Journal of Textile Design Research and Practice

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rftd20

Evaluating Degrees of “Softness” in Therapeutic Systems of Knitted Wearable Technology with Brain Injury Survivors

Laura J Salisbury

To cite this article: Laura J Salisbury (2021) Evaluating Degrees of “Softness” in Therapeutic Systems of Knitted Wearable Technology with Brain Injury Survivors, Journal of Textile Design Research and Practice, 9:2, 226-251, DOI: 10.1080/20511787.2021.1935111

To link to this article: https://doi.org/10.1080/20511787.2021.1935111

Evaluating Degrees of "Softness" in Therapeutic Systems of Knitted Wearable Technology with Brain Injury Survivors

Laura J Salisbury

Laura J Salisbury is a current PhD candidate at the Royal College of Art and the Helen Hamlyn Centre for Design. Her PhD explores the use of piezoelectric theory as a method to disrupt the recovery process of upper limb movement deficits from ischemic stroke through textiles. The textile properties are developed in a manner so as to directly modify descending neural pathway input to the brain. As such, the garment becomes a platform for care, targeted specifically towards the upper body. Specialising in the area of technical textiles within fashion, the work is underpinned by a framework that mixes textile practice, material characterisation, clinical observation and design anthropology methods (of working with, being with and responding with stroke survivors). It should be noted that such anthropological methods have been used to identify need, understand the context of need and develop a response to this need through practice. The work is currently under a patent pending status.
laura.salisbury@network.rca.ac.uk

ABSTRACT Wearable energy harvesting methods have been increasingly researched over the past decade. Due to demands for finding suitable ways of powering wearable devices suited to garment contexts, yarn-based "components" gather increasing interest. However, the focus of textile properties of energy harvesting components often place emphasis on functional performance and limited elements concerning wearability; using terms such as "flexible", "breathable" and "wearable". Rarely, is there consideration for degrees of "comfort", and "softness". Yet, if such methods are to become integrated into wearable garments and worn on a daily basis, or even in niche contexts, the tactile experience requires attention. To address this, the following research details an exploration of softness of a polyvinylidene fluoride (PVDF) yarn-based energy harvesting method, amongst brain injury survivors where degrees of sensitivity can vary to extremes; accruing

Journal of Textile Design Research and Practice
Volume 9, Issue 2, pp 226–251
DOI: 10.1080/20511787.2021.1935111

either reduced or heightened levels of sensitivity as a result of stroke, for example. Levels of softness have been defined and quantified from earlier samples responded to by stroke survivors. This has been formed into a chart and used in reference within the development process to refine and detail the methods used to improve the quality of softness in the process of knitting. In contexts, such as the knit lab, participant presence can be limited, yet feedback, especially on subjective matters such as softness, is critical to the development process. The method presented of grading softness in accordance with previous samples is seen to aid the researcher to analyse samples made in situ, within an iterative process of development. The paper focuses on providing conversations around technical data within the knit process to deliver soft and wearable energy harvesting textiles. This forms a part of a wider body of PhD research that explores the use of piezoelectric theory as a technological tool for recovery of upper limb deficits for stroke survivors.

KEYWORDS: Wearable technology, energy harvesting, textiles, inclusive design, soft

Introduction

Currently, a vast amount of research is directed towards the development of energy harvesting yarns for powering wearable technology (Hammock et al., 2013; Wan and Bowen 2017; Yaqoob et al., 2017; Paosangthong et al., 2019). In terms of harvesting mechanical energy using piezoelectricity, which this paper will focus on, materials such as PVDF (Hadimani et al., 2013; Yan et al., 2019), as well as lead zirconate titanate (PZT) (Ounaies et al., 2008; Chou et al., 2018) have been extensively investigated in studies. Attempts of integrating energy harvesting components into wearables is increasing; Shenck and Paradiso (2001) combines both PVDF and PZT within a shoe to power a low energy device and Granstrom et al. (2007) embedded piezoelectric PVDF films into the straps of backpacks to name but a few. Aside from output performance, there exists limitations in terms of the material form, flexibility and methods of manufacture which are regularly presented in studies as key barriers towards the compatibility of use of energy harvesting methods within garments. Beyond this, properties which contribute towards degrees of “softness” and “comfort” have been underexplored.

Within the textile industry, “softness” is highly valued, since this is a trait which holds considerable influence on the “wearability” of a garment as a direct result on levels of comfort during wear. Notably, the finishing and aftercare of a garment typically involves the use of softeners; *“[They] are the most important global textile finishing chemicals in terms of value and amount [used]”* (Choudhury, 2017).

However, within energy harvesting studies, it is often difficult to understand the handle and degree of softness that the samples hold. Greater emphasis is often placed on the output performance and other properties that contribute to "wearability"; flexibility, porosity/breathability and stretch for example. Where such properties contribute to "softness" and "comfort", the data isn't brought together, nor does it take into consideration subjective perspectives of perceived levels of "softness" and "comfort" by the intended wearers, not just by the researcher themselves. This is important, since the tactile experience can vary quite dramatically between different groups of people with different lived experiences.

This paper will embark on exploring methods of evaluating "softness" of samples developed with brain injury survivors. Following a stroke, "one in two stroke survivors experience impairment in touch sensation" (Goodin et al., 2018). This may be in terms of reduced or enhanced sensation. The tactile experience was integral to understand when developing a textile based "medical device" within the wider study that this paper fits within. Although this presents participants with more extreme experiences of sensation than others, in terms of Inclusive Design principles, it is considered that the study can be useful for wider groups of individuals that do not face the same experiences. Myerson (2010) explains that, by catering for "extremes", or marginalised groups of individuals, this encompasses wider considerations that automatically include other "everyday" considerations that are suited to the "mainstream".

An importance is placed on accounts collected through anthropological studies of individual experience. Placing the voice of the participants directly within the text illustrates the conversation beyond where the author and scholars from the literature "speak for" them (Spivak, 1988). Details of individual medical history and levels of sensory perception are not included for the purposes of strict anonymity. Levels of sensitivity were considered in so much as, data from participants with extreme heightened degrees of sensitivity were grouped and cross-referenced against those with "normal" or reduced degrees of sensitivity. Heightened sensitivity was prioritised and guided the "Grading Chart" (as detailed in Grading "Softness"/Technical Investigations and Discussion Methods section) in the most part, since levels of "roughness" and/or "discomfort" are less likely to be tolerated in this group versus the other two groups of participants, meaning the benchmark for wearability was increased, but in a way that would mean the garment is more inclusive.

The paper will begin by providing a context to the paper ("Background" section):

Firstly, in terms of current developments of energy harvesting materials ("Energy Harvesting: A context" section), focusing on material behaviour;

Secondly, by defining "softness" and "comfort" ("Understanding "Softness" section), drawing upon the underlying theory and methods to do so;

Thirdly, providing context to methods of “measuring softness” (“Measuring Softness” section);
Fourthly, providing perspective of the studies within the paper (“Perspective and Focus of Study” section).

Following this, the paper will proceed to outline the technical investigations, introducing the methods (“Sampling” section), results (“Results” section) and discussion (“Findings and Discussion” section); before concluding the paper (“Conclusion” section).

The purpose of this paper is not to extensively explore what softness is or how we calculate it, since this exists in numerous areas of the literature (Lindberg et al., 1961; Peirce,1930) but rather to demonstrate how we can manipulate levels of softness for integrating suitably wearable energy harvesting components.

Background

Energy Harvesting: A Context

The development of energy harvesting textiles can be achieved in numerous ways; overall, this either involves constructing non-woven new materials (Chou et al., 2018), functionalizing textiles (Almusallam et al., 2017; Dong et al., 2017) or individual yarns (Li et al., 2014; Kim et al. 2017). Often, studies demonstrating non-woven new materials present rubbery matrices which are synonymously difficult to integrate within a garment and indeed, within garment manufacturing processes. Although the aim of these respective studies succeed in creating a flexible material from typically brittle PZT, (which has benefits in having a high piezoelectric activity, low Young’s modulus and flexibility), the placement of the resulting material is often better positioned within footwear (i.e. soles of shoes, where rubber typically exists), accessories and in some cases, fastenings/embellishments. However, further limitations exist in the connection of such “components”, if placed in a shoe, to power components embedded within the garment. Without wireless solutions of connecting footwear to the garment via textile antenna and rectenna (Ibanez-Labiano et al., 2020) for example, this method is less suited for the pursuit of mainstream wearable technology.

