Singing Knit: Soft Knit Biosensing for Augmenting Vocal Performances

Courtney N. Reed*
Queen Mary University of London
London, UK
c.n.reed@qmul.ac.uk

Sophie Skach
Queen Mary University of London
London, UK
s.skach@qmul.ac.uk

Paul Strohmeier
Max Planck Institute for Informatics
Saarbrücken, Germany
paul.strohmeier@mpi-inf.mpg.de

Andrew P. McPherson
Queen Mary University of London
London, UK
a.mcpherson@qmul.ac.uk

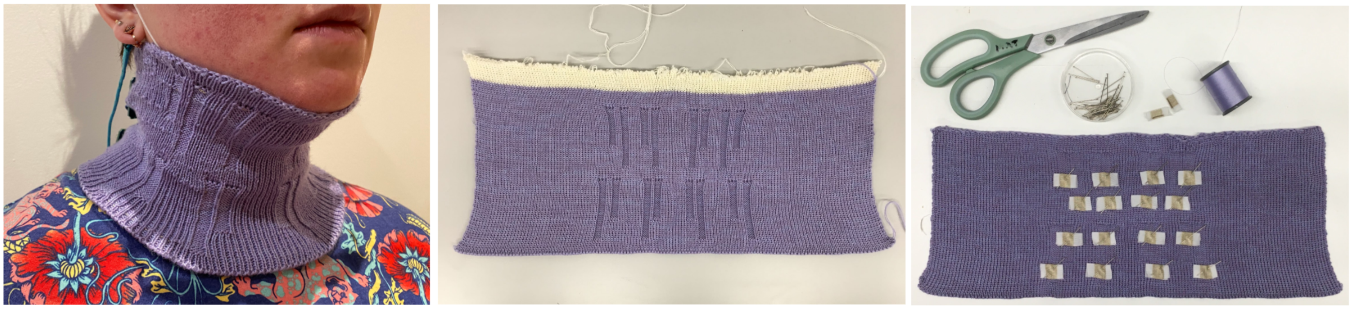

Figure 1: The *Singing Knit*, worn by Reed (left). Alternating ribbing on the outside of the collar highlights the position of the muscles and electrode placements (middle). Fabric electrodes made from zebra jersey are stitched by hand into the correct locations (right).

ABSTRACT

This paper discusses the design of the *Singing Knit*, a wearable knit collar for measuring a singer's vocal interactions through surface electromyography. We improve the ease and comfort of multi-electrode bio-sensing systems by adapting knit e-textile methods. The goal of the design was to preserve the capabilities of rigid electrode sensing while addressing its shortcomings, focusing on comfort and reliability during extended wear, practicality and convenience for performance settings, and aesthetic value. We use conductive, silver-plated nylon jersey fabric electrodes in a full rib knit accessory for sensing laryngeal muscular activation. We discuss the iterative design and the material decision-making process as a method for building integrated soft-sensing wearable systems for similar settings. Additionally, we discuss how the design choices through the construction process reflect its use in a musical performance context.

CCS CONCEPTS

• **Human-centered computing** → **Interaction design process and methods**; **Activity centered design**; *Gestural input*; *Sound-based input / output*; • **Applied computing** → **Performing arts**; *Sound and music computing*.

KEYWORDS

Design, wearables, knit, fabric sensors, biosignals, music performance, electromyography, singing

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1 INTRODUCTION

Multi-electrode systems have become common platforms for HCI [9, 38]. Bio-signals collected at multiple body locations are used in bio-feedback systems for behavior regulation [37] and improved understanding of our own bodies [30]. They are also used to reconstruct gestures [53] and poses [38] provide a supplementary channel to influence artistic performances [36, 67, 72]. Multi-electrode muscle stimulation can create complex physical motion as output in interactive systems [46].

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[*] As of the time of publication, the author is now also affiliated with the Max Planck Institute for Informatics in Saarbrücken, Germany

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While such systems have shown great promise in multiple areas of HCI, they face a multitude of problems in real world settings. Securing multiple electrodes to the body often results in skin irritations and general discomfort [38]. As users move, electrodes may come losoe or cables might be caught, leading to reduced functionality [38]. Deploying such systems is difficult, often requiring help from an additional person to be able to wear them correctly [18, 38]. Finally, many of these systems do not have an aesthetic which might allow them to be worn without the user drawing attention to themselves [38, 40, 41].

In this paper we present *Singing Knit*, a soft wearable multi-electrode EMG-collar, which is used for augmenting human vocal performances. In its design, we address these issues of comfort, function, deployability, and aesthetics. *Singing Knit* is a system which allows augmenting vocal performances, with one's own voice, as originally demonstrated by Reed and McPherson [66]. When wearing *Singing Knit*, muscle activation involved in breathing and singing is captured. These signals can be used to provide feedback to better understand one's own singing practice. *Singing Knit* can be used as a teaching tool to support the communication between student and teacher, or as an augmentation device, allowing the singer to digitally enhance their voice in real time, or use their muscular movements as a controller by using the bio-signals to continuously adjust parameters of vocal filters or modulation. In all of these contexts, the collar presents vocal-performance friendly setup which can be comfortably worn and used by a singer with minimal assistance from others or existing knowledge of the electrical components. *Singing Knit* was created specifically to improve a system originally presented by Reed and McPherson [66]. We use this system to highlight general problems with multi-electrode systems by means of concrete examples.

The contributions of this paper are (a) *Singing Knit*, a prototype wearable Vocal EMG collar, (b) the design process of adapting a multi-electrode system into a single wearable garment, highlighting design features such as ribbing patterns for tactile feedback and stitching techniques for ensuring appropriate elasticity and (c) open source modular PCBs for local EMG signal processing, designed for easy integration into fabric materials, and (d) the use of an earring as reference electrode. Together these contributions expand the state of the art in the design of wearable multi-electrode systems.

2 RELATED WORK

Here we first present examples of multi-electrode systems, before looking at knit interactive textiles. Finally, we discuss issues specific to using EMG in performance context. This will be followed by an analysis of problems with existing multi-electrodes systems using an existing vocal EMG device as case study.

2.1 Multi-electrode Wearables

The oldest use of multi-electrode systems is most likely in surface electromyography (sEMG[1]). EMG is used to measure neural muscular activations from the surface of the skin using electrodes. This has found a broad range of applications related to HCI [32]. For example, bio-feedback systems have been designed to support physical therapy [25, 45, 83] or to simply provide users with additional insights on the actions they are performing [30]. Other uses include EMG for identifying gestures [53], for example to be used as explicit computer input [3, 4, 42, 81] or robotic control [35].

