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Examining the Wearability and Implementation of Knitted Sensor Garments for Long Term Monitoring of Breathing Health: Thematic Analysis and Sensor Performance Characterization

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Submitted to: JMIR Biomedical Engineering
on: March 08, 2024

Preprint
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Abstract

Background: Long term unobtrusive monitoring of breathing patterns can potentially give a more realistic insight into the respiratory health of people with asthma or chronic obstructive pulmonary disease than brief tests performed in medical environments. However, it is uncertain whether users would be willing to wear these sensor garments long term.

Objective: Our objective was to explore whether users would wear knitted garments with knitted-in breathing sensors long term to monitor their lung health and under what conditions.

Methods: Multiple knitted breathing sensor garments, developed and fabricated by the research team, were presented during a demonstration. Participants were encouraged to touch and feel the garments and ask questions. This was followed by two semi-structured, independently led focus groups with a total of 16 participants of which 4 had asthma. The focus group conversations were recorded and transcribed. Thematic analysis was carried out by three independent researchers in three phases consisting of: familiarization with the data, independent coding and overarching theme definition. Participants also completed a web-based questionnaire to probe opinion about wearability and functionality of the garments. Quantitative analysis of the sensors' performance was mapped to participants' garment preference to support the feasibility of the technology for long term wear.

Results: Key points extracted from the qualitative data were: 1) garments more likely to be worn if medically prescribed, 2) cotton vest as underwear was preferred, and 3) a breathing crisis warning system was seen as a promising application. The qualitative analysis showed a preference for loose short sleeved T-shirts with a 81% acceptability rate, a 69% acceptability rate for snug fitting garments and 0% for tight-fitting garments. 62% of the participants would wear the knit for the whole day and 81% only during the night if not too hot. The sensitivity demands on the knitted wearable sensors can be aligned with users' garment preferences.

Conclusions: There is an overall positive opinion about wearing a knitted sensor garment over a long period of time for monitoring of respiratory health. The knit cannot be tight but should be able to be worn as a vest as underwear in a breathable material. These requirements can be fulfilled with the proposed garments. Participants with asthma supported using it as a sensor garment connected to an asthma attack alert system.

(JMIR Preprints 08/03/2024:58166)
DOI: https://doi.org/10.2196/preprints.58166

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Keywords: health technology; wearability of knitted sensors; focus groups; asthma observation.

Introduction

Smart garments are a type of wearable technology where the sensors are integrated into clothing that is being worn during day-to-day activities. The technology incorporated in the clothing provides various functions [1], such as tracking biometric data [2], controlling other smart devices [3], or enhancing comfort [4] and performance [5]. This wearable technology is different from smart watches, rings, or glasses (smart accessories) as the tech in garments sits within elastic shirts or trousers. Therefore, these garments impose higher demands on wearability and signal processing [6]. While smart accessories already have a large market share, smart garments are awaiting further investments in research and development to potentially break through into the commercial market [7]. One of the observations that can be made from the smart garment products currently available on the market is that their style relates closely with sportswear [8,9]. Commercial implementations provide insights into the user's health and wellness, as well as personalized coaching and sports performance improvement recommendations. The application areas of commercial smart garment implementations offer real-time feedback on e.g. sleep quality [10] or sport performance [11–15] by measuring heart and respiration rate, body temperature and body position. The marketing of smart garments for medical applications however does face challenges [16,17]. Many smart garments are not yet affordable for the mass consumer market as they use expensive fibers, fabrication processes and technology [18]. Since this technology is new, further development in reliability is needed and regulatory approvals and certification processes are slow and expensive, forming a hurdle at the initial stages of commercialization. As a result, the main areas that are being targeted by this technology are sports and wellbeing wear. This might lead to the perception that smart garments are mainly for fitness rather than for the people who need wearable health devices for continuous health monitoring, such as those with cardiovascular or lung disease [19]. Thus, the style of currently available smart garments can influence consumer acceptance, especially for the older generation or those less fitness inclined. Therefore, alternative approaches towards smart wearable garments for healthcare and their acceptability for the user are investigated [20]. We developed a knitted breathing sensor garment [21,22] with a more classical look and feel that could potentially lead to wider user acceptance and market adoption, especially in areas related to long term breathing monitoring.

Long term breathing monitoring has been identified as a method to help people with lung diseases such as asthma [23, 24]. Exploring the preferences of users is an important ingredient in developing wearable sensor garments for long term use [25]. In this research we present the thematic analysis of the results of 2 focus groups relating to the perceived wearability and use of the knitted breathing sensors garment. We then investigate whether the preferred sensor implementation can also output good quality breathing signals. With the aim to map compatibility of user requirements to sensor performance, we report on quality of the knitted sensors in terms of sensitivity to chest and abdomen circumference variations during simulated breathing using an in-house made chest phantom.