Methods of functionalizing textiles and individual yarns have been increasingly explored in order to incorporate energy harvesting properties directly into existing textile manufacturing processes and form materials with complimentary behaviours to that of existing textiles used in garment construction. Printing energy harvesting materials onto textiles via screen printing methods, presents one option (Almusallam et al., 2017). Lamination methods have also been used in studies (Shi and Beeby, 2019) to convert existing textiles into ferroelectrets. In a similar manner to printing of piezoelectric inks onto existing textiles, this method of lamination changes the textile behaviour; creating stiffer, although smooth, structure on the body, which influences garment identity and therefore the choice to wear or to not wear. Aside from the change in handle of the textile, the benefit of the screen printing method presents opportunities to apply piezoelectric ink anywhere (where levels of porosity permit) on the garment, pre or post production.

Further methods provide an opportunity to create garments with energy harvesting capabilities, in ways in which vast styles of textiles and therefore garments have been created for centuries (Kamiya et al. 2000); via traditional weave and knitting techniques. As an alternative to piezoelectricity, triboelectric properties can be utilised, combining "positive" and "negative" textiles with opposing charges; Paosangthong et al (2019) utilise nylon and PVC, a somewhat familiar tactile experience. Other studies explore the use of existing yarns (e.g. nylon) to create dielectric layers (Yu et al., 2017) within yarns via methods of twisting, or coating layers of piezoelectric materials to construct fully integrated yarns that may be assimilated into the construction of many varieties of textiles (Almusallam et al., 2017). Alternatively, the textile itself may consist of multiple functional yarn types to create a textile-based triboelectric or piezoelectric structure (Zhao et al., 2016; Dong et al., 2017). Yet where smooth encapsulation layers are often required to protect the material components, the limited "fibrous nature" and torque of such yarns restricts the level/diversity of "softness" that can be achieved. This may, in turn, limit the diversity of textile and garment types.

Consideration for how yarns can be combined with other more fibrous yarns within the textile is useful in this instance, whilst advances in material science rethink how such yarns may be created.

It should be finally noted that the textile structure of such "components" has a direct impact on output performance, influencing yarn contact (Dong et al. 2017). In a comparative study between single bed (10% stretch = 0.9 V/0.07 μA), double bed (20% stretch = 2.4 V/0.20 μA), and 2 × 1 rib structure (30% stretch = 5.3 V/0.29 μA), Kwak et al. (2017) demonstrate the importance of stretch on the functional performance of the device. The stretch percentage is influenced by the space surrounding the yarns and therefore the level of yarn density (manipulable by altering stitch length and tension), since for both the piezoelectric and triboelectric effect to take place, there needs to be a cyclic presence of both applied strain and/or contact between the yarns as well as a release of this strain and/or contact, respectively. However, generating high stretch with looser tensions can have negative consequences on the surface texture and degrees of comfort. The following studies presented within this paper show from a technical textile perspective, how this may happen and how this can be alleviated.

Understanding "Softness"

The tactile property of a textile can be defined by numerous characteristics (Figure 1), one of which is softness (Kilinc-Balci 2011). Softness or soft, an adjective, meaning to have a smooth surface or

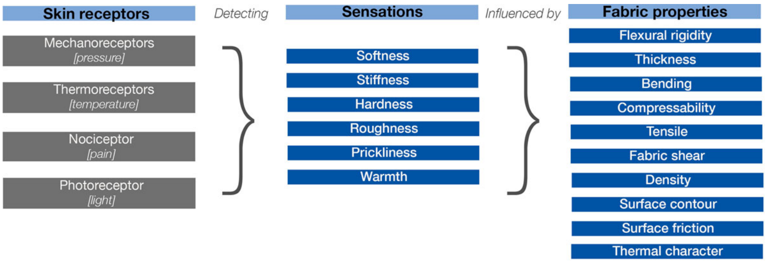

Figure 1

A summary of the sensations related to fabric properties and the relevant skin receptors within a textile: body dialogue (Influenced by literature: Peirce, 1930; Lindberg et al., 1961).

texture, has been defined by researchers in numerous ways; through associations with hysteresis, tensile properties, and shear stiffness (Abbott, 1951; Bishop, 1996; 1997; 2008; Sun, 2018); via compressive qualities (Elder et al., 1984) or via a direct comparison to bending length (Peirce, 1930).

We may consider the term soft within a wider term; that of “comfort”; a property which depends largely on softness (Choudhury, 2017). There exists an interconnected range of variables which correspond to, and determine one another. The handle of a textile is determined by softness, for example, as well as other factors including twist, count, friction, flexural rigidity, stiffness and “hairiness” (Peirce, 1930; Li and Wong, 2006).

Various *types* of “soft” can be expressed including “supple, smooth” properties exhibited by silks, for example. Or by combining “a springy property” experienced during the compression of the textile, along with a “thickness” and “a warm feeling” (Kawabata, 1980) relating to, for example, more fibrous cashmeres or mohairs. As such, the influence of softness does not solely impact comfort but also, the physical appearance of the garment via yarn type, and therefore expression of diversity in garment type. The incorporation of energy harvesting yarns into textiles with other yarn combinations will therefore impact the sensory expression of the garment type.

Furthermore, the development of yarn-based energy harvesting components challenges typical roles of garments as adornment. The “body” is no longer solely seen as a “passive surface inscribed by various forms” and thus for “social performances” (Goffman, 1959; Bovone and Mora, 1997; Finkelstein, 2007). Rather, the correspondence held between garment and self becomes more complex, with additional “purpose”. The purpose that the garment typically holds becomes entangled with another: identity is intertwined with generating power and therefore becomes obscured. Where it is not the purpose of this paper to attend to this, it is important to note how this may impact behaviour and perception of the garment (in comparison to garments which don’t hold this function); a factor which may influence the evaluation of degrees of softness by the participants. The function of the textile was purposely withheld during the tactile evaluation process ("Technical Investigations and Discussion" section).

It is recognised that ranges of physiological factors (e.g. heart rate) expressed by the individual experiencing the textile, contributes to feelings of "comfort" and sensations such as "softness" (Alagirusamy, 2010). This is influenced by wider factors such as environmental conditions and behaviour influencing types, rates and extents of body movements. Figure 1 summarises the correspondence between the body, sensations and fabric properties.

The following definitions of "softness" and "comfort", formed from literature and participant discussions, are used to broadly introduce the terms:

> ***Softness***
>
> Related to flexibility, compression and/or to smoothness, quantifiable by a range of experimental tools. Perceived softness is context dependent, an individual experience that can differ from person-to-person; influenced by body conditions as much as the textile, albeit largely by the aforementioned textile properties.
>
> ***Comfort***
>
> A feeling absent of pain/discomfort generated and dependent upon the following factors: (a) "Climatic variables" externally (from the environment), internally (from the wearer), and the space between the textile and body. These include temperature, humidity and airflow; (b) "Textile properties" including stretch, porosity, compression; (c) "Emotional and physical state of the wearer" which encompasses context (including health) and mood-depended experiences.

Measuring softness

Within the literature, "fabric prickle", "softness", "stiffness" and "roughness" are all evaluated with different methods. "Fabric prickle" as a result of fibers protruding from fabric surfaces, may be tested via low-pressure compression using a Kawabata Evaluation System for Fabrics (KES-FB) compression tester, laser-counting, or audio-pick up methods (Matsudaira et al., 1990). Softness is regularly quantified by compression measurements in the literature. Therefore an Instron Tensile Tester with 1 kN load cell may be used to assess degrees of compression (Elder et al., 1984). Stiffness, a characteristic associated with flexural rigidity, may be quantified using bending-hysteresis measurements via, for example, a Shirley Cyclic Bending Tester (Elder et al., 1985). Roughness may be defined in accordance with the size of surface irregularities, or by friction coefficients (Behmann, 1990), which equally defines levels of smoothness.

