Skill-Sleeves: Designing Electrode Garments for Wearability

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Figure 1: Wearable Electrode Sleeves. (1) The Calibration Sleeve; (2) the Manufacturing Sleeve; and (3) the Typing Sleeve.

ABSTRACT

Many existing explorations of wearables for HCI consider functionality first and wearability second. Typically, as the technologies, designs, and experiential understandings develop, attention can shift towards questions of deployment and wearability. To support this shift of focus we present a case study of the iterative design of electrode sleeves. We consider the design motivations and background that led to the existing, prototype EMS sleeves, and the resultant challenges around their wearability. Through our own design research practice, we seek to reveal design criteria towards the wearability of such a sleeve, and provide designs that optimise for those criteria. We contribute (1) new electrode sleeve designs, which begin to make it practicable to take EMS beyond the lab, (2) new fabrication processes that support rapid production and personalisation, and (3) reflections on criteria for wearability across new eTextile garments.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**;

KEYWORDS

Wearability; Smart Garments; eTextiles; Electric Muscle Stimulation; motor control

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1 INTRODUCTION

Currently there is a paradigm shift away from computers as something we consciously control – mostly with our hands and fingers – to computers which engage directly with our body [42]. This ranges from continuously warn physiological tracking devices [22], to interfaces that modulate their function based on cognitive load [73] or complex epidermal biometric devices [44]. Within the human-computer interaction (HCI) community, such technologies are often presented as working prototypes, with the goal of demonstrating their functionality; typically within a controlled setting. For example, Affordance++ [37] presents a powerful concept and working prototype of using electric muscle stimulation (EMS) to convey object affordances, and Cruise Control for Pedestrians [51] prototypes steering people whilst they walk. These deployments in controlled lab settings typically require expert assistance and, as such, do not easily transfer to day-to-day social life.

With the increasingly sophisticated functionality of such prototypes, however, deployment outside of laboratory settings becomes increasingly desirable. To support this, one must also consider the context in which the technology will be used. A cognitive load monitoring interface, or a device which subtly conveys additional affordances, are of little value in practice if the user cannot conveniently wear them. The effort of wearing the technology must not outweigh the benefit it provides. As such, more attention should be provided to how these technologies might practically be used in day-to-day settings – to how *wearable* they are.

We explore wearability through the iterative design of *Skill-Sleeves*. We envision Skill-Sleeves as EMS training and performance sleeves, with the ability to capture and analyze human muscle activity, and selectively adjust the activity by stimulating the required muscles. For example, a skill sleeve might help a novice pianist play polyrhythms, such as triplets with the right hand and doublets with the left hand. Alternate use cases might include helping a tennis player with the perfect top-spin, or supporting a surgeon in complex procedures. We consider this vision as an alternative to the classical concept of augmented feedback discussed in motor control theory [67] and implemented in haptic guidance devices such as Flow [19].

We present and reflect on the iterative design process of Skill-Sleeves to identify strategies and design considerations towards making complex technology easier to wear. Skill-Sleeves are an ideal candidate for such a case study. First, they require a solid mechanical and electrical connection to the body, inheriting constraints from where and how the device is to be worn. Skill-Sleeves use a large number of components, in this case electrodes, each requiring an independent electrical connection. This creates a high demand on the layout of the garment and on cable management. Finally, Skill-Sleeves are intended to support sports and other high-performance applications, which requires that they not impede movement or hamper performance in any way.

We present four designs[1], starting with the default approach – using off-the shelf electrodes, and then continuing with three implemented sleeves. With each iteration we highlight what worked well, and the constraints we met which required development of the next prototype. Finally we synthesize these reflections in design recommendations, which may act as a set of design guidelines complementary to those already present in the related work. Unlike previous explorations of wearability [12, 17], which have mostly presented top-down approaches focusing on considerations such as ergonomics [17], sensor placement strategies [80], or social factors [29], our approach is rooted in craft and practice. Therefore, the guidelines we derive are primarily focused on materials, design, and manufacturing processes as well as deployability and customization. Additionally, we share many of the insights we have collected over the course of multiple years of prototyping work.

[1] Additional documentation at https://skillsleeves.github.io/

2 RELATED WORK

2.1 Electric Muscle Stimulation

Electric Muscle Stimulation (EMS) has emerged as a popular input-output modality in HCI, affording the computer physical control of the user. This is achieved by passing small signals to the users' muscles through surface-based electrodes; stimulating muscle contractions.