Multi-electrode systems are not constrained to measuring body activity, but through electrical muscle stimulation (EMS) might also induce body activity. In the HCI literature, such systems have been suggested for improved learning [76], communicating information to users through their own movement [46], or simulating virtual objects [47]. More recently, a number of systems have interleaved sensing and actuation in such multi-electrode devices. For example, Nishida et al. presented a system designed to support users sharing kinesthetic experiences [54], while Knibbe et al. designed a device which can be used to record and play back movements [39].

While often not explicitly discussed, applying such devices is one of the main hurdles in their deployment. For example, the system used by Hassab et al. to explore embodied emotion required ∼ 60 minutes to deploy [18]. Similar limitations were also reported with initial prototypes used by Knibbe et al. [39]. Generic multi-electrode systems have been proposed, including the MYO as a prominent (discontinued) product, or Zap++ [9], however, these are not flexible enough to support the requirements of the *Singing Knit* or most of the systems described in this literature review. In practice, most custom applications require custom layouts [55].

Case-studies of creating devices based on such custom designs do exist, typically incorporating multiple electrodes into a single garment [38]. However, just as many of the multi-electrode devices do not generalize well. Here too it is unclear how to generalize to other applications or body parts. To add to the existing body of knowledge, we therefore present a case study of a throat-worn multi-electrode device: we share the design process of *Singing Knit*. While the *Singing Knit* is not currently designed for use with EMS, the design lessons generalize, as EMS and EMG systems underlie similar constraints.

Soft-sensors for EMG have been increasing in popularity for wearable designs and the use of body and gestural information in interaction. Textile electrodes [1] and embroidered electrodes [69] have been used for flexibility and comfort in wearables for communication of biosignals for health application. Additionally, soft EMG electrodes have been employed in body extensions for social interactions, where they are used in combination with other sensors on the body to convey and exaggerate gestures for emotional communication settings [16, 17].

2.2 Knit Structures & Soft Wearables

Finding materials and manufacturing methods to create elastic, flexible, and soft devices in place of traditional rigid electronic components has a long tradition. An early example of such work in the textile area was presented by Orth and Post over 25 years ago in the form of embroidered capacitive touch sensors [64]. With work like the *Kit-Of-No-Parts* [59] and many other accessible projects, the High-Low tech group at the MIT Media Lab highlighted how anyone might create electrically functional garments. For the last 10 years, the world has seen hobbyists and researchers alike, for

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[1] Existing computer science and HCI literature typically does not draw a distinction between sEMG and EMG, for the rest of the paper we will use EMG.

example Limor [12] and Becky Stern [73], augment their garments with sensors and actuators [70].

More recent work has explored how to deeply integrate electrical functionality into textiles and garments. Rather than attaching functional objects to a soft structure, the soft structure itself might become functional. This might be achieved by the use of functional dyes [21], or by weaving or knitting fabric or clothing consisting of multi-material yarns [22, 60]. Such multi-material fabrication enables creating devices with integrated sensors [48, 52] as well as detailed characterization of interaction between textile design and sensor performance [84, 85]. For example, depending on knitting configuration used, one might measure pressure [65] or stretch [2, 44].

When the electrical device is so intimately linked with the garment, the design of the textiles structure itself becomes relevant for its function [14]. Custom design of textile structure was explored by Hofmann et al., who designed programmatic ways of controlling [19] and designing for digital knitting machines [20], supporting designers to implement custom material properties. This enables creating custom garments, where material properties such as texture or elasticity can be fine-tuned dynamically [28, 34]. Such material properties are essential for chronic deployment of wearable systems [24] both with regards to maintaining electrical functionality [23] and user comfort [38].

While most wearable multi-electrode systems are deployed on the limbs, *Singing Knit* is worn around the throat. This area is especially sensitive to pressure, so finding a garment which is both snug enough to maintain good electrode contact, while loose enough to not provide an experience of strangulation, is challenging. In the case study of *Singing Knit*, we show how we address this issue with a machine knit, and how this knit also guides the integration of electrical conductors in a way which minimizes strain.

2.3 Wearables & EMG in Performance

Art and Performance has been a strong driving factor in the development of both wearable and multi-electrode systems. Prominent early examples are the electrical fashion of Diane Dew [27] and the performance art of Stelarc [72]. Within HCI research, art (particularly music) has also played a strong role in the development of these research areas. Amongst the first embroidered electronics developed by Orth was a jacket that served as a music-controller [58] and a set of soft musical instruments [57]. Similar themes can be found in recent explorations of New Instruments, exploring the use of soft materials for performing [8, 11], and wearable devices for creating [74] or conducting [13] music. Work in EMS and EMG is often motivated around music performance. EMS [76] and EMG [33] are often used with the intention of supporting learning of musical instruments or improving the expressiveness of existing instruments [31, 36].

EMG in particular has garnered interest for artistic performance due the highly responsive yet noisy quality of the signals [79], which can offer simultaneous elements of control by the user and ambiguity in interaction [10, 67]. EMG can offer interesting interaction perspectives as the sensing is responsive to movement from both intended and unintended gestures and can be thought of as an "input" to movement or action [77]; the neural activations measured are a precursor to action and can still be measured without the presence of any visible resulting movement. There are many examples of EMG applications in qualitative artistic applications where the muscular activations are sonified or used as parameters to manipulate interactive sound design. EMG has been used in an extensive body of biosignal feedback and musical interaction work by artists and researchers such as Tanaka [77–79], Donnarumma [7], Jensenius [26, 56], and Martin [50]. Pamela Z [86] has created several custom wearables for EMG-based interaction in live performance; however, the other examples mentioned here utilize the MYO armbands, which are now discontinued but were previously the main commercially available EMG wearable.

In terms of deployability, the result is that EMG interactions are often limited to wear on the arms. This would not be applicable for measuring the muscular activation of the laryngeal muscles, so further vocal EMG systems have been created by [29] and [66]. We here focus on the measurement of vocal EMG signals: the feasibility and application of EMG in capturing muscular activations from the laryngeal muscles active in speech [29] and singing [66] has allowed researchers to examine the movement of these muscles, which are normally not visible. This distinguishes EMG from other biosignals in measuring gesture and interaction during singing. Where movements are more subtle and unnoticed by an observer or even the singer themselves, EMG has been found to provide suitable access to observing and interacting with laryngeal activations in creative performance [67]. With *Singing Knit* we present a system designed specifically for wearability in a performance context.

2.4 Design Goals for the *Singing Knit*

To improve our understanding of how integrated, wearable multi-electrode systems might be designed and how existing systems using individual electrodes might be implemented as integrated systems, we present the design process of *Singing Knit* as a case study. *Singing Knit* is a device that uses EMG for augmentation of vocal performances. It is a redesign of an open-source system originally presented by Reed and McPherson [66, 67]. A unique property of this system which makes it particularly interesting for this type of case study is that all electrodes are connected on and around the throat. The sensitivity of its body location provides additional challenges not considered in previous case studies on wearability [24, 38] or multi-electrode systems [9].