Methods

Recruitment

A standard e-mail was sent to final year engineering students, research fellows and support staff in the Electrical Engineering Department of Imperial College London and encouraged the engagement of associated contacts. A total of 16 participants were recruited. 8 (50%) had a background in research, 2 (12.5%) worked as healthcare professionals and 6 (37.5%) did not have research experience. 4 participants (25%) had asthma. 7 (44%) of participants were female. The total age range of participants was 23 to 55 years with 10 (62%) in the 18-30, 3 (19%) in the 31 – 50 and 3 (19%) in the > 51 age group. Written and verbal consent was obtained from all participants. An on-line questionnaire was designed in Qualtrics[1]. The protocol for this study was approved by the

[1] Qualtrics XM // The Leading Experience Management Software (Imperial College London license)

SETREC committee of Imperial College London[2].

Methodology

Different knitted sensor garments were introduced by the lead investigator (KF) – pictures are presented in Figure 1. These garments were designed and created by the research team with a variety of knitting techniques and materials, including modular sensor implementations in cotton and normal fit (Figure 1 a & b), fully handknitted snug fit in microfibra 92% and elastane 8% (Figure 1 c) and two machine knitted implementations – one snug fit in wool using a Kniterate tabletop circular knitting machine by Ecoknitware, UK (Figure 1 d) and one tight fit using Fluid (2% elastane, 7% nylon, 91% viscose) plated with an elastomeric yarn (19% Lycra, 81% nylon) for the bodice and a conductive yarn (Elektrisola yarn – 80% silver, 20% copper) plated with the same elastomeric yarn for the sensors using a 12 gauge SES Shima Seiki knitting machine at the Winchester School of Art, UK (Figure 1 e).Participants were encouraged to touch and feel the garments during the presentation and subsequent focus groups.

The theme of knitted garments and their sensor capabilities was introduced at the start of the focus groups using a PowerPoint presentation. Two focus groups were set up with 8 participants in each. Each focus group had an equal gender ratio. Each focus group was led by an independent facilitator, one with an MSc in Analogue and Digital Integrated Circuit Design and the other, a junior doctor in GP training. The discussion topics for the focus group were pre-determined to facilitate and guide conversations and give some structure but focus group leaders allowed participants to go beyond these questions. The focus group topics were:

1. Probe the participants' impressions of the wearability of the knitted garments that were demonstrated.
2. Breach the topic of the necessity for electronic readout in smart garments and probe acceptance.
3. Probe the opinion of the participants on the access to the data and their use.
4. Allow participants to voice concerns and contribute ideas.

The participants also completed an online survey concerning their personal opinion on the wearability of the knitted garments presented immediately after the focus groups. The online survey was hosted by Qualtrics.

Figure 1: Pictures of the different implementations of the knitted sensor garment. The inset zooms in on the sensors. Top row: modular systems where the knitted sensors are added to a garment. (a) knitted sensors added at the inside of a sewn top from knitted cotton material. (b) knitted sensors added onto a cotton T-shirt in a way that is visible. Bottom row: fully knitted implementations. (c) hand knit with elastic yarn, (d) machine knit in wool (e) machine knit in elastomers.

[2] Ethics approval overview | Research and Innovation | Imperial College London. Application ID 6620621.

Data Analysis

Transcripts were made by NM from both recordings after the meeting and fully anonymised for the analysis. Thematic analysis [26] was used to identify, analyse and report themes within the qualitative data contained in the transcripts of the focus groups. It involved six phases that were carried out by a set of 3 independent researchers, one with expertise in the field of thematic analysis. The phases were as follows: familiarization with the data (all researchers involved – KF, NM, MT), generating initial codes (2 involved – KF, NM), searching for themes (2 involved - KT, NM), reviewing themes (specialist involved - MT), defining and naming themes (specialist involved - MT), and producing the report (all researchers involved - KF, NM, MT, LT).
Qualtrics was used for the statistical analysis of the questionnaire.
The breathing sensors' operational characteristics were determined by using a specially designed rib phantom that simulates breathing and home-built battery powered readout electronics [21]. The sensitivity of each sensor was extracted from the measurements that relate the changes in readout output to the changes in circumference of the rib phantom. The sensors were snug fitted on the rib phantom except for the tight fit design of Figure 1(e).