Across numerous systems and studies, we are gaining an understanding of the opportunities that EMS presents, for example in conveying information ([21, 38]), working dynamically with the user to improve performance (both overtly [39, 78] and covertly [25]), and creating bidirectional channels of communication between user and machine (e.g., [36]).

To date, however, the examples we see remain predominantly conceptual, considering themes of opportunities within the space of computer-human control, as opposed to real-world, deployable systems with tangible performance gains or user experience benefits, per more traditional HCI. A primary reason for this is the difficulty in achieving fine-grained control through EMS [10, 28, 52].

EMS setups typically enable coarse, ballistic movements, around large joints [28]. Existing HCI literature focuses primarily (with a few notable exceptions, [51, 75, 78]) on stimulating the forearms and biceps, using pairs of large electrodes to drive rotations around the wrist and the elbow (e.g., [36, 55]). Research suggests, however, that more complex movement patterns (i.e., individual finger-level control) can be achieved by increasing electrode complexity [10, 28, 57, 58]. This requires rethinking our use of electrodes.

Individual electrode pads, as they are commonly available, enable quick deployment, can be easily reconfigured, and are relatively low cost. To achieve more degrees of control, researchers use multiple electrodes concurrently. For example, Lopes et al. rotate the hand up and down around the wrist with four electrodes [36] and are able to produce five different gestures using eight electrodes [37]. Even greater resolution of control can be achieved through higher numbers of electrodes and complex patterns of multi-electrode stimulation. For example, Duente et al. use 20 electrodes to stimulate finger movement [10]. However, with increasing numbers of electrodes, the benefits of individual electrodes are quickly outweighed by their problems. The time taken to peel them off the sheet, place them on the arm, connect them to the EMS device, re-place them based on a calibration step (if their location does not result in the desired movement), and continuously monitor their physical connection, does not scale to support more complex electrode arrangements [10, 28].

Table 1: Electrode Garment Design Criteria based on literature

Design Focus	Design Criteria	Associated Questions
Technology	Function	Where should an antenna be placed so that it is not shielded by the body? How can skin contact of an EMG electrode be ensured?
	Information	Where should an accelerometer be placed to collect the most information? What is the ideal location for measuring blood oxygen levels?
Sensorimotor	Psychophysical	How much attention does the device demand when worn? Does it start irritating the user after prolonged use?
	Biomechanical	Does the device inhibit the range of motion of the user? Can the user reach the device?
Human Abilities	Perception	Does the device provide output which the user can interpret?
	Reaction Time	How well can the user react to information provided by the device?
	Performance	How well can users provide explicit information to the device?
Social	Aesthetics	Does the device look visually appealing? Can the device adapt to different stylistic preferences?
	Acceptability	Does the device draw unwanted attention? What are the effects on the wearer's social image? What is the effect of the device on interactions with other people?

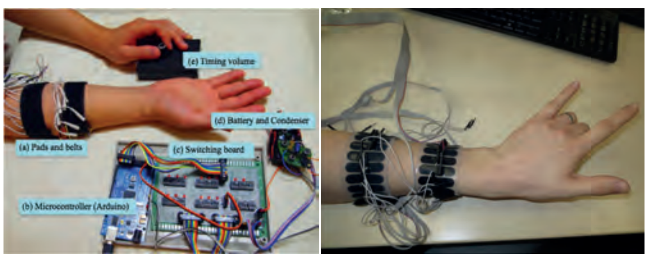

Figure 2: Tamaki et al. [75] (left) and Duente et al. [10] (right) pioneered the use of electrode bands and 'sleeves' for HCI. Their emphasis was on producing functional, high-resolution prototypes. Here, we turn our attention to the wearability of electrode sleeves.

What is needed is a simpler solution to achieve high resolution stimulation that maintains the customisability of individually placed electrodes, while optimising for more universal usability (i.e., ease of use, time taken to setup, etc.). Researchers have proposed wearable electrode arrays [10, 28, 52] in the form of garment sleeves, as one such solution. Tamaki et al. [75] and Duente et al. [10] proposed strap-based electrode 'sleeves' (Figure 2), where multiple electrodes in the form of wristbands could be wrapped around the arm. Knibbe et al. embedded electrodes throughout an existing sports sleeve, to cover the entirety of the forearm [28]. Recent advances in functional textile and tailoring methods for eTextiles create opportunities for deeply integrating such devices into garments. In this paper, we build upon the EMS literature by exploring how such integration can improve the wearability of complex body-mounted technologies.