However, in all examples, subjective evaluations via methods such as wearer tests are mentioned.

Subjective measures have been previously used within the literature (Winakor et al., 1980; Philippe et al., 2003; Soufflet et al., 2004; Sular and Okur, 2008). The method of tactile evaluations in wearer trials has been demonstrated in 1997, where Naylor and Phillips (Naylor and Phillips, 1997) tested a range of jersey textiles on groups of “experienced adult judges” and “unskilled group of school children”. The AATCC (2006) standard “Fabric Hand: Guidelines for the Subjective Evaluation” provides guidance for subjective analysis. However, the “Tactile Triangle” (Atkinson et al., 2016) was constructed due to a disparity in opinion with the AATCC standard, suggesting that it “promote[s] unnatural interactions with textiles and so are incompatible with consumer experience” (ibid). Indeed, the subjective nature of tactile experiences means it can be difficult to quantify and convey. Only by experiencing the sensation oneself can one say that they may understand what another person means. We often say; “feel this” and attach loose expressions in an attempt to describe the sensation. It is often not reasonable, nor possible to define a comfort scale for the “psychophysical phenomenon” of softness without complexity (Alagirusamy, 2010; Choudhury, 2017). During wear, the tactile becomes associated with other ranges of stimuli, forming a memory of a lived experience, informing us as we navigate the world. We learn to associate particular “feelings” with particular contexts and “things”, including garments. This also means that the tactile experience is in constant flux, in the same way that memories are constantly re-created and re-defined as experiences develop, so too is the felt experience.

Where there exists common learned experiences and associations we hold to be able to identify things, sensory experiences differ slightly for each of us (Choudhury, 2017). This difference becomes heightened in cases where the somatosensory functionality may become damaged as a result of brain injury. Damage can lead to neuropathic pain (where individuals may feel heightened stabbing, burning, prickling or numbness sensations on the skin (Vestergaard et al., 1995; Lima et al., 2015); an element of “recovery” that receives less attention during rehabilitation (Bolognini et al., 2016).

Perspective and Focus of Study

For the purpose of this study, it becomes necessary to obtain subjective ratings from brain injury participants, placing people-centred approaches at the fore to determine sample softness, supplemented by quantitative data for sample thickness and stretch. Fabric thickness and stretch percentages are included to observe any correlations between these properties (thickness and stretch) and the level of softness; but more so, due to their significance in influencing garment type, seasonal and body temperature requirements, garment fit, and purposes specific to the intended use of the garment in the wider context of PhD research (Salisbury, 2021).

The range of technical investigations ("Technical Investigations and Discussion" section), focus on the creation of a close fitting, stretch black jumper. The physical identity, degree of softness and fit of the garment have all been determined by the intended end use supporting the integration of a patent pending textile component for muscle stimulation (Salisbury, n.d). It is particularly important to deliver a garment which is seemingly "familiar" and indistinguishable from other "plain black jumpers" (Salisbury, 2021). As such, a seamless and almost "invisible" integration of the energy harvesting components is pursued.

Technical Investigations and Discussion

Methods

Sampling

A Stoll CMS ADF 32 W multigauge machine was used to develop a fully fashioned garment with piezoelectric PVDF melt extruded yarn (dtex 90, obtained from Swicofil), with ranges of conductive yarn (sourced from Bart Francis), and varieties of "base yarns" which range from cash wools, various lycras (Table 1), to a cotton-zinc antibacterial yarn (provided by Perma).

Grading "Softness"

Participants were asked to rank a range of "Initial Samples" made prior to the study. These samples were created based on findings from earlier within the research (Salisbury, 2021) in which participant feedback was favouring simpler "familiar" (CE, 2019) textile structures, particularly, double bed, half milano, 2 × 1 rib and cardigan structures: "If it was changed into something like that [drop stitch] then I would wear it outside" (MM, 2019).

Spacer structures were introduced by the researcher as an option informed by the literature and participant feedback in so much as it allows for a "plainer" (FF, 2019), "familiar" (CE, 2019) surface, with reduced complexity in textile structure, without neglecting output performance.

Engagement with participants took place in the form of focus groups. Focus groups were conducted over three months in various locations, containing a maximum of two individuals per session. The groups consisted of a 65:35 male to female ratio, of ages ranging from 25 to 70. Textile samples (to an average scale of width [weft]: 15 cm by length [warp]: 12 cm) were used as provocations to explore participants' views of:

i. Textile structure
ii. The form of the energy harvesting material
iii. The tactile experience of the samples
iv. Perceptions of self
v. Participant requirements and desires of a garment.

Table 1. A summary of yarns used within technical investigations for samples 1 to 24.

Yarn name *(as stated in the text)*	Colour	Composition	Count (Dtex)[1]	Metric count (Nm)[2]	Supplier
PVDF (monofilament)[3]	Transparent	PVDF	90	–	Monoswiss: Swicofil
Cotton- Zinc (ZTK 20/1)	White	ZnO infused cotton	–	20/1	Perma Corporation
Inox (100%)	Grey	Stainless steel	120	–	Bart Francis
Cash Wool	Blue; Off-white	100% WV	–	2/30	Zegna Baruffa
Lycra	Blue; White; Grey	Undisclosed amounts of Polyester and Polyurethane	–	1/65	Filati be.mi.va
Black Lycra	Black	Unknown	–	2/50	E. Miroglio srl
Elastane	Blue	69% Polyester 31% Lycra	100	–	Yeoman Yarns

[1] Calculated as grams per 10 km of length of yarn.
[2] Calculated as the ratio of length in meters to mass in grams.
[3] Elongation (30-31%); Shrinkage (4-8%); melting point (160 °C).
[4] 0.08 mm melt extruded homopolymer.

Feedback was obtained through independent review, led by researchers who had not previously met the participants, but who knew the research. Participants had not previously seen the samples or been informed of the textile-stimulation concept explored.

Participants made a comparative analysis of the samples, ranking them in order of softness relative to the other samples. All individual ranks were then averaged out. Discussions were then held within the groups to categorise the samples; using keywords originating from participants to describe the tactile quality of the samples: "Very rough", "rough", "wearable" and "soft". From this, a chart has been developed (Figure 2) which grades degrees of softness on a scale of 1 (being most rough) to 9 (softest). Responses were considered in terms of heightened degrees of sensitivity and repeated a week later to see if perceptions had changed. A total of two repeat enquiries were conducted with participants, averaged out per person and then within the group to categorise the samples. Results from repeat tests verified the first response in 96% of participants, mainly due to a recollection of previously ranking the samples. Results varied mostly between the lower end of the spectrum in the categories of "Rough" and "Very Rough". Samples 1:1 rib, cardigan and half cardigan were most frequently re-ranked as a result of repeat tests, but only by a degree of 1 grade (i.e. from 1 to 2 and vice versa).

The aim of this chart is to therefore provide context to the researcher and reader.

Sample thickness was calculated using a digital caliper to a 0.01 mm degree of accuracy.

The stretch percentage of the samples was calculated by clamping the textile within a test rig and using the following equation:

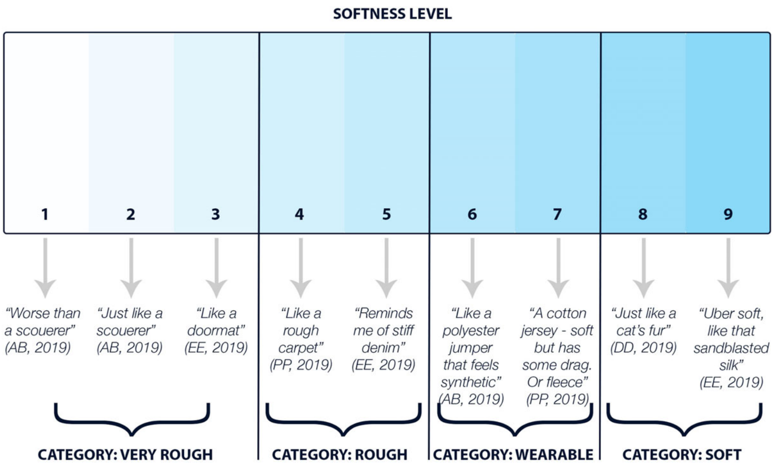

Figure 2
Softness level scale; categories and boundaries.

$$\textit{Maximum stretch width } [a] / \textit{unstretched width } [b] - 1 \times 100 = \textit{stretch percentage } [c]$$

$$i.e.\ a/b - 1 \times 100 = c$$

Results

The results are outlined as follows:

i. "Initial Samples" section displays the technical specifications of "Initial Samples" and their respective "softness grade" (Tables 2 and 3);
ii. Thereafter, "Developed Samples" section displays the technical specifications and respective grading of samples developed as a result of feedback of the "Initial Samples" from participants, named "Developed Samples" (Table 4 and Figure 3). These "Developed Samples" work towards the intended requirements of use of the garment as previously specified ("Methods" section).
iii. Finally, "Average Characteristics per Softness Level" section provides data compiling the average thickness (Figure 4) and stretch percentages (Figure 5) of samples classified in each "softness level".