Results

Thematic Analysis

Based on the coding, three overarching themes with each two to three additional subthemes were identified and are given in Table 1 with some specific representative coding examples.

Findings on everyday garment usage.

The focus group on everyday usage of the garment revealed some insights and preferences of potential customers. Participants expressed that they would like the style and materials of the garment to be appropriate for different seasons: "*I was looking at all the knits and they seemed like they'd keep me so warm. I wouldn't be able to wear them in summer*." and proposed a cotton underwear implementation that would not be subject to specific style requirements: "*If you want this to fit into all sorts of all kinds of clothing then of course it is difficult. But if they're just underwear then they can be simple just one style cotton and that's it.*"

Table 1: Three overarching themes each with 2 or 3 subthemes identified from the coding of the transcripts of the two focus group discussions. Some specific coding is added for each subtheme.

Everyday usage of garment			**Intention for the use of the garment**			**Data output**	
Wearability of the garment	**Maintenance of the garment**	**Placement and comfort of the electronics**	**Commercial vs Health**	**Cost of garment**	**How the garment could be used**	**How the data is used**	**Awareness of wearing the garment**
Underwear in cotton	Can it be washed?	Not a big box	Visual appeal/ style.	For health "not expensive"	Reduce hospital admissions.	Warning or alert.	Overwhelming.
Feeling of coils against the skin	Longevity	Hidden	Prescribed by GP.	For athletes "high end stuff"	Caught off guard.	Training.	Conscious.
More "giveable" fabric	Waterproof electronics	Pocket	Illness connotation.	Needs-based.	Second clearance.	Trend.	Influence breathing.

They also preferred a more relaxed knit that is not rigid and tight, and easy to slip on: "*I probably wouldn't wear the one that was rigid because I'd be worried that it actually changes my breathing pattern.*". In this they found the garment of Figure 1(d) to be particularly suitable. They were concerned about the sensor wires that would be embedded in the garment, and they wanted them to have no skin contact, and to be smooth and hidden: "*It would be better if it wouldn't press against the skin directly. I'd prefer if it is disguised in order to wear them on a regular basis*." Comfort related to textiles used in clothing has been and is still a major aspect in garment design. The traditional techniques used should still be applied for smart garments [27]. Participants suggested two possible implementations: a modular garment that allows them to detach the sensors and add them to other garments: "*I can bring my own top and then yeah, put the wire… So, you don't have repeated cost of wire, but just the cost of doing it*." or the sensor implementation of Figure 1(e) that integrates them smoothly and seamlessly into the fabric: "*…the coil is more like hidden and smoother in the yellow garment.*" They also wanted the hardware to be small, thin, hidden, and waterproof, and suggested that a purpose-built integrated circuit could be placed in a pocket: "*You could get them on a chip and provide a waterproof coating*." Finally, they emphasized that longevity is important for them: "*For me personally, if I was spending that much money that would have to*

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last me years." and they wanted the sensor wire insulation properties to be durable and wear and tear resistant: "*Over time, there would be wear and tear of the garment. Would that influence the working of the coils*?"

Opinions on the use of knitted sensors garments.

The participants indicated that they would be more willing to wear sensor garments if they had a medical condition that required monitoring or if their doctor recommended it to them. They did not care much about the cost or the style of the garments if this was the case: *"Personally, I probably won't get this if I walk into a shop. Yeah, but if it suggested by a doctor, I could just ignore the appearance*." The participants expressed doubts about the feasibility of knitted sensor garments as a commercial product for healthy people. They cited issues such as style, aesthetics, and cost: "*If it wasn't prescribed by a healthcare professional and is just commercial, the material and cost matter*." The importance of aesthetics in smart garments is a recurring theme in literature, as e.g. directly captured in the title of [28]. The participants acknowledged the potential benefits of sensor garments as a medical device, especially for preventing or detecting health problems that could lead to hospitalization: "*From a paramedic point of view, I think this product could really help people learn inhaling techniques… Visualising the patterns can assist them in training.*" They suggested that sensor garments could improve their quality of life and reduce healthcare costs by reduced visits to the GP (general medical practitioner) or hospital.

Opinions on smart output data.