The system presented by Reed and McPherson used gold-plated silver electrodes secured to laryngeal muscles, namely the omohyoids [66] and the suprahyoid muscle groups. The electrodes were secured through conductive adhesive paste and are taped down on the neck to prevent movement. They are then connected to a pre-amplification circuit on a nearby table. The setup is effective in capturing the laryngeal activation and was used in improvisatory performance and an autoethnographic study of interaction with the body and muscular movements as they are mapped to sound [67]. However, the setup requires the wearer to work around a number of wearability and deployment issues, which make the system difficult to use in a performance context. The existing system was primarily used in lab-like settings, which do not require the user to move around or perform exerting tasks.

With the *Singing Knit* we intend to improve various aspects of the system, improving comfort, functionality, deployability, and aesthetics:

1) Comfort: The rigid cup electrodes used by Reed and McPherson must be attached securely to ensure consistent measurement, often for hours at a time. As a result, there can be irritation, especially to the sensitive skin of the neck from prolonged contact with the conductive paste, which can cause dry skin, as well as from the adhesive medical fabric tape, which causes mechanical stress to the skin as the performer moves, pulling on sensitive skin and vellus hair. For a professional musician, who might have a multiple hour long performance, or perform multiple events per week, this unnecessary discomfort is not sustainable. **We therefore aim to use conductive fabrics as an alternative to rigid, discrete electrodes, creating a garment with the comfort of a normal piece of clothing.**

2) Functionality: Taped electrodes are not only unpleasant, but – much like commercial fabric electrodes – also fragile, frequently peeling off during prolonged wear. This is especially of concern in musical performance settings, where the problem is further exacerbated due to the sweating caused by the exertion of performing and the high temperatures a performer might encounter while working under stage lighting. Gravity also works against the electrode placement in some of the examined muscles, particularly those under the jaw. It is therefore common for the electrodes to fall off or need to be re-positioned by the wearer. This requires time to do accurately and is not feasible in a performance context.

Additionally, the system by Reed and McPherson relies on an amplification circuit which is not wearable. This means that the performer must restrict their movement to accommodate the wiring of the system. Disturbing the connections can lead to either disconnection of an element of the electronics or introduction of noise into the system. Longer cables might improve the range of motion of the performer, but lead to signal degradation. This is a further risk to the functionality of the system in the context of live performance. **We therefore aim to design a wearable which is robust, even under extreme conditions. The system should support performers to move freely while performing, without worry of signal degradation or electrode failures.**

3) Deployability: The problem of lacking robustness is further amplified by how difficult it is to apply the system. Attaching an electrode requires searching for the correct placement through self-palpation on the muscle, then placing the electrode at the correct location before taping it down. Sometimes it is of advantage to mark the location with a pen, to ensure that the electrode is not inadvertently moved while affixing it. At a minimum, this process requires experience and training as well as access to a well-lit mirror. Ideally, it requires assistance from another person.

Lengthy setup times prevents changes mid-set, and add an additional level of complexity to activities such as sound-checking and general setup for performances. It essentially eliminates the ability for any spontaneous performances, and is prohibitive for quick sets. These problems are especially problematic for solo performers. **We therefore aim to design a system which is both easy to put on and take off and keeps the electrodes in the correct position. Additionally, it should be easy for the wearer to easily confirm the placement of the electrodes is correct.**

4) Aesthetics: In performances by Reed [49] the electrodes are clearly visible. In the context of Reed's performances, revealing the technology in this way is desirable as the performance is not only about the music but also about new technologies for musical expression. However, this may not be the case for all performers. Based on context the display of technology and the medical appearance of the electrodes my not be desirable. Many musical artists use very elaborate costuming in their performance and this system should aim to act synergetically to such efforts, much as an additional piece of clothing would. **Our goal is thus to further align the use of biosignals and physiological sensors within artistic, specifically musical, applications and create a garment implementation which can be incorporated into all types of existing artistic culture and practices.**

3 DESIGN PROCESS

The core team of this project consisted of researchers with a background in music technology and bio-sensing. To address the above design goals, a textile design expert was added to the team. The first activity was familiarizing the textile designer with the required physiological background, and for the textile designer to share initial ideas of what a textile solution might. Then, creation of the knit collar involved four main design activities: selecting a knit to use for the body of the collar, selecting an appropriate conductive fabric for electrodes, determining a way to host the EMG signal acquisition on the wearable itself, and designing the reference electrode.

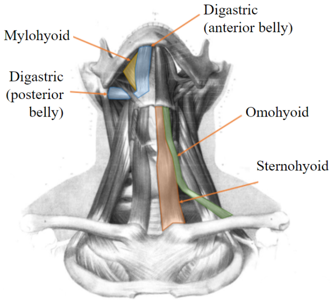
3.1 Sharing Competencies

Singing Knit is intended to measure the electrical activity of the 4 pairs of largest extrinsic laryngeal muscles (8 muscles total, on either side of the neck, Figure 2). These pairs of muscles, active during singing, became the focus for interaction (Figure 2a). Larger muscles provide stronger, cleaner signals and are easier to identify through self-palpation of the throat, making placement of the electrodes easier. The muscles include symmetrical muscular pairs: two suprahyoid pairs, the mylohyoid and digastric (anterior belly) muscles and two infrahyoid pairs, the omohyoid and sternohyoid muscles (Figure 2a). The suprahyoid (above the hyoid bone) muscles lie beneath the chin and work to elevate the larynx. They are also active in moving the floor of the mouth and the tongue. The infrahyoid muscles (below the hyoid bone), depress the larynx, giving a lower fundamental frequency to the voice and assisting in articulation.

After familiarizing themselves with the above background, the textile designer suggested that a knit structure might be a useful candidate to explore, and created several sketches, an excerpt of which are shown in Figure 2b.

3.2 Selecting Knit

We use a knit collar to provide the right structure for the wearable; using a knit garment provides a balance between comfort and sturdiness to house the conductive electrodes. The base knit body for the collar can be constructed from different knitting techniques,



	Muscle	General Function
Suprahyoid Muscles	Mylohyoid	Elevates the floor of the mouth, active in consonant articulation and jaw movement
	Digastric (anterior belly)	Raises the hyoid bone and the larynx, increases supraglottal pressure to generate higher pitches, move the tongue up and forward
Infrahyoid Muscles	Sternohyoid	Lowers the larynx for producing lower pitch, tilting the hyoid for articulations
	Omohyoid	Similar to the sternohyoid, a laryngeal depressor

(a) The laryngeal muscles measured by the collar (adapted from image available in the public domain, retrieved from Flickr: https://flic.kr/p/uKQ8eb) and their function in speech and singing [15].