Findings and Discussion

"Initial Samples"

Samples 5 to 7 were received with the greatest negativity, being described as "rough", "unwearable" and rejected: "Oh this one is really rough. No, there's no way that this could be worn. It would scratch your skin off!" (AB, 2018). Notably, the greater the stretch the more the stitches of PVDF protruded from the surface. This was

Table 2. Summary of textile structure and yarn combinations of Samples 1–12

		Yarn Combination					
Sample Number	Textile Structure	PVDF	Nylon	Cotton-Zinc	Lycra (Blue etc.)	Inox	Cash Wool
1	Double Bed	x				x	
2	Double Bed	x			x	x	x
3	Half Milano & Mock Rib	x		x	x		
4	Half Milano & Mock Rib	x		x			
5	Half Cardigan	x		x	x		
6	Cardigan	x		x	x		
7	1:1 Rib	x		x	x		
8	Tubular Spacer	x		x			
9	Tubular Spacer	x					x
10	Tubular Spacer		x		x		x
11	Tubular Spacer		x		x		x
12	Tubular Spacer		x		x		x

Table 3. Sample softness grading and common characteristics of "Initial Samples"

			Yarns combined with PVDF					
Category	Grade	Textile Structure	Lycra (Blue etc.)	Cotton-Zinc	CashWool	Inox	Thickness (mm)*	Av. Stretch Warp: Weft (%)
Very Rough	1	1:1 Rib	x	x			1.46	165: 170
	2	Half Cardigan	x	x			1.4	130: 170
	2	Cardigan	x	x			1.4	210: 200
	3	Half Milano & Mock Rib	x	x			1.17	105:110
Rough	4	Double Bed				x	1.02	100:45
	4	Double Bed	x			x	1.39	115:50
	5	Double Bed	x		x	x	1.39	115:50
Wearable	6	Half Milano & Mock Rib		x			0.59 ± 0.04	85:60
	7	Spacer		x			0.62	70:80
Soft	8	Spacer			x		1.81	75:45
	9	Spacer**	x		x		1.56***	80:25
	9	Spacer**	x		x		0.83****	65:30

*Tension was not recorded for the "Initial Samples".
**Samples used Nylon monofilament (with same dtex) as a replacement to PVDF.
***Sample used two ends of cash wool.
****Sample used just one end of cash wool rather than two to reduce thickness.

seen to contribute towards the rough texture that caused participants to liken the textile to a "scouring pad" (ibid), placing it in a category of textiles that was not suited to wear on the body.

The use of Lycra increases stretch in Sample 2, however, it also contributes to a "bandage" aesthetic (MM, 2019) and increases surface roughness (DF, 2019): "I wouldn't want to wear something that looks like a bandage" (MM, 2019). This roughness persists when the textile structure is changed in Sample 3, but to an elevated degree,

Table 4. Summary of textile structure and yarn combinations of Samples 13–24

		Yarn Combination				
Sample Number	Textile Structure	PVDF	Cotton-Zinc	Black Lycra	Lycra (Blue etc.)	Elastane
13	Tubular Spacer	x	x		x	
14	Tubular Spacer	x			x	x
15	Interlock	x	x			
16	Interlock with Float	x	x		x	
17	Interlock with Float	x	x		x	
18	Interlock Spacer	x	x		x	
19	Interlock Spacer	x	x		x	
20	Interlock Spacer	x	x		x	
21	Interlock Spacer	x	x		x	
22	Interlock Spacer	x		x		
23	Interlock Spacer	x		x		
24	Interlock Spacer	x		x		

suggesting that the textile structure impacts surface roughness: "I like how it looks. It reminds me of some jumpers I have. But it's quite scratchy. I wouldn't wear it" (PP, 2019). The PVDF appears to be looping above the surface rather than sitting flat (Figure 6).

Upon removing the Lycra in Sample 4, the softness levels increase. However, this had its own limitations: "It's quite flimsy isn't it. I always say that jumpers like this wear out really quickly and loose their shape. Then it's no good so you have to throw it out" (TT, 2019); "This is quite see-through. It's not practical" (PP, 2019).

Softness levels decreased when Lycra was added back into Samples 5 to 7: "Wow this [Sample 5] is very rough" (AB, 2018). The absence of stretch properties in the PVDF yarn means that, as the lycra contracts, the PVDF is pushed out above the surface and simultaneously holds the other stitches closer together, creating a more compact, stiffer structure, albeit depending on yarn combination and tension.

Changing the textile structure to a spacer (Samples 8 to 12), improved surface softness: "It's soft [Sample 9]. Lovely. I have a jumper like this at home" (FF, 2019).

However, issues persisted in terms of "transparency" and additional issues arose in regards to compressive qualities: "This one is also see-through [Sample 8]. It seems quite delicate. I'm not sure it's good for everyday, maybe for ladies on special occasions?" (SS, 2019). "This is lovely and soft [Sample 8]. Definitely something you could wear. But it does squish doesn't it. It feels weird when you press it. Almost like there's something in there" (GG, 2019). By employing spacer structures, the PVDF yarn could be tucked in between the two outer layers of the textile (Figure 7). In this instance the two outer layers of the textile contributed more to surface texture; catching the PVDF yarn within the textile and reducing contact of the