There were divided opinions about what part of the biosignals should be made available. Some participants preferred to have access to the raw data, while others were satisfied with the summary statistics. The reasons for preferring the raw data included curiosity and personal research: "… *Various data that is stored over time can then be used to identify certain patterns or stages to look out for… and figure situations personal to the consumer*." The reasons for preferring the metrics included simplicity, convenience, and avoiding information overload: "*I think that you can get obsessed if you have access to the signals… Especially for people suffering with respiratory problems like asthma for example, it might be triggering.*" All participants agreed that notifications were a must feature for smart garments, especially for critical situations such as an imminent asthma attack. Notifications were also seen as useful for reminders, trends and feedback on progress: "*General pop ups and an alert if something is not in order.*" Participants expressed interest in a feature that would provide visual guidance on how to inhale properly to help them improve their breathing quality: "*Provide general advice on good breathing practices and certain exercises to follow. It could also give more specific instructions based on your patterns and thresholds that are personalized to the consumer.*" Product functionality is a major aspect in the interest of users and can drive the uptake of smart wearables if other aspects concerning wearability, comfort and aesthetics are fulfilled [29]. The participants input on the need for machine learning to improve the accuracy and personalization of the product might be mainly triggered by the majority of the participants being involved in some type of research: "*Something like models to detect abnormal behavior or stuff, but following this is the customized problem that is that the data is different for individuals… it might not necessarily work for the new customer*."

Of note was that recyclability and the ecologically beneficial implementation of the knitted garment (which is the aim of the company Ecoknitware) was not a priority for the participants, with a lack of understanding of the material and waste issues related to fashion: *"Umm, I'm not very familiar with the material*." One participant mentioned recyclability but seemed unsure of the implementation of this: "*So you could have some sort of recycling set up by which people send you the stuff, and maybe I don't know whether you can recycle that or reuse it*." There was more focus on style and aesthetics than sustainability: "*But if it is from a commercial brand, it's better to visually appeal*." "*Bit more*

trendy maybe."
Another observation is that although the facilitators of the two focus groups had different academic background knowledge, the overall themes and conclusions of both groups were similar.

Overall, the main points extracted from the qualitative data of the focus groups were:

- garments would be more likely to be used/worn if prescribed by a GP to be used as a medical device for health reasons.
- due to specific style requirements on outerwear, a cotton underwear (vest) implementation was preferred.
- garments must be comfortable, meaning smooth sensors and small electronics, and relatively easy to maintain.
- the collected data needs to be accessible and easy to read. A warning system of imminent breathing crisis was seen as the most promising application.

Survey Analysis.

The survey covered three overarching themes:
1. Whether the participants like to wear knits for everyday use.
2. Whether participants preferred a certain knitted style within a given selection (Fig. 2).
3. Whether participants would wear a knit to obtain health related information.

Each theme was split into multiple questions, probing specific items within each theme. For instance, on the theme of whether a participant would wear knitted garments for everyday use, sub-questions probed for the reasons such as aesthetics, need for thermal insulation and wearing comfort. A summary of the results of the questionnaire is given in Table 2.

The result of the questionnaire shows that personal preference for style can have a big impact on whether a knit is worn or not. For instance, there is a preference for loose short sleeved T-shirts and a 69% acceptability rate for snug fitting garments but none of the participants want to wear tight fitting garments. From a technical viewpoint, a snug fit is a pre-requisite to obtain good quality signals during normal wear to minimise motion artifacts [30]. A tight fit would be required for sports activities that are more energetic and would cause major movement in the sensors' position during the activities, deteriorating signal quality. Also of interest is that night wear would be an option if the style and material is right.

Table 2: Result of the questionnaire. The strongly agree and agree or the very likely to likely options are summed in the results row. This gives the positive feedback on the questions only. The neutral option is not counted.

	Like wearing knits?				**Style/yarn**[(a)]		**Health related information**		
	You like wearing knitted clothes.	n.You wear knitted clothes only to	.You wear knitted clothes because	.You wear knitted clothes because	Do you like fabric of a knitted top	How likely is it that you would wear a knit in that fabric but in a style of your choice?	How likely is it that you would que look at this information to get feedback on your breathing	ack?How likely would you use the information for inhaler use	e?Would you use it to train inhaler
Results (n=16)	75%	50%	69%	75%	63%	82%	94%	86%	80%

[a)]Additional information on preferred style and when it would be worn is given here. Participants were allowed to choose multiple options and thus the % reflect on preference order. A short-sleeved T-shirt style was preferred at 63% over a long-sleeved jumper at 44%, with a tank top the least preferred style at 25%. Most preferred a loose-fitting garment at 81%, closely followed by a snug fitting style at 69%. Few wanted to wear a baggy garment (13%) and none wanted to wear a tight-fitted garment. 62% of the participants would wear the knit for the whole day. Although, if the knit would come in a pyjama style then 81% would also wear it during the night.