(b) Sketching potential structures for the collar.

Figure 2: Initial design planning for the vocal collar, matching the garment's structure to fit the muscles being measured.

each resulting in slightly different textile properties regarding elasticity, robustness, and volume. An appropriate structure to be worn around the neck, providing enough elasticity to be pulled above the head, as well as sitting tight around the neck are double bedded ribs. This knit structure is often found in high collared turtleneck jumpers or ribbed hems - the places on a garment where maximum stretch is required when put on and enough grip and fit when worn. The throat is a vulnerable part of the body, meaning that the fit of the device cannot be too tight, although beneficial to the contact between the skin and the electrodes. Unlike other EMG wearables [38], the fit cannot simply be designed to be as snug as possible. We therefore opt for the elasticity of a knit garment compared to other woven fabric materials, which do not offer the same flexibility. The garment must be tight enough to ensure contact but also flexible to provide comfort, to protect the wearer's neck, and to not restrict head movement.

Several double-bedded knit structures were created and examined for different amounts of stretch and shape related robustness. Amongst these structures created are two Milano Rib variations (Figure3a and b), a 2x3 rib (Figure 3c), and a two variations on a 1x1 or full bed rib stitches (Figure 3d and e). The difference between these rib variations are characteristics in their stretchability, rolling of fabric sides, and volume. These differences have, amongst other factors, determined the use cases of different double bedded knit structures. For example, Milano Rib has commonly been used as a structure for Jaquard patterns; 1x1 ribs for smoother knit surfaces; and larger ribs like 2x3, 3x4, etc. for soft, voluminous accessories like bonnets. The technical differences of these structures consist of the arrangements of needles on the knitting machine: the numbers in the rib types indicate how many needles are knitted in each needle bed, in an alternating manner. The Milano Rib is in this sense a 1x1 rib with added rows on only one side, making it unique from the other rib structures.

3.2.1 Yarn & Gauge. Several knit swatches were created to test both the feel and stretch of the knit. The yarn composition used to create the knit probes is a Merino extra-fine Nm 30/2[2] yarn - a high quality sheep's wool yarn. Two strands of the yarn were used to produce the samples presented here. The thickness and weight, as well as twist of the yarn further determine the gauge range that can be produced. All probes, as well as the final collar piece, were knitted on an industrial mechanical hand-flat double bedded knitting machine (Dubied) in gauge E7[3].

Figure 3: Samples of different knit structures for the collar body. Three Milano rib variations (a, b) were compared to a 2x3 rib (c) and two full bed rib stitches (d, e).

3.2.2 Stretch Behaviour. The stretchability was the most critical element to examine for each knit. As the collar must be held tight enough to hold the electrodes in place, yet not as tight as to cause discomfort to the wearer. With the Milano Ribs displaying the most robust surface, they offered the least movement when pulled. Additionally, adjusting the stitch length of the structure with the alternating rows, this structure proved most error-prone in fabrication, with either being too loose or too tight. The other two knits, as expected, outperformed the Milano Ribs. They offered a more elastic fit overall, although the different rib sizes showed differences. Generally, the larger the ribs are, the more loosely they fit and the quicker they wear out. After examining the different swatches in terms of their stretchability, rolling, and optics, the most suitable option in all factors was to use a full rib, or 1x1 rib stitch. Most importantly, the knit provides a suitable balance in its

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[2] Labelling yarn in a Metric (Nm) system reports the weight and twist of it. In our case, it is double twisted and requires 30 meters to weigh 1 gram.

[3] Referring to the distribution of knitting needles per inch (in our case, 7 needles spread across one inch on the knitting machine.)

stretch, meaning the swatch feels secure when wrapped around the neck but in a way similar to a turtleneck sweater.

3.2.3 Relief Stripes to Highlight Muscle Locations. Although affixing electrodes directly onto the skin using adhesive paste is not ideal in terms of practical wear and movement, the visual cues this approach provides are valuable for exact positioning and locating of the muscles. To preserve this characteristic, an additional structural feature was embedded: a needle transfer pattern, where selected stitches are transferred from one needle bed to the other, excluding the now empty needle from use. This creates a relief structure, or inset (Figure 4), that is visible on one side of the knit fabric. Therefore, when integrated at the exact position of the electrodes, the wearer has instant visual and haptic information and can move the collar in place. Figure 5 shows these effects on the final collar (left), where the relief stripes' end points represent the positions of the electrodes.

Figure 4: Samples of different rib structures added to the full-knit to provide indication of electrode sites.

Figure 5: The ribbing added to the collar body, providing a visual for the muscles and electrodes situated on the inside of the collar.

3.3 Replacing Traditional Electrodes

Several textile materials were examined as replacements for the cup-electrodes used in the original design. The materials examined were chosen to match the collar's body; they also consist of flexible knits. We compared 5 knit conductive materials - two single-bed jersey fabrics and two double-bedded metal mesh fabrics, and one conductive foam. The conductive foam features a knitted backing and so the feel of the pad is similar to the jersey fabrics. We created a set of electrode swatches (Figure 6) for testing the materials. The materials were compared against the same rigid gold-plated silver cup electrodes (MediMaxTech, New Malden, UK) used in the setup presented by Reed and McPherson [66, 67]. For each material, a 1 cm^2 "electrode" was used for appropriate comparison to the same size cup electrode. The conductive fabric electrodes were stitched into a small knit body, similar to how they would be attached to the full collar, with the appropriate spacing to be worn and tested on the left omohyoid muscle on the lower neck. A highly conductive silvered copper yarn (Karl Grimm) [68] was used to provide a connection to the fabric pads. The swatch was secured to the neck using an elastic band, as if they were part of the full collar wrapped around the neck. The swatches were worn to test if the conduction was appropriate to replace the traditional electrodes, and to test comfort and feel against the skin.