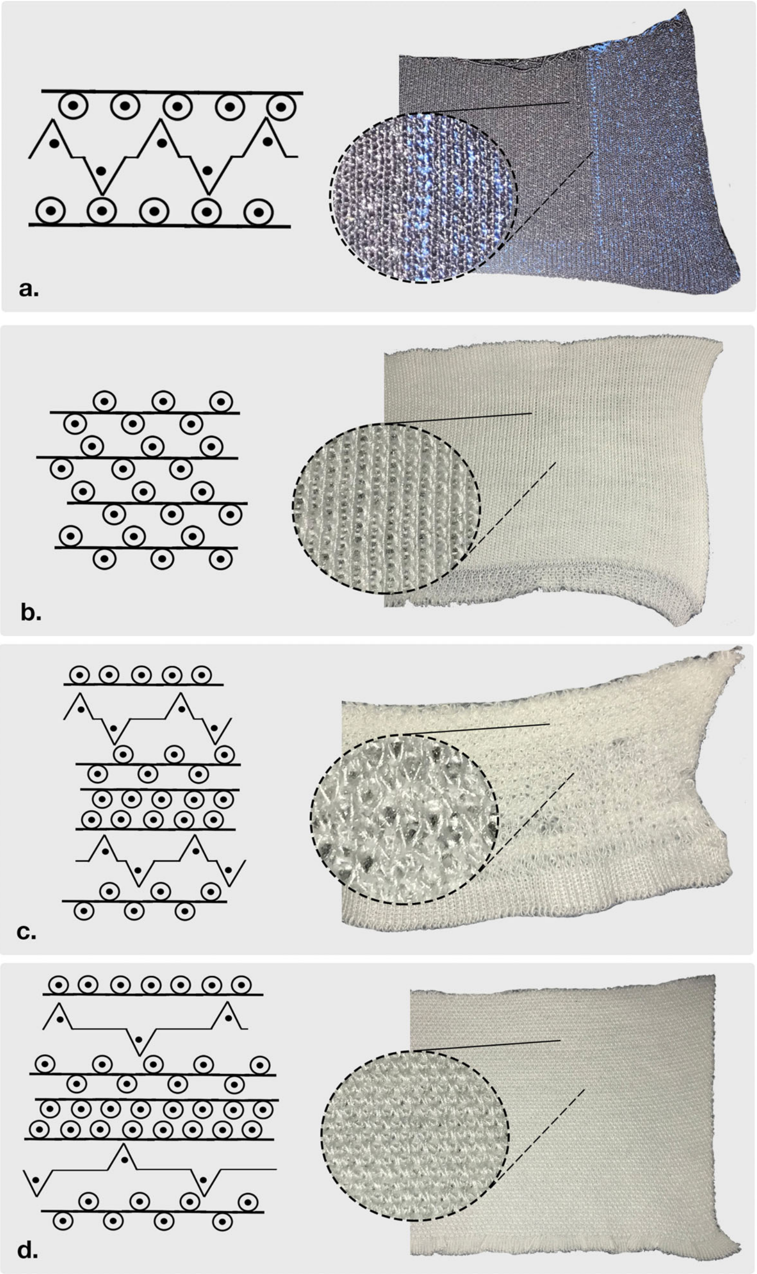

Figure 3
Visualisation of textile structures for developed samples.

PVDF with the skin. Samples employing a spacer structure saw an increase in sample softness to 7 and 8 (Samples 8 and 9 respectively). Softness levels were all below 6 in Samples 1 to 6, and as low as 1 (Sample 7) and 2 (Samples 5 and 6).

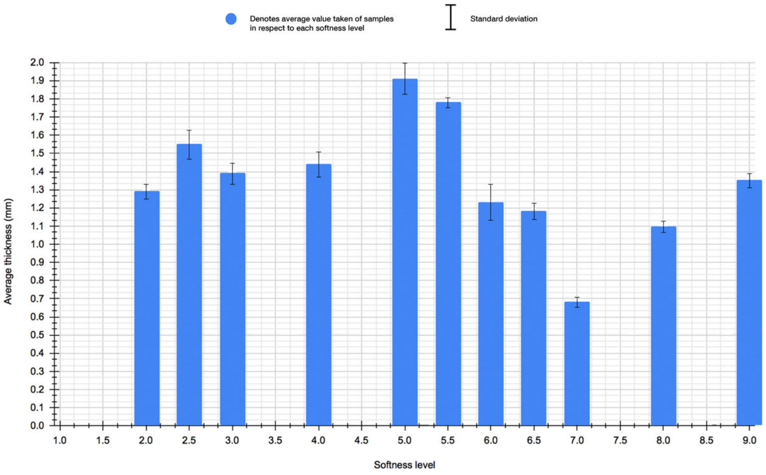

Figure 4
A graph depicting average thickness (mm) of samples in each respective "softness level".

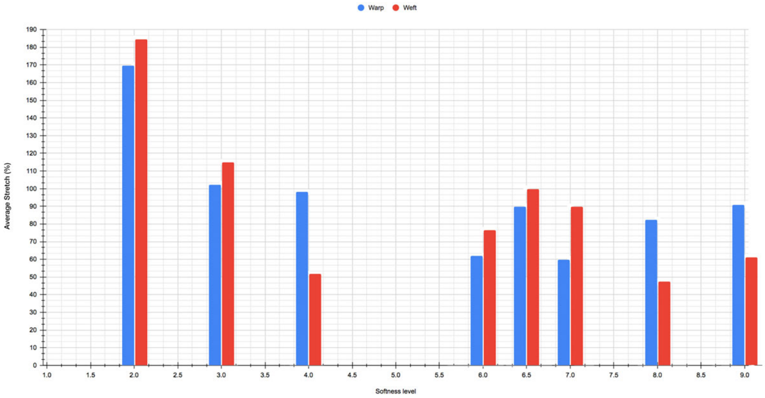

Figure 5
A graph depicting average stretch percentage (%) of the warp and weft of samples in each respective "softness level".

Spacer structures are also noted useful for improving energy harvesting output performance. Soin et al. (2014) have demonstrated higher outputs and efficiencies of spacer structures versus "2D" woven, knit and non-wovens; with a maximum output power density of 5.10μWcm−2 (under pressures of 0.02 – 0.10 MPa).

However, within the spacer structures, the integration of Lycra was lacking and the level of stretch was reduced. Even though the impact of a tighter structure with an enhanced stretch ratio is deemed desirable for improving output performance (Kwak et al., 2017), the surface roughness would be undesirable and prohibitive to wear (CE, 2019). Furthermore, in cases where stretch is required in order to deliver a particular garment type, delivering a tight-fit, stretch

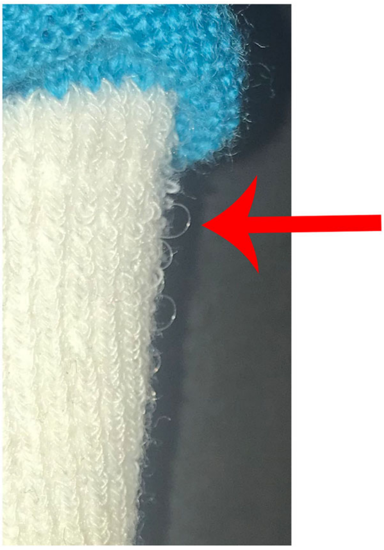

Figure 6
Close-up of surface structure. The arrow indicates protruding PVDF stitches.

energy harvesting garment with a polymer-based yarn can be challenging. The following investigations focus on delivering exactly that.

A series of technical data and analysis is included from key samples, selected from a range of 24 samples in total, to demonstrate repeatable steps that can be used to achieve a “super soft”, high stretch energy harvesting garment.

“Developed Samples”

Sample thickness, yarn combination and arrangement. It is widely known that samples using spacer structures typically increase sample thickness (up to 65 mm reported on warp knitted spacers; Yip and Ng, 2008; Hou et al., 2012). In general, thicker samples saw greater perceived levels of softness (Samples 10 to 13; 9; 23; Figure 4) with a range of thinner samples being exceptions to this (Samples 4; 15; 19; 22), whereby tension and yarn quantity also influences thickness. However, this can be manipulated. Depending on yarn combinations and tension, tubular structures are notably thicker than full interlock. By varying a tubular structure with interlock, it was found that the thickness of the sample could be controlled and reduced. Tucking the PVDF at every other stitch was also used to help reduce the overall thickness of the sample (from 0.99 mm in Sample 23 to 0.83 mm in Sample 22). However, tucking at every other stitch increased roughness, with less stitches catching the PVDF yarn in the structure (Samples 22 and 23).

Sample softness level also reduced when the PVDF yarn broke due to stitch arrangement (Sample 24; Figure 8). To avoid yarn

Figure 7
Spacer structure: PVDF yarns inlay between tubular cash-wool outer surfaces (indicated by arrow).

breaks, the racking should take place on a tubular rather than an inlay row (Figure 9).

Yarn arrangement is also a contributing factor to surface roughness. In Sample 15 the cotton-zinc and PVDF yarns are randomly oriented in the structure since they are simply “knitted in”. This can be controlled by employing a plating technique, as seen in Sample 16, generating a distinct difference in surface roughness between the “right” and “wrong” sides of the textile, thereby selectively orientating softer surfaces to that in direct contact with the wearer’s body. This does not account for contact with the outer surfaces via stroking or resting of the hand, for example, either by the wearer or another individual.

Notably, in Sample 19, the placement of the Lycra notably influenced perceived softness. By knitting the Lycra with the cotton-zinc, (rather than with the PVDF in the spacer in Sample 18), softness levels increased.

Body temperature requirements post-stroke are seen to influence the degree of softness and needs for maintaining a comfortable body temperature: “Because of the stroke I get really cold easily, especially in my affected arm. And when it gets cold it can be painful and gets really stiff. But in summer I wouldn’t be able to wear this [Sample 9]. It needs to be a bit lighter for summer” (PP, 2019). A lighter layer is considered beneficial since it can either be worn on its own or layered with other garments. Technical investigations aim to reduce the overall thickness of the textile for this purpose.