Overall, most participants are happy to wear knitted clothes because they look and feel nice. There was a 50/50 opinion on the thermal insulation characteristics of knits. This was also reflected in the concerns mentioned in the focus group that knits might be too warm to wear. Therefore, the material and thickness of the yarns used in the knit should be such that the knit can be worn in all seasons.

Sensor Characteristics.

While the focus groups explored user preferences on wearability, there is a need to map these onto the technical capabilities of the sensors as a mismatch in the sense of poor technical performance for the preferred garment design would prevent the sensor garment from being useful. Dynamic and static measurements of the response of the knitted breathing sensors were carried out on a rib phantom. The sensitivity of the sensors together with key sensor implementation characteristics is given in Table 3. All garments had the same knitted sensor implementation – 10 consecutive rows with Elektrisola yarn – 80% silver, 20% copper. The diameter of garments were approximately the same by adapting the number of stitches in one row to the gauge of the yarn used.

Garments that excluded float stitches performed better, had a higher sensitivity, than the other snug implementations. This is a positive result as the participants did not like the float stitch implementation and thus can be avoided in future designs. The tight fitted design did not perform as well as the others due to its mechanical resistance against change. This is also a positive result as tight fits were unpopular with the participants, although they liked the smoothness of the sensors implementation. This smoothness is more related to the size of the stitches than the tightness of the fit and can thus be resolved in future designs.

Since fully knitted implementations and the modular designs' characteristics are similar, the option of both implementations remains and can be decided in view of cost of implementation and personalised style preference.

Table 3: The performance parameters of the different knitted breathing sensors and some key characteristics. Garment type are as defined in Figure 1.

Garment type	Implementation	Metal wire float stitches[a)]	Stitch size (mm)	Fit	Sensitivity (kHz/cm)
(a)	modular	0	2.5	snug	7.83
(b)	modular	0	2.5	snug	7.88
(c)	full hand knit	0	3	snug	7.83
(d) – wool implementation	full machine knit(a)	2 knit/2 float	2	snug	7.01
(d) - cotton implementation	full machine knit(a)	2 knit/2 float	2	snug	7.01
(e)	full machine knit(b)	0	1	tight	6.03

[a)]The insulated metal wire in the sensor is not included in all stitches in some implementations. In those cases, 2 stitches were knit with yarn and wire, then 2 stitches without the metal wire guiding the unstitched metal wire at the back of the garment. These are called float stitches.

Conclusions

Thematic analysis on the qualitative data of two focus groups and quantitative analysis based on a survey, have highlighted an inclination amongst the participants to wear the knitted sensor garment during the day or the night for medical purposes. They did not see the garment as a commercial fashion garment nor as a lifestyle statement. For long time medical wear, the participants suggested underwear (vest) in the style of the short-sleeved T-shirt in cotton that sits snug but not tight to the body and that is made in a material for all seasons. The wearer should be unaware of the sensors and the readout electronics. For ease of maintenance, the participants preferred not to have to remove the electronics for laundering. Longevity of the garment is essential while price would not be a main decision factor if prescribed by a medical professional for health benefits. The participants saw a warning or alert system that is triggered when a respiratory attack is imminent as essential for the medical use of the garment.

The technical response of the garment showed excellent performance for the preferred design supporting the feasibility of this wearable breathing sensing garment for personal health monitoring. A power supply challenge exists for all smart wearables especially in view of participants' desire not to have to remove any electronics for laundering.

Overall, there is a strong positive opinion about wearing a cotton knit with smooth sensors over a long period of time for health monitoring and training in healthy breathing techniques. The yarn material must be appropriate for all seasons. A use case could be made in relationship to an alert system to warn the user before a respiratory attack occurs.

While a large proportion of the participants in this work have a research background that might cause bias in the qualitative data, our findings are consistent with the results of previous studies [e.g. 16,18,20,27,28,29] relating to the acceptability of smart garments for health monitoring. This similarity suggests a common trend in user perception largely independent of the garment under study.

Acknowledgements

The work was supported by the National Institute for Health Research Invention for Innovation (NIHR i4i) Programme (Grant Reference Number: 205935).

KF thanks the owners of Ecoknitware - UK based ethical knitware manufacturer - for valuable contributions to the design of the knits made using a Kniterate tabletop circular digital knitting machine.

KF thanks Prof. Omar Usmani of the Faculty of Medicine, National Heart & Lung Institute, Imperial College London, South Kensington Campus, London SW7 2AZ, UK, for advice and support for the project.

Conflicts of Interest

None declared.

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