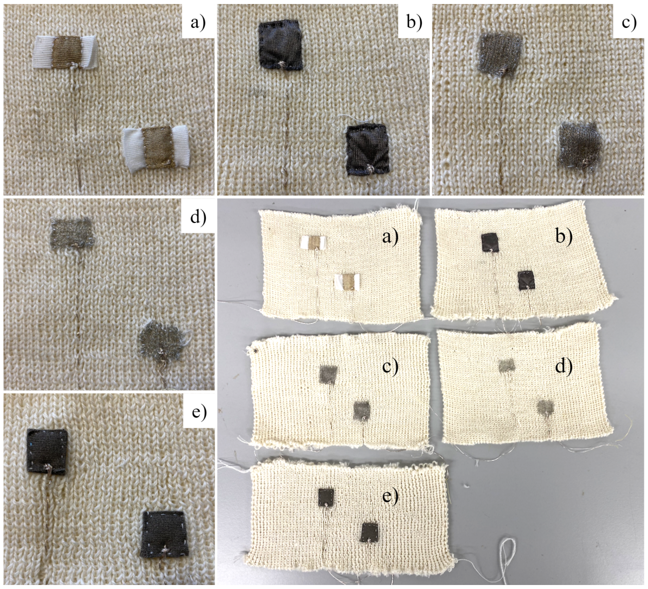


Figure 6: Swatches with stitched, soft fabric electrode probes for comparing materials. In order: a) silver-plated nylon zebra jersey, b) silver-plated jersey, c) tin-coated canopy mesh fabric, d) stainless steel mesh fabric, e) RayPad foam cushion.

The resistance across the 1 cm^2 pad was measured using a multimeter. All the materials tested had similar resistance to the cup electrode (0.6 Ω), with the exception of the foam. Overall, the density of the foam lead to a higher resistance (1.4 Ω). The two double-bedded knits had a similar resistance to the cup electrode, 0.6 Ω for the tin and 0.7 Ω for the stainless-steel fabric (Table 1).

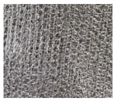
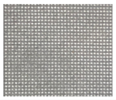
		Resistance (Ω) (1 cm^2 sample)	Amplitude (mV)
 (2).png	Gold-plated silver cup electrode (MediMaxTech)	0.6	320
	Silver-plated nylon zebra jersey (HITEK)	0.8	220
	Silver-plated nylon jersey (LessEMF)	0.8	220
	Tin-coated canopy mesh fabric (LessEMF)	0.6	80
	Stainless steel mesh fabric (LessEMF)	0.7	80
	RayPad foam cushion (LessEMF)	1.4	260

Table 1: The conductive materials examined, approximate resistances and the average amplitudes of the output muscular activation signal through the VoxEMG board in the test singing exercise for each material.

To test the electrodes in context, the swatches were used in a singing task, where Reed checked the activation of the omohyoid by singing a low note in her vocal register (G3). The signal was passed through the VoxEMG board and the amplitude of the muscular activation captured was measured with an oscilloscope. She performed this task a number of times, singing the pitch with a tuner to ensure as much consistency as possible. The average peak-to-peak amplitude of the signal conveyed is listed in Table 1. All materials conveyed a usable signal in an amplitude range similar to the rigid electrode, with the exception of the metal mesh fabrics. This difference for the meshes may be the result of the difficulty in wearing in this small electrode-sized piece, which is discussed in the following sections about the qualitative properties of the fabrics.

3.3.1 Single Jerseys. The two single jersey (one-bedded knit) fabrics examined, a gold-colored zebra jersey (Hitek) [51] and a grey stretch conductive fabric (LessEMF) [43], are both made from silver-plated nylon yarn but of different weights. In comparison, the grey jersey was the heavier fabric (150g/m^2). It also has a slippery surface due to a slightly higher percentage of elastane than the zebra fabric (128g/m^2). Due to the elastane content and slippery feel of the grey jersey, the fabric can have a variable resistance when integrated into the knit collar body, as some of the material comes in and out of contact with the skin, or shift during stretching of the base material. The zebra jersey is most easily attached to the main collar body with a smooth surface, yet non-slippery grip; particularly because it is striped with non-conductive fabric, it is possible for a larger area of material to be secured while keeping the conductive surface restricted to a 1 cm^2 space. The non-conductive fabric stripes can be stitched into the base material, leaving an even contact across the conductive space in between.

3.3.2 Double Bedded Knits. The double-bedded knits examined were a light grey, tin-coated copper canopy mesh (Less EMF) and a dark grey stainless-steel mesh (Less EMF). Two different ribs were cut in shape and compared: one interlock 1x1 rib, and one 2x1 rib. Both are significantly heavier fabrics than the single jerseys (both around 190g/m^2). Although these are most similar to the cup electrodes in terms of their conductivity, the wear on the skin makes them unsuitable to replace the electrodes. When cut into the needed electrode size, the fabric becomes uncomfortable, especially on the sensitive skin of the neck. Additionally, on integration into the knit body, the mesh structure remains too rigid, leaving space between the electrode and the body of the collar, rather than the two materials feeling as one garment. Because of this space, there can be too much movement between the conductive fabric and the knit, causing the resistance to be variable depending on how tight the collar is. With the scratchy electrodes, the collar cannot be held too tight around the neck, which increases this variability in the resistance.

3.3.3 Foam. The thickest and heaviest material tested in our samples is RayPad conductive polyurethane foam (Less EMF) with nickel and copper elements. Although not a fully knit material, the foam pad is covered by a knitted material and offers additional tactile information to the wearer through pressure on the skin. Its disadvantage, however, is that it is compressed slightly when stitched to the base fabric. This can cause a discrepancy in resistance when further compressed against the skin during wear. Additionally, the thickness of the pad creates extra space between the collar and the skin. The body of the collar needs to be tight to keep it secure in the case of using foam, this results in the foam being always "pressed." This creates an interesting tactile interaction, where the wearer can easily feel pressure at the electrode site and sense where the connection to the fabric is being made. This may offer an interesting affordance to provide attention to the wearer about certain parts of the body. In this sense, a similar non-conductive foam may be beneficial to give the wearer more information about the presence of the garment on their body.

The two single jerseys provided the best compromise between the conductive materials. They are only slightly more resistive than the cup electrode (0.8 Ω for both) and are able to convey a useable signal in a similar amplitude range to the rigid electrodes because they maintain consistent resistances. They have the most comfortable feel as well, and are less distinguishable from the rest of the collar than the other three materials. The zebra jersey provides the best balance of qualities amongst those examined. It is the easiest to integrate and secure into the knit material and provides suitable contact with the skin which does not shift during wear, due to having less elastane than the grey jersey.

New electrodes were cut and sitched into the knit body of the collar. The collar was knit into the desired shape and size, so no waste material was created, and no post-fabrication cutting was required. The electrodes were then stitched into the collar at the dedicated points; on the outward-facing side of the garment, the ribbing was alternated to mark the location of each pair of electrodes (Figure 1).

3.4 On-Board Signal Acquisition

We designed a custom open source PCB implementation of the amplifier circuit, designed specifically for integration into wearables for on-board processing. It was decided that the PCB should be versatile, to use it in this work and also provide a platform for others wishing to incorporate EMG into their wearables. Therefore, we offer different connection types for the signal input (both traditional connectors or fabric integrations), and ensure that the PCB is as small as possible, to be easily fitted into a garment without adding bulk or distraction in the design.