Combining properties within a single yarn (Sample 22) by using a softer yarn with elastane properties can reduce overall textile thickness, by reducing the need to use multiple yarns (Sample 21). However, this raises concerns for textile recycling at the garment’s “end-of-life”. The integration of PVDF yarns further adds to this complexity. Multiple yarns are considered to be easier to recycle than fibre-based methods of integrating nanofibers into existing yarns (e.g. PVDF nanofibers into cotton). The separation of materials can prove more difficult (Navone et al., 2020).

Figure 8
Close-up of surface structure with broken protruding PVDF stitches (indicated by arrow).

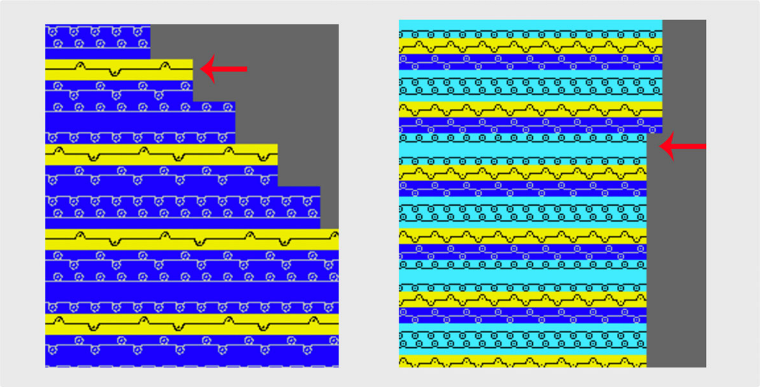

Figure 9
Details of textile structure influencing yarn breaks and surface roughness: Left - Arrow indicates racking starting on inlay which subsequently breaks the PVDF yarn; Right - Racking starting on tubular row (indicated by arrow) prevents yarn breaks.

Tension. Tensions vary according to the yarn combination used. Combining Lycra and PVDF in the inlay (Samples 18; 20; 21) increases surface roughness as the PVDF protrudes more so from the surface. Loosening the tension from 10.5 to 11.5 in Sample 21 increased sample thickness from 1.5 to 2 mm respectively.

Tensions were also seen to change the physical appearance of the textile; Samples 17 and 21 display a “polo” appearance, Samples 18 and 19 a “soft cardigan”, whilst Samples 13 and 14 may be considered appropriate for use in compression socks or tight fitting sportswear. “It seems like that type of fabric you would wear for thermals [Sample 8]. Like thermal vests” (DD, 2019). A tighter tension contributes towards a “stiffer” handle of the textile (e.g. Sample 20) and, in some cases, an increased stretch percentage (e.g. Sample 19).

Limitations and Considerations for Further Study

There are, of course, limitations in regards to how such tests are conducted:

i. The yarn combinations used for the samples in each series was limited. This impacts the scope of the research and explorations of "softness". Since the use of wools was likely to lend itself to colder seasonal wear, this became the focus of the research. To counter this, discussions were held around spring and "summer wear", with additional yarns (cotton and lycra) included for these purposes. Personal clothing and fabric swatches were referenced in cases where samples did not represent need.
ii. The colour of the samples was also limited, influencing participant responses; the off-white yarn influenced analogies of bandages (FF, 2019).
iii. Within this study, fabric thickness, density (depicted via measurements of tension) are used in line with the findings demonstrated by Elder et al. (1984) to show that these are critical characteristics that contribute to softness. In addition, further records of the textile structure, yarn combinations and the positioning of the energy harvesting yarn relative to the other yarns is seen as important and therefore detailed throughout "Technical Investigations and Discussion" section.

However, due to limitations in accessing tensile testing equipment, regrettably, this information is not included. Instead, stretch percentage is included. Should readers wish to investigate further, it is considered possible to calculate the Young's modulus from the information given.

iv. Although participant experience and self classification of textile softness can be useful in gathering "lived experience" responses from people, it is acknowledged that such responses can vary from day to day. The tactile experience can be mood dependent. Mood, seasons, weather and the context in which the sessions are held are all factors that can influence the response of participants. Although this cannot be fully mitigated, focus groups were spaced out over a two month period and sessions repeated to explore if opinions had changed.
v. The words "soft", "wearable", "rough" and "very rough" have been used to categorise the samples in accordance with remarks made by the participants. Although it should be stated that these are by no way the only words and methods used to convey degrees of softness by participants. It is, however, important to retain the participants' voices since the experiences belong to them, and so a range of quotes have

been included within the chart to enhance the reflections when categorizing further samples during the making process.

vi. It was acknowledged that some individuals who did not take part at all could provide some additional, particularly important insights. This was due to factors ranging from communication issues resulting from brain injury (e.g. aphasia), or needs to be in a quieter space where overwhelming auditory stimulation can limit participation for some individuals who experience heightened levels of sensitivity post brain injury.

A strategy was constructed to engage with them on a different level; e.g. on a one-to-one basis, or in consultation with the support worker who was either simply present or asked questions to the individuals on behalf of the researcher.

vii. Finally, the studies have solely focused on newly created samples and do not account for wear. Indeed, through wear, textiles that were previously “soft” can become rougher (e.g. due to fibres entangling and clumping together, from fibre breaks and loss of fibres revealing rougher underlying textile structures) that result in non-use. Further work is needed to identify the impact of wear via controlled testing/wearer tests to investigate this further.

Conclusion

Due to the increase in studies exploring the technical capacity and output performance of energy harvesting yarns, there exists a real need to understand how energy harvesting yarns may be integrated into wearable garments. In particular, how the tactile experience, particularly in terms of “softness” can be manipulated.

To support the process of classifying degrees of softness, objective measures (in the form of textile thickness and stretch) and subjective measures (in the form of participant feedback) were used, for which a “Grading Chart” (Figure 2, Tables 3 and 5) was created. In this method, the samples are seen to include the participants within the making process, when they are used as a reflective tool by the maker, who employs their own sensory experience in order to compare further samples in direct comparison to the grades given to prior (initial) samples by the participants.

The act of wearing clothing generates tactile sensations that can elicit pleasant or unpleasant responses. Of the most irritating sensations from wearing clothing, a “fabric-evoked prickle” is rated as being the worst (Li and Wong, 2006). Associations with feelings of being uncomfortable when wearing a textile that is “prickly” (Smith, 1987; Garnsworthy et al., 1988b) can be identified as triggering pain nerve endings from a threshold of 0.74 mN (Garnsworthy et al., 1988a). Within this study, samples which ranked worst were those where the PVDF yarn floated above the surface, protruding out,

Table 5. Sample softness grading and common characteristics of “Developed Samples”

		Common Properties						
			Yarns combined with PVDF*					
Category	Grade	Textile Structure	Lycra (Blue)	Black Lycra	Elastane	Cotton-Zinc	Thickness (mm) & Tension [T]	Av. Stretch Warp: Weft (%)**
Very Rough	2	Interlock Spacer	x			x	1.09 [9.5 T]	70:100
	2.5	Interlock Spacer	x			x	0.87 [11 T]	95:67
	3	Tubular Spacer	x		x		1.44 ± 0.12 [11 T]	100:120
Rough	3.5	Interlock with Float	x			x	1.75 [11.5 T]	90:60
	4	Interlock with Float	x			x	1.66 [11 T]	90:60
	5	Interlock Spacer	x	x		x	2.18 ± 0.04 [10.5 T]	40:100
Wearable	5.5	Interlock with Float	x			x	1.73 [11 T]	90:60
	6	Interlock Spacer		x			0.83 [10.5 T]	40:100
	6	Interlock Spacer	x			x	1.72 [10 T]	70:60
	6.5	Interlock Spacer		x			1.43 [11 T]	70:70
	6.5	Interlock Spacer	x			x	0.94 ± 0.2 [10 T]	90:60
Soft	8	Full Interlock				x	0.74 [9.5 T]	90:50
	8	Tubular Spacer	x		x	x	0.95 ± 0.09 [12 T]	100:110
	9	Full Interlock				x	0.48 [9.5 T]	90:50
	9	Tubular Spacer	x		x	x	2.14 ± 0.1 [12 T]	100:110
	9	Interlock Spacer		x			0.99 [10 T]	60:100

*Alternative lycra (named black lycra) and elastane yarns with different metric counts (Nm) were added In this set of “Developed Samples”. Cashwool and inox were removed from experiments to focus the enquiry on stretch yarn combinations for acquiring desirable fit as per the overall garment specification needs (“Perspective and Focus of Study” section). See Table 1 for further details.
**See Figure 5 for plotted warp and weft trends.

producing a rough surface. Small pieces of broken PVDF yarn (Figure 8), were caused by issues during the shaping process where the racking starts on a row of tucked stitches (Figure 9).