2.2 Highly Integrated Electronic Textiles

To integrate electronic functionality into clothing, the simplest approach is to mechanically attach conventional electronics. The FLORA ecosystem (based on the Arduino Lillypad) is a prototypical example of this. It consists of rigid electronic development boards, containing microcontrollers, LEDs, vibration motors and other gadgets. These boards have holes large enough to be sewn into clothing. A resulting wearable system then consists of soft textile, adorned with rigid, functional electronics. While this design approach can be found in the bulk of today's functional garments, we are at the cusp of a trend in wearable computing to push this boundary towards offloading functionality into the fabric itself (e.g., [15, 60]).

Early on, for example, embroidery machines were used to create fabric with custom capacitive input [59]. Weaving has been used to enable the creation of photonic textiles that integrate fibre-optical light-guides as visible output [4]. Similarly, fibres with other specialized properties (e.g., piezo-resistive or piezoelectric) have also been woven [48] or knitted [56] into textiles, supporting the creation of custom behaviors.

Further customisation can be achieved by borrowing from traditional dyeing techniques such as Ikat [64], or by knitting textiles from functional [56] or multi-functional yarns [46, 56]. Chemical treatments [48] and functional dyes [6, 23] provide further options for embedding electrical functionality in textiles. For example Honnet et al. have demonstrated that fully functional circuits can be integrated in fabric by selectively etching, masking and polymerizing a material [23].

In combination, these approaches can be used to create fabric objects [3], accessories [45] and full garments [15, 16] with complex functionality. Along the same lines, the Skill Sleeve prototypes we present in this paper, utilize a variety of novel manufacturing methods to create a highly integrated electronic textile. They are heavily inspired by designs presented by Freire [15, 16]. Freire, in turn, appropriates materials and methods usually deployed in the manufacturing of sports garments and sneakers, in particular the layering and bonding of multiple materials to achieve desired functionality.

2.3 Wearability

With the advent of wearable technology, *wearability* is increasingly noted as a desirable, even necessary, property. In consequence, there is a growing body of research investigating the wearability of specific devices and wearability in general. Zeagler et al. provide a useful starting point for exploring this space [80].

Wearability is investigated from a diverse set of perspectives, including the extraction of wearability criteria from user preferences, e.g., by analyzing online user reviews [18], and considerations of specific paradigms and interface types, e.g., on-skin interfaces [35]. There is also a large body of work covering wearability aspects of animal tagging [8], which contributes useful guidelines [47].

The design guidelines most readily applicable to the design of future highly integrated textile devices might be clustered by the perspective taken, focusing either on technological requirements, general human sensorimotor activity, specific human abilities, or human social interactions. We summarize their design criteria in Table 1 and elaborate in the following.

2.3.1 Technology. Taking a technology centred perspective, the first criteria for wearability is if the device can **function** as desired. For example, an antenna should be placed so that it is not shielded by the wearers body [80] and an EMG electrode should have a solid contact with the human skin [40]. Going beyond functionality, a typical design consideration is optimization of the **information** which can be collected. For example, to detect grasping with EMG, it is not sufficient to have a good quality contact with the skin; the contact should also be placed where it can collect the required information. This also transfers to other technologies, a glucose monitor will predominantly be attached to the abdomen, and weight distribution would be measured in shoes or on ones' buttocks [72].

2.3.2 Human-Centric: Sensorimotor. Similar placement guidelines can also be collected by focusing on the human. When taking a sensorimotor approach to wearability, one might distinguish between two main approaches: **psychophysical** and **biomechanical**. Exemplifying the psychophysical approach, Dunne and Smyth state that *"Wearability is about texture, thermal balance, moisture transport, and freedom of movement"* [12]. They suggest that *"wearability can be described psychophysically as the degree to which sensory stimuli generated by a worn object intrude into the wearer's conscious attention"*. They hypothesize that, once a wearable technology demands too much attention, it is removed from our body-schema and instead enters our peripersonal space [12]. Representing the biomechanical definition, Gemperle et al. state *"Wearability concerns the physical shape and their active relationship with the human form"* [17]. Here wearability is concerned with not inhibiting natural motion, distribution of weight on the body, or reachability. An important consideration here are the large diversity of human body shapes.