The resulting VoxEMG PCB[4] measures 3.6 x 3.15 cm, ensuring compact integration for prototyping. The board offers fine precision resistance tuning, which provides further CMR at -54.06 dB for the EMG signal frequency range. The board features header connectors for integration into other electronics, as well as castellated holes for connection with textiles. The castellated inputs were adapted from designs for the Bela E-textile Capelet [75, 80] for Innovate UK. Additionally, loops were added to either side of the board so that it could be affixed into a garment.

The VoxEMG boards were secured to the back of the collar using loops in the PCBs, added for affixing the board to a fabric element. By stitching the loops to the collar between rows of knit underneath of the board itself, some allowance for the rigid PCB is made to keep the collar stretchable. If the garment is stretched (Figure 7), the board will not be pulled from the collar and the knit underneath will be able to expand fully. The wired connections were then stitched between the board and the electrode pads; as seen in Figure 7, the conductive thread is able to be wrapped around the castellated hole inputs at the top of the VoxEMG boards.

The conductive thread was then stitched by hand along the knit itself (Figure 8); rather than stitching straight across from the electrodes to the boards, this allows the conductive thread to move with the knit. In a sense, the knit has been restitched and so the traces take on the same elastic properties as the rest of the knit. This ensures the conductive thread will not break if the collar is stretched or pulled to the knit body's maximum displacement.

The traces were added after the creation of the knit because we used an industrial handflat machine to create the collar body. Adding the conductive thread, in the manner described, ensures that it does not impact the overall knit structure, which would result from additional conductive yarn added by means of conventional sitching or sewing. Rather, the thread is integrated with the garment seamlessly and maintains the characteristics of the full rib. In addition, this method is easier to employ during the prototyping process, as it separates the components in a way where it is easier to correct or modify the design or layout of the traces as needed, without re-knitting the entire collar.

3.5 Wearable Reference Electrode

The last piece of design was in the construction of an aesthetically appropriate and easy-to-affix reference electrode. Previously, the electrode had been glued to the earlobe using medical tape. Rather than just securing a fabric electrode to the ear as a replacement, we continued the pursuit of wearables and stage-appropriate costuming replacements and constructed a reference electrode earring.

The reference electrode is made using generic a clip-on earring. The electrode was constructed first by creating a "knit" cable, to give the connection a feeling of being a part of the wearable collar [61, 62]. This was done by threading an insulated wire through a piece of cording [63]. The end of the wire is stripped and folded over to make a hoop, through which conductive thread is tied and wound (Figure 9a). The clip-on earring came with a soft silicon pad to be inserted into the back side of the clip and hold the earring against the wearer's ear without discomfort (Figure 9b). The conductive thread was used to stitch another 1 cm^2 fabric electrode, made of the same zebra fabric as the collar's electrodes, directly into the soft silicon (Figure 9c). This provides connection to the pad and insulation for the connection otherwise. The other end of the "knit" cable was connected to an alligator clip, which could then be secured to a conductive thread knot, which was stitched into the edge of the collar (Figure 9d), leading to the reference inputs of each of the VoxEMG boards (they are able to use the same reference). An alligator clip was used to ensure that the electrode could be easily attached after putting on the knit collar.

The final reference electrode earring is pictured in (Figure 9e). The ends of the cording were burned to prevent fraying. It can be seen that the electrode provides appropriate aesthetics as a piece of costuming, blending in with the other earrings worn normally by Reed (Figure 9f, 9g). The clip-on ensures that anyone could wear it on their earlobe; as well, a different style of clip-on earring could be used, or indeed other types of ear jewelry, such as a cuff to be worn on the upper helix of the ear.

4 FINAL DESIGN

The final version of the wearable collar is pictured in Figure 10, with the soft electrodes stitched into the flat, neck-facing side in the measured positions, and the alternated ribbing patterns in the outward-facing side, providing the location of the electrodes beneath. Additional elastic has been added to the top of the inside to ensure that the knit remains in place around the jaw when worn.

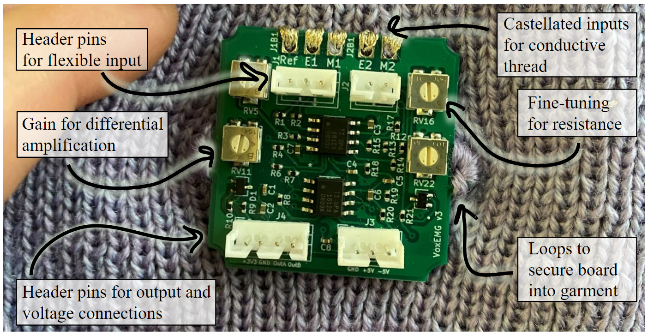


Figure 7: The VoxEMG board secured into the back of the collar.

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[4] https://github.com/courtcourtaney/voxEMG

Figure 8: The conductive thread stitched along the knit, connecting the electrode pads to the board inputs (top). When stretched, the conductive traces stretch with the knit (bottom).

As well, the ear straps hold the collar up and prevent it from folding over or moving around while on the neck (Figure 10). A set of buttons and elastic loops at the ends of the open piece close the two ends together after the collar is around the wearer's neck. This makes it easy for the wearer to put the collar on by themselves. Once on, the ribbing in the front of the collar allows the wearer to check that the electrodes align with the muscles, which can be felt beneath the fabric. For the top pair of VoxEMG boards on the back of the collar, the cables were tucked into the folds, which were stitched down at the top and bottom except for a small hole through which the cables could be passed through.

The final version of *Singing Knit* (Figure 11) was tested by Reed for suitability in recording signals as done previously with rigid cup electrodes. Testing was done first qualitatively by Reed in aspects of wearability, and also in a quantitative comparison between the signal conveyed by the traditional electrode setup and the fabric electrodes in the collar. For a qualitative evaluation, Reed wore the collar for two hours while moving around her home to assess the feel in lengthy wear. While wearing the collar, she was able to move normally and the knit stayed in position. They felt that the knit was comfortable and could have been even a bit tighter, if needed, as the fabric stretched easily. The ribbing was especially beneficial for preventing slippage of *Singing Knit*, as the wearer is easily able to check whether the knit is in the right place on the neck and reassure themselves of the placements. The ear straps however were able to keep the collar in place and prevented any shifting. In further musical interaction, Reed was able to recreate qualitative examples of use with the collar, for instance in visualising particular vocal muscle movements as done in [66] or sonic interactions with the vocal muscles as in [67].