The study presented in this paper demonstrates that the level of softness can be controlled by altering the tension, textile structure, yarn combination and the position of the energy harvesting yarn in the structure. The examples included also show how shaping a garment provides further considerations, demonstrating that this requires attention within the construction of garment patterns further down the line. Where there existed limitations in terms of yarn combinations used within this study, this exists as a starting point, from which further yarn combinations may be explored.

Within the initial introductory sections of this paper, the use of rubbery matrices were discussed in regards to their use within the development of flexible energy harvesting materials (Chou et al., 2018). A final note is made towards this particular process. Where larger pieces of rubbery matrices may not be most suited for integration into garments, a reconsideration into how the use of silicones are used may present a better opportunity. Interestingly, the use of silicone is frequently used to create fabric softeners, specifically for wools, in order to increase fiber flexibility; specifically bend and twist (Naebe et al., 2013). Similarly to methods used for carbonising cotton yarns and other methods for energy storage (Mirvakili et al., 2015), considerations may turn towards the exploration of impregnated fabrics with PZT/silicone nanofibers (or alternatives to PZT) that simultaneously soften whilst embedding functionality may be a desirable route to integration.

Disclosure Statement

The author has nothing to disclose.

Funding

This work was supported by the Stavros Niarchos Foundation (a PhD scholarship); Research England (issued by the MedTech Superconnector) under Grant number CCF07-3270; and the EPSRC (issued by the Henry Royce Institute) under Grant number EP/R00661X/1. It should also be noted that Perma Corporation Ltd. have provided the poly-zinc yarns in the form of a textile sponsorship for PhD research.

References

AB. 2018. Clinical observation of Upper Limb Programme, Hospital of Neurology and Neurosurgery, Queen Square, London, [23/01/18 and 27/04/2018]

Abbott, N. 1951. "The Measurement of Stiffness in Textile Fabrics," *Textile Research Journal*, 21(6): 435–441.

Alagirusamy, A.D.R. 2010. "Psychology and Comfort." In A. Das and R. Alagirusamy (eds.) *Science in Clothing Comfort*, pp. 13–30. Sawston, UK: Woodhead Publishing.

Almusallam, A., et al. 2017. "Flexible Piezoelectric Nano-Composite Films for Kinetic Energy Harvesting from Textiles," *Nano Energy*, 33: 146–156.

American Association of Textile Chemists and Colorists (AATCC) Evaluation Procedure 1990. 5 (2006) Fabric Hand: Guidelines for the Subjective Evaluation, Developed in by AATCC Committee RA89.

Atkinson, D., Baurley, S., Petreca, B., Bianchi-Berthouze, N. and Watkins, P. 2016. "The Tactile Triangle: A Design Research Framework Demonstrated Through Tactile Comparisons of Textile Materials," *Journal of Design Research*, 21. Available online at https://discovery.ucl.ac.uk/id/eprint/1476178/1/X%20ATKINSON_reduced%20file%20size.pdf (accessed: September 2020)

Behmann, F.W. 1990. "Tests on the Roughness of Textile Surfaces," *Melliand Textilberichte*, 71(6): 438–440.

Bishop, P. 2008. "Testing for Fabric Comfort." In J. Hu (ed.) *Fabric Testing: Woodhead Publishing Series in Textiles*, pp. 228–284. Sawston, UK: Woodhead Publishing.

Bishop, D., Heine, E. and Hollfelder, B. 1997. "Reducing Wool Prickle by Enzyme Processing." In *The Fiber Society Joint International Conference University of Mulhouse*, Mulhouse, France, pp. 282–284.

Bishop, D.P. 1996. "Fabrics: Sensory and Mechanical Properties," *Textile Progress*, 26(3): 1–63.

Bolognini, N., et al. 2016. "The sensory side of post-stroke motor rehabilitation," *Restorative Neurology and Neuroscience*, 34(4): 571–586.

Bovone, L. and Mora, E. 1997. *Fashion in the Metropolis*. Milano: Franco Angeli.

CE. 2019. Focus group by Ninela Ivanova and Luka Kille-Speckter, Headway East London, 19 October to 22 November 2019.

Chou, X., et al. 2018. "All-in-One Filler-Elastomer-Based High-Performance Stretchable Piezoelectric Nanogenerator for Kinetic Energy Harvesting and Self-Powered Motion Monitoring," *Nano Energy*, 53: 550–558.

Choudhury, A.K.R. 2017. "Softness: Kawaba system." In A.K.R. Choudhury (ed.) *Principles of Textile Finishing*, First Edition, 109–148. Sawston, UK: Woodhead Publishing.

DD. 2019. Focus group by Ninela Ivanova and Luka Kille-Speckter, Headway East London, 19 October to 22 November 2019.

DF. 2019. Focus group by Ninela Ivanova and Luka Kille-Speckter, Headway East London, 19 October to 22 November 2019.

Dong, K., et al. 2017. "3D Orthogonal Woven Triboelectric Nanogenerator for Effective Biomechanical Energy Harvesting and as Self-Powered Active Motion Sensors," *Advanced Materials*, 29: 1702648.

Elder, H., et al. 1984. "Fabric Stiffness, Handle, and Flexion," *The Journal of the Textile Institute*, 75: 99.

Elder, H.M., et al. 1985. "A Psychological Scale for Fabric Stiffness," *The Journal of the Textile Institute*, 76: 442–449.

FF. 2019. Workshop by Laura Salisbury, Headway East London, 19 October to 22 November 2019.

Finkelstein, J. 2007. *The Art of Self Invention*. London: Taurus.

Garnsworthy, R.K., et al. 1988a. "Identification of the Physical Stimulus and the Neural Basis of Fabric-Evoked Prickle," *Journal of Neurophysiology*, 59(4): 1083–1097.

Garnsworthy, R.K., et al. 1988b. “Understanding the Cause of Prickle and Itch from the Skin Contact of Fabrics, Australian Textile,” *Australian Textile*, 8(4): 26–29.

GG. 2019. Workshop by Laura Salisbury, Headway East London, 19 October to 22 November 2019.

Goffman, E. 1959. *The Presentation of Self in Everyday Life*. Garden City, NY: Doubleday.

Goodin, P., Lamp, G., Vidyasagar, R., McArdle, D., Seitz, R.J. and Carey, L.M. 2018. “Altered functional connectivity differs in stroke survivors with impaired touch sensation following left and right hemisphere lesions,” *NeuroImage Clinical*, *18*: 342–355.

Granstrom, J., et al. 2007. “Energy Harvesting from a Backpack Instrumented with Piezoelectric Shoulder Straps,” *Smart Materials and Structures*, 16(5): 1810.

Hadimani, R., et al. 2013. “Continuous Production of Piezoelectric PVDF Fibre for e-Textile Applications,” *Smart Materials and Structures*, 22(7): 075017.

Hammock, M.L., et al. 2013. “25th Anniversary Article: The Evolution of Electronic Skin (e-skin): A Brief History, Design Considerations, and Recent Progress,” *Advanced Materials (Deerfield Beach, Fla.)*, 25: 5997–6038.

Hou, X., Hu, H., Silberschmidt, V.V. 2012. “A Study of Computational Mechanics of 3D Spacer Fabric: Factorsaffecting its Compression Deformation,” *Journal of Materials Science*, 47(9): 3989.

Ibanez-Labiano, I., et al. 2020. “Graphene-Based Soft Wearable Antennas,” *Applied Materials Today*, 20:100727.

