles); carbon nanotube-based filament and dielectric

coated conductive yarns for conductors and heaters; light emitting polymers for therapies. These materials must survive the rigours of use in the relevant application scenarios. Existing e-textiles are typically unsatisfactory in terms of reliability during use and durability (e.g., bending, stretching, washing). Biocompatibility (e.g., cytotoxicity, irritation, sensitisation) is also an essential requirement to ensure user safety and comfort is another issue.

2. **Discrete sensor/device integration in textiles** – Electronics (e.g., inertial sensors, pulse oximetry, temperature, circuit) and textile integration has progressed to the point where flexible circuits can be woven into a fabric or formed into a yarn. Both approaches allow the potential for electronics to be unobtrusive and effectively hidden within the textile. However, challenges remain regarding e-yarn length, numbers and reliability of interconnections, component sizes and flexibility.

3. **Garment/textile engineering/manufacturing** – Research regarding the influence of garment fit on sensor performance and engineering garment/textile structures that maximise coupling to sensors and actuators. The widespread manufacturing of e-textiles has been limited by the diverse range of techniques required to produce a set of functions in an e-textile. Ideally the e-textiles manufacturing process should be compatible with existing equipment (e.g., spinning, knitting, weaving, printing, coating, dyeing, finishing) already in use for conventional textile manufacturing to enable mass production. This is not straightforward and the specific challenges will depend on the electronics functionality and manufacturing process. For example, printing functional materials requires a much higher quality print than would be the case for patterning a fabric since any errors will result in failure. The structural design of sensors and actuators (e.g. capacitive sensors, electroactive polymer actuators, textile compatible electrochemical sensor) also requires investigation.

4. **End user validation**—The majority of research has been carried out in the lab with little or no input from end users. This leads to a disconnection between the technology and the end user requirements which delays uptake and the development of new products. Involvement of the end user and other key stakeholders (e.g., clinicians, regulators) from the outset of the project is essential to ensure the research effectively addresses the users' need and smooths the transfer from lab research to adoption in the market.

It should be noted that this review and roadmapping exercise has focused on the research challenges that relate *in particular* to healthy ageing. It has deliberately not included more generic technical challenges that are common to e-textile applications in general. These more generic challenges include the following:

- Integrated electronics in textiles
- Conductive textiles and fabric interconnects and connectors
- Supply of electrical power
- Manufacturing and sustainability
- Wireless communications and associated textile antenna design
- Data processing, storage and associated privacy issues.

Another consideration to be aware of is regulatory requirements. Compliance with medical device regulations is necessary for medical devices in order to demonstrate the safety and clinical effectiveness. This sets an entry barrier and lengthens the time required to take medical devices to market. The change in EU medical device regulation with the Medical Device Regulation (MDR) replacing the Medical Device Directive (MDD), with full effect from May 2020, will make the entry barrier even higher. Clinical evaluation (e.g., randomized controlled trials) are needed for new emerging products.

It is clear that as the technologies continue to evolve, wearable healthcare systems based-on e-textiles will be an attractive solution for comfortable and un-obtrusive monitoring of health parameters within a smart home/smart city environment. Achieving the required functionality and performance and using scalable manufacturing approaches compatible with conventional textile methods such as weaving, knitting, stitching and printing have a great potential for developing low-cost wearable solutions.

## Skills and People

The multidisciplinary nature of the research challenges is clearly evident and developing solutions requires a complimentary blend of skills and expertise. At present e-textiles research is often approached by researchers with a background in textiles or electronics but there is clearly the opportunity to increase the involvement of other communities such as materials scientists, chemists and instrumentation engineers. The research challenges can only effectively be met by interdisciplinary teams sharing expertise and methods and involving end users/stakeholders at an early stage in the research. This combination is necessary to appreciate the requirements of the application and constraints imposed by textile manufacturing methods and application environments.

## Appendix 1 – Workshop Agenda

# E-Textiles for Healthy Ageing

**Manchester Metropolitan University, 14th February 2019**
Benzie Building, Higher Chatham Street, Manchester, M15 6ED

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| 9.30 | Registration & coffee |
| 10.00 | Welcome and Introduction |
| 10.10 | Short presentation – Dr Laura Brown "What is Healthy Ageing?"<br>*The World Health Organization (WHO) defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". This highlights the importance of taking a broad and holistic view when deciding what the target outcomes of healthy ageing interventions should be. This talk will provide an overview of some of the common health issues associated with ageing, and will also consider definitions of healthy ageing from a variety of perspectives.* |
| 10.30 | Short presentation – Prof. William Harwin "Classification and assessment of movements from inertial sensors."<br>*Low energy inertial sensors make it feasible to embed mesh networks of sealed sensors. With sufficient sensors and an ability to store and transmit information, it would be easy to determine activities and quantify movement quality. These measurements are of value in healthcare, the safety industry, sports science, and military as well as providing a valuable mechanism for ongoing research. This presentation will consider how data from multiple inertial sensors that can be incorporated into casual clothing could be processed and used for applications in healthcare and allied research.* |
| 10.50 | Panel discussion – Q&A and general discussion |
| 11.10 | Facilitated workshop session: (excluding e-textiles) What could technology do for healthy ageing |
| 12.00 | Lunch and networking |
| 12.45 | Short presentation – Tim Brownstone (Kymira) "How e-textiles can change domestic health care forever"<br>*The original computer programmes where inspired by automated binary code used by the textiles industry. Today computing and sensing functionality is being built into the textiles themselves giving rise to entirely new methods of generating data. Perhaps the greatest ramifications of these advances will be seen in healthcare which has fallen behind other industries with its adoption of wearable electronics due to a lack of accuracy and functionality. Do e-textiles hold the answer?* |
| 13.05 | Short presentation – Prof. Cathy Treadaway "Keeping the person at the heart - designing for dementia and cognitive impairment"<br>*Over the last 6 years Professor Cathy Treadaway has been leading international design research, informing the development of playful* |

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| | *products for older people living with cognitive impairment as a result of dementia and stroke. The presentation will describe how e-textiles have been used in the design of highly personalised sensory products that enhance the quality of life of people living with advanced dementia with severe cognitive and communication difficulties.* |
| 13.25 | Short presentation – Mark Pedley (Smartlife) "Insight to live better, everyday"<br><br>*Smartlife have developed innovative textile sensors and electronics which can be integrated into any close-fitting garment and are capable of detecting the body's biophysical signals (e.g. ECG, EMG, respiration), and mechanical forces on the body.*<br>*Smartlife technology is discreet, comfortable, cost-competitive, and its accuracy has been independently verified by leading academic institutions.* |
| 13.45 | Panel discussion – Q&A and general discussion |
| 14.05 | Coffee break |
| 14.15 | Facilitated workshop session: The research challenges in converting the identified technologies into e-textile embodiments and timeframe for implementation |
| 15.50 | Wrap up and next steps |
| 16.00 | Close |

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