Additionally, the output signal of the stitched fabric electrodes were compared with that of the original, rigid electrode setup. The goal was to determine whether the collar was able to detect the activation of the muscle faithfully compared to the rigid electrode setup. As determined during material selection, the resistance and amplitude of the signal conveyed through the materials were comparable. To check the final design, Reed performed the same exercise again, measuring the signal of the omohyoid activation when singing a low note in her vocal register (G3), first with the rigid electrode setup and then wearing the final collar. The onsets of the signals generated during this exercise were captured and examined using an oscilloscope (Tektronix MSO 2024B). The signals are pictured in Figure 12; the traditional electrode had a peak-to-peak voltage of 340 mV, where the fabric electrodes for the same muscle gave a voltage of 300 mV. The period for both was 10 ms. As the action will never be exactly the same, there is allowance for some small difference in the signal; we see that the fabric electrodes are able to produce consistent results to that of the rigid electrode setup. In the use case by Reed, the electrodes need to be able to measure signals which can trigger and be mapped to elements of sound design; in this case, the signal can be accurately detected and would be sufficient for sound design. It should be noted however that there is slightly higher variability with fabric electrodes, which is to be expected. However, due to the live feedback one receives during performing, this variability did not prove to have any negative impact.

5 DISCUSSION

The purpose of *Singing Knit* was to to explore how an existing multi-electrode design by Reed and McPherson [66] might be modified to improve Comfort, Functionality, Deployability, and Aesthetics.

With regard to **Comfort**, the decision to use a soft knit and fabric electrodes provided a more suitable platform for the technology. We encounter knit garments constantly, making the feel of the collar something familiar and comparable to wearing another piece of clothing, namely a turtleneck sweater. By using a full rib stitch, we have captured a balance between the garment being tight enough to hold the electrodes against the skin, but not so tight as to cause discomfort to the sensitive skin of the neck or a sensation of binding around the throat. This provides an improved affordance over other, non-stretchable fabrics, which would need to be secured as tightly as possible. Additionally, the electrodes themselves were tested for feel; in using electrode pads made from a similarly knit jersey fabric, the conductive materials blend into the garment and are not noticeable within the knit body. In a performance setting, a singer would be able to move freely without the discomfort of medical tape constraining movements of the throat and neck. This prevents the irritation caused by prolonged wear.

In terms of **Functionality**, the custom open-source modular EMG PCB significantly increased the robustness of the system. Integrating the EMG sensing into the *Singing Knit* prevents noise or failures previously caused by disconnecting cables from the tethered station. The ability to directly sew the VoxEMG into the knit minimizes cable length, while sewing the cables along the knit (Figure 8) ensures that all connections have the appropriate level of elasticity. In using a stretchable knit, the collar creates a tight, secure fit; additionally, the use of elastic banding in the key trouble area for the electrode placement, the muscles under the chin,

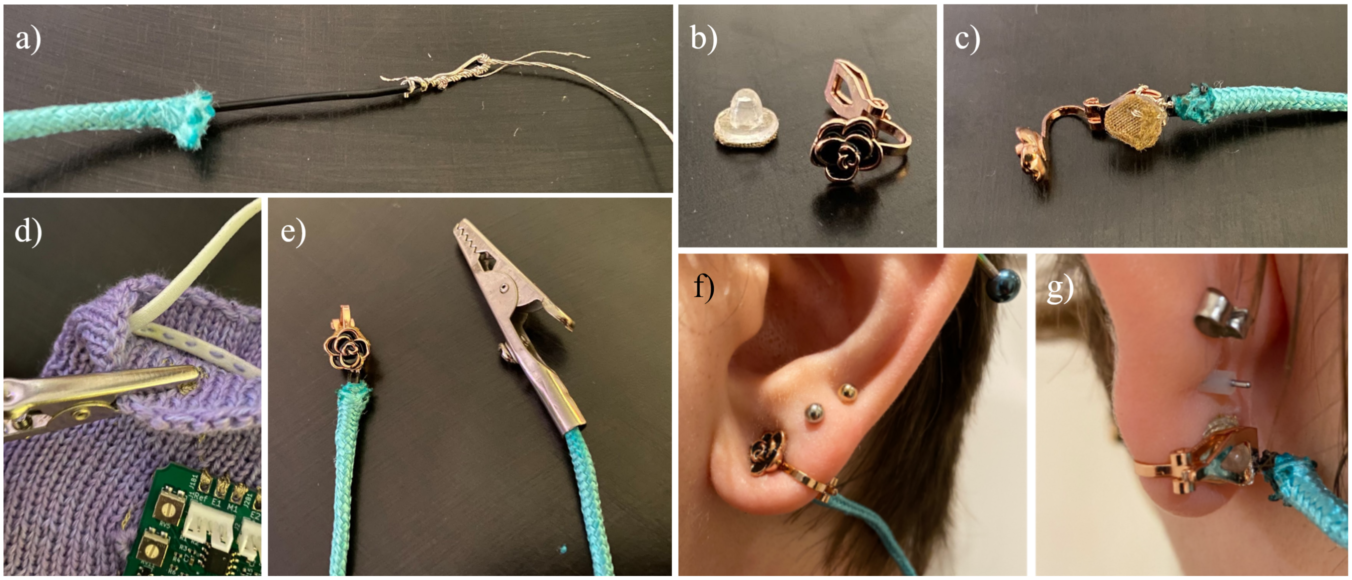

Figure 9: The construction of the earring reference electrode, starting with the cabling (a), stitching the conductive fabric to the earring pad (b-c), and securing the electrode to the collar and reference inputs (d) for a complete wearable (e). Reed wears the the electrode as part of their normal jewelry (f, g).

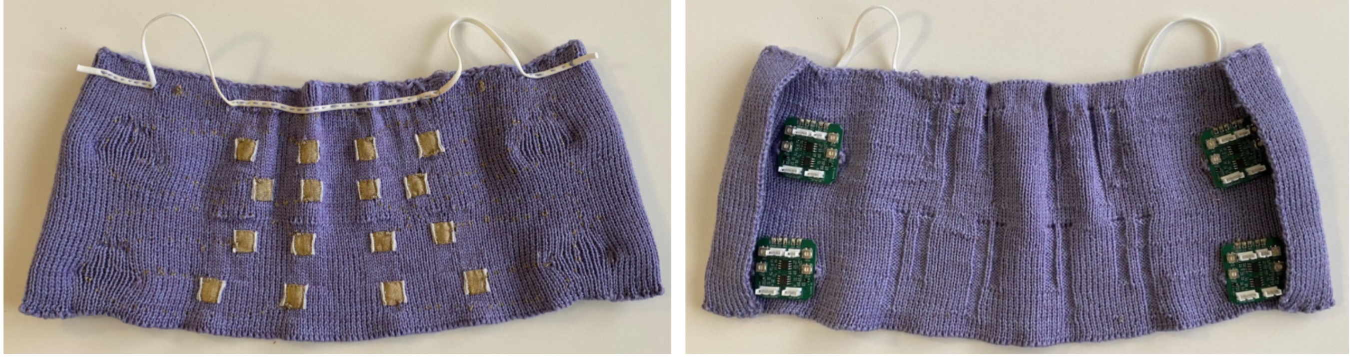

Figure 10: Amendments made to the collar: additional elastic is added to the inside of the collar to hold it up around the chin and provide support with straps around the ears (left). The excess fabric is folded over on the back to ensure a tight fit (right); these ends will be joined once the collar is on the wearer.

prevents the electrodes from falling off or the collar from slipping. This removes the requirement of using medical tape to connect electrodes, consequently the problem of electrodes disconnecting due to movement or sweat is also avoided.