Kamiya, R., et al. 2000. “Some Recent Advances in the Fabrication and Design of Three-Dimensional Textile Preforms: A Review,” *Composites Science and Technology*, 60: 33–47.

Kawabata, S. 1980. *The Standardization and Analysis of Hand Evaluation*. Osaka: Textile Machinery Society of Japan.

Kilinc-Balci, F.S. 2011. “Testing, Analyzing and Predicting the Comfort Properties of Textiles.” In G. Song (ed.) *Improving Comfort in Clothing*. Sawston, UK: Woodhead Publishing.

Kim, K., et al. 2017. “Multifunctional Woven Structure Operating as Triboelectric Energy Harvester, Capacitive Tactile Sensor Array, and Piezoresistive Strain Sensor Array,” *Sensors*, 17: 2582.

Kwak, S.S., et al. 2017. “Fully Stretchable Textile Triboelectric Nanogenerator with Knitted Fabric Structures,” *ACS Nano*, 11(11): 10733–10741.

Li, X., et al. 2014. “3D Fiber-based Hybrid Nanogenerator for Energy Harvesting and as a self-powered Pressure Sensor,” *ACS Nano*, 8: 10674–10681.

Li, Y.I. and Wong, A.S.W. 2006. “Tactile sensations.” In Y. Li and A.S.W. Wong (eds.) *Clothing Biosensory Engineering*, pp. 116–150. Sawston, UK: Woodhead Publishing.

Lima, N.M.F.V., et al. 2015. “Sensory Deficits in Ipsilesional Upper-Extremity in Chronic Stroke Patients,” *SciELO* 73: 1678–4227.

Lindberg, J., Behre, B. and Dahlberg, B. 1961. “Shearing and Buckling of Various Commercial Fabrics,” *Textile Research Journal*, *31*: 99–122.

Matsudaira, M., Watt, J.D., Carnaby, G.A. 1990. “Measurement of the Surface Prickle of Fabrics Part I: The Evaluation of Potential Objective Methods,” *Journal of the Textile Institute*, 81(3): 288–299.

Mirvakili, S.M., et al. 2015. “High-Performance Supercapacitors from Niobium Nanowire Yarns,” *ACS Applied Materials & Interfaces*, 7(25): 13882–13888.

MM. 2019. Focus group by Ninela Ivanova and Luka Kille-Speckter, Headway East London, 19 October to 22 November 2019.

Myerson, J. 2010. “Bulls Eye Diagram.” In O. Eikhaug & R. Gheerawo (eds.) *Innovating with People: The Business of Inclusive Design*. Norway: Norwegian Design Council.

Naebe, M., et al. 2013. “Effect of Surface Treatment and Knit Structure on Comfort Properties of Wool Fabrics,” *Journal of the Textile Institute*, 104(6): 600–605.

Navone, L., Moffitt, K., Hansen, K.-A., Blinco, J., Payne, A. and Speight, R. 2020. “Closing the Textile Loop: Enzymatic Fibre Separation and Recycling of Wool/Polyester Fabric Blends,” *Waste Management*, 102: 149–160.

Naylor, G.R.S., Phillips, D.G. 1997. “Fabric-Evoked Prickle in Worsted Spun Single Jersey Fabrics Part III: Wear Trial Studies of Absolute Fabric Acceptability,” *Textile Research Journal*, 67(6): 413–416.

Ounaies, Z., et al. 2008. “Evidence of Piezoelectricity in SWNT-Polyimide and SWNT-PZT-Polyimide Composites,” *Journal of Thermoplastic Composite Materials*, 21(5): 393–409.

Paosangthong, W., et al. 2019. “Textile-based Triboelectric Nanogenerator with Alternating Positive and Negative Freestanding Grating Structure,” *Nano Energy*, 66: 104148.

Peirce, F.T. 1930. “The “Handle” of Cloth AS A Measurable Quantity,” *Journal of the Textile Institute Transactions*, 21(9): T377–T416.

Philippe, F., Schacher, L., Adolphe, D.C. and Dacremont, C. 2003. “The Sensory Panel Applied to Textile Goods – A New Marketing Tool,” *Journal of Fashion Marketing and Management*, 7(3): 235–248.

PP. 2019. Focus group by Ninela Ivanova and Luka Kille-Speckter, Headway East London, 19 October to 22 November 2019.

Salisbury, (n.d.) *Muscle stimulation.* UK Patent Office. Patent no. 2013574.5.

Salisbury, L.J. 2021. Wearing your Recovery. PhD Thesis. Royal College of Art.

Shenck, N.S., Paradiso, J.A. 2001. “Energy Scavenging with Shoe-Mounted Piezoelectrics,” *IEEE Micro*, 21(3): 30–42.

Shi, J., Beeby, S.P. 2019. “Textile based Ferroelectret for Wearable Energy Harvesting,” *Journal of Physics: Conference Series*, 1407: 012117.

Smith, J.E. 1987. The Evaluation and Optimization of Sensorial Comfort. PhD Thesis. The University of Salford.

Soin, N., et al. 2014. “Novel “3-D spacer” all Fibre Piezoelectric Textiles for Energy Harvesting Applications,” *Energy & Environmental Sci*, 5: 1670–1679.

Soufflet, I., Calonnier, M. and Dacremont, C.A. 2004. “Comparison Between Industrial Experts’ and Novices’ Haptic Perceptual Organisation: A Tool to Identify Descriptors of the Handle of Fabrics,” *Food Quality and Preference*, 15(7): 689–699.

Spivak, G.C. 1988. “Can the Subaltern Speak?.” In C. Nelson and L. Grossberg (eds.) *Marxism and the Interpretation of Culture*, pp. 66–111. Urbana: University of Illinois Press.

SS. 2019. Focus group by Ninela Ivanova and Luka Kille-Speckter, Headway East London, 19 October to 22 November 2019.

Sular, V. and Okur, A. 2008. “Handle Evaluation of Men’s Suitings Produced in Turkey,” *Fibers and Textiles in Eastern Europe*, 16(2): 61–68.

Sun, D. 2018. “Fabric Handle as a Concept for High-Performance Apparel.” In J. McLoughlin and T. Sabir (eds.) *High-Performance Apparel: Materials, Development and Applications*, pp. 307–323. Sawston, UK: Woodhead Publishing.

TT. 2019. Focus group by Ninela Ivanova and Luka Kille-Speckter, Headway East London, 19 October to 22 November 2019.

Vestergaard, K., et al. 1995. “Sensory Abnormalities in Consecutive, Unselected Patients with Central Post-Stroke Pain,” *Pain*, 61(2): 177–186.

Wan, C. and Bowen, C.R. 2017. “Multiscale-Structuring of Polyvinylidene Fluoride for Energy Harvesting: The Impact of Molecular-, Micro- and Macro-Structure,” *Journal of Materials Chemistry A*, 5: 3091.

Winakor, G., Kim, C.J. and Wolins, L. 1980. “Fabric Hand: Tactile Sensory Assessment,” *Textile Research Journal*, 50(10): 601–610.

Yan, J., et al. 2019. “Performance Enhancements in Poly(vinylidene fluoride)-based Piezoelectric Nanogenerators for Efficient Energy harvesting,” *Nano Energy*, 56: 662–692.

Yaqoob, U., et al. 2017. “A Novel Tri-Layer Flexible Piezoelectric Nanogenerator Based on Surface- Modified Graphene and PVDF-$BaTiO_3$ Nanocomposites,” *Applied Surface Science*, 405: 420–426.

Yip, J. and Ng, S.P. 2008. “Study of Three-Dimensional Spacer Fabrics: Physical and Mechanical Properties,” *Journal of Materials Processing Technology.*, 206(1): 359.

Yu, A., et al. 2017. “Core-Shell-Yarn-Based Triboelectric Nanogenerator Textiles as Power Cloths,” *ACS Nano*, 11: 12764–12771.

Zhao, Z., et al. 2016. “Machine-washable textile Triboelectric Nanogenerators for Effective Human Respiratory Monitoring through Loom Weaving of Metallic Yarns,” *Advanced Materials (Deerfield Beach, Fla.)*, 28: 10267–10274.