Regarding **Deployability**, the use of the button-back closure means that the collar can be fit tightly and easily by the wearer alone. Further, if the wearer wishes to check the positioning of the electrodes, they can do so using the ribbing texture on the outside of the collar. The novel use of the ribbing for checking the structure on the other side of the garment allows the wearer to quickly confirm the electrodes are correct by feeling the location of the muscles through palpation with the fingers, and making sure the ribbing aligns with them. Should they not align, the *Singing Knit* can easily be adjusted, without requiring to disconnect and re-attach individual electrodes. This means that setup, and quick adjustments can easily be done on stage and without the help of another person.

Regarding **Aesthetics**, we have shown how the rather medical appearance of the original system could be transformed into something which superficially looks like an everyday garment. As long as the structural the design decisions, for instance the knit type, are maintained, there is lots of opportunity for others to further customize the design to fir their respective needs. The design can even be incorporated into a full garment, such as a knit top or other piece of costuming (see also [34]). At the same time, the design also supports the singer to further engage with their body. The collar provides external information through the ribbing construction about the anatomy of the muscles underneath.

Figure 11: Reed wearing the completed knit collar, showing the knit's form on the neck compared to the original EMG setup.

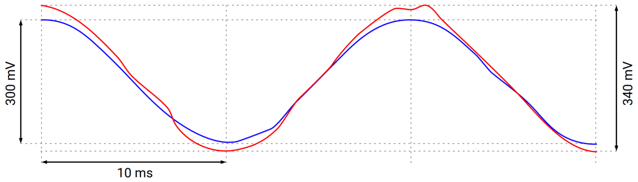

Figure 12: The vectorized signals from rigid electrode setup (red) and the fabric electrodes (blue) stitched into the collar. The signals measured are from the activation of the omohyoid during the singing exercise, as captured by the oscilloscope.

5.1 Adapting Multi-Electrode Systems

Through the adaptation process of an existing rigid sensing technology to a soft-sensing wearable, we found that the use of knit fabric to provide a sense of familiarity and flexibility (in both a literal stretchy way, and a figurative adaptable way) which we believe will be useful for other systems too. Adapting the design followed a number of steps, which we believe might generalize to other design processes: The design of *Singing Knit* started with an exchange between disciplines, with the core team exchanging their technical knowledge of EMG systems with textile design knowledge of a new team-member with a textiles and fashion background. Together, context-specific needs to be addressed through soft-sensing were identified (e.g., ease of putting on, quickly setting up, and wearing the collar for extended periods of time in vocal performance). Then it was determined which aspects of the existing system should be preserved and which should become part of the textile, to balance the sensing capabilities but increase accessibility for the target context (e.g., providing connection to and awareness of the muscles while placing the EMG outside of a medical context). Then testing was performed, both for determining suitable replacement for the traditional cup electrodes as well as for (in our case, the conductive fabrics), and for determining the structure needed to properly house the sensors on body and function in-context (the knits). Only then could the *Singing Knit* be constructed, before finally testing and comparing systems, both quantitatively in terms of sensing suitability and qualitatively in terms of aesthetic and feel, with the original sensing method.

It should be highlighted that these steps are highly iterative. For instance, the body of the collar itself began as a selection for elasticity and comfort - how to get the collar on and off the body and how to ensure that it would stay upright. After examining the suitable fabric electrodes, it was apparent that the knit structure would need to be tighter toward the front of the garment to ensure there was little-to-no movement between the different materials (to reduce the variability of the resistance). Finally, the decisions on structure changed again when re-examining what was beneficial about the traditional electrodes; in seeing and feeling where the measured points were, there was feedback regarding correct placement of the electrodes. Consequently, the ribbing of the *Singing Knit* was introduced to provide tactile feedback to the wearer on its positioning relative to their muscles. This adds a sense of transparency and understanding to a very covert, internalized bodily function. Through the iterative process and adaptation in choosing materials, we were not only able to preserve the function of the original sensing technology and address some impracticalities, but also to add to and extend its positive features.

5.2 Soft Knits for Different Bodies

The knit collar was designed as a bespoke garment for a single user. In different wearers, the muscular placement will be different, as will be the overall size and diameter of the collar itself. There is both negative and positive to using this individual design. On the negative side, the custom-made collar means that others could not effectively wear it. In addition to points of discomfort in wearing a collar which is not sized correctly, the electrodes, if not placed correctly, can end up on two different muscles or have the potential to pick up cross-talk from other nearby muscles with different activations and action potential differences. The inclusion of more electrode pads, potentially placed in an array to occupy multiple potential measurement sites [38], could allow a flexibility for different wearers' anatomy.

On the other hand, there are benefits to bespoke design and the attention given to individual bodies in design. Creating custom collars allows for individual differences, however subtle, to be taken into account and for the best possible fit to be achieved. Also, a prominent theme in vocal wearables, is the exploration of the connection of the singer to their body and their body perception [5, 6, 67, 82]. Therefore, achieving a "one-size-fits-all" collar might not be desireable, in fact it might negatively impact this theme, in masking the breadth of human body-diversity [71]. In pragmatic terms, creating bespoke vocal garments might be more reasonable than assumed, as it is already common for many elements of costuming in vocal performance settings, namely opera and musical theatre, to be custom-made for the performer. It is therefore not unreasonable to design individual wearable e-textiles for performers, given the benefits to the wearer's comfort and the biosignals captured.

6 CONCLUSION

The creation of this collar for vocal interaction involved the adaptation and converting of design using traditional sensors into embedded, knit design. We identify areas for improvement in an existing EMG-based vocal interaction and performance setup and use them to motivate the design of a wearable collar specifically for this context. In doing so, we have converted an application and design for vocal EMG using traditional sensors into one that utilizes embedded soft sensing technology. We here outline a template for converting similar existing rigid sensing methods and present a number of design aspects which will be valuable to creating other wearables.

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