2.3.3 Human-Centric: Human Abilities. Many design considerations established through HCI methods focus on human abilities, usually around the following key themes:

The first is human **perception** of system output. While psychophysics perspectives aim to minimize the attention that a wearable device demands, there are moments when we need the device to demand our attention. Here it is important that the channel used matches the location selected. For example, our tactile sensory acuity varies strongly by location [80]. However, this does not directly mean that areas with high tactile acuity are better suited for tactile communication. Israr et al., for example, demonstrate how the low tactile acuity of the back might make it an ideal location for tactile communication [24].

Another approach to wearability might focus on human abilities to interact with the wearable device. One might focus on human performance, asking question such as where on the body a user might **react to notifications** fastest [20], or where a device should be located so that it can be accessed with minimal temporal demand [2], or how to display on-body information so that users can understand it with minimal delay [7].

The complement to this investigates how wearables might maximize the ability of the user to **provide input**. For example, Strohmeier et al. present a preliminary investigation of the effect of location on a pressure targeting task [74].

2.3.4 Human-Centric: Social. Wearables are both social (or public) and, being close to the body, intimate (or private). As they affect how wearers perceive themselves, and how they are perceived by bystanders [30, 32], social acceptability is becoming an increasingly relevant theme in HCI [29]. Social aspects are also highly relevant for electronic garments. Worn items are an element of self expression; they become part of the self and the public image the wearer displays to others [76]. In consequence, wearability also comprises social and aesthetic aspects. Wearables that deviate from social expectations, e.g., by attracting unwanted attention, by being conspicuous, stigmatizing or socially awkward, face issues with **social acceptability** [63]; they have an increased social weight [77]. HCI typically understands social acceptability as an interplay between the user's self-image, and how they are perceived by on-lookers [5, 29, 41]: a wearable that negatively impacts the wearer's self and external image shows a lack of social acceptability. In consequence, social acceptability is tightly coupled to visual appearance, including both static aesthetic qualities (e.g., color, material or style) and dynamic "interactive" qualities (e.g., visible in- or output) [11].

Despite this overlap, **aesthetic considerations** also differ from social acceptability in several ways [26]. For instance, a plain black wrist band would not be considered aesthetically appealing, but is neither awkward nor stigmatizing, and does not create social tension: it would simply not affect the wearer's social image. A certain style or aesthetic might be appropriate – or acceptable – in one social context (e.g., a tennis court), but not in another (e.g., an opera or job interview). As a result, considerations for wearability need to include both dimensions, fashion-oriented and aesthetic values, as well as contextual values, based on social norms and standards, and including associated stereotypes [69], stigmata [63, 71] and cultural expectations [62].

3 MOTIVATION

The availability of novel technologies to HCI researchers enables the design and validation of new interaction techniques and applications in context [66]. Pioneering work on EMS in HCI has

Figure 3: Examples of existing wearable sleeves. Top: GestureSleeve [68], Affordances++ [37] and PneuSleeve [81]. Bottom: Textile for reconstructing joint angles [34] and SmartSleeve [49]

provided a valuable foundation by making EMS' functionality accessible [50] and by exploring and showcasing interaction possibilities [37, 39, 51]. This has paved the way for more design-oriented considerations (e.g., fabrication), as well as more pragmatic aspects, such as 'could this be worn in day-to-day life'.

In this work, we take this closer look at the wearing context(s) and design aspects of EMS garments by considering 'wearability' as an additional core characteristic beyond technological opportunities. In particular, we exemplify the design considerations and practices required to fabricate truly 'wearable' complex electronics. By analyzing our different design iterations, we identify goals and challenges in creating complex wearable devices like EMS/EMG sleeves for skill augmentation that approach the day-to-day wearability of ready-made garments.

Why a Sleeve? Arms present special challenges due to their mobility and deform-ability. We move our arms during most activities, even if arm movements are technically not required – for example when talking. Not only do we move our arms, as our arms move they completely deform due to the double-articulation of the elbow and the elongation and contraction of muscles. Design choices which can accommodate such complex shapes are likely to also transfer to simpler shapes.

The arm has also proved both a practical and desirable body part for augmentation. Examples include EMG-based activity detection systems [14], wearable implementations of EMS as in Affordance++ [37] (See Figure 3), wearable haptic feedback systems [81], a multitude of input devices [49, 68], and health-based devices for monitoring posture [65] or avoiding repetitive strain injuries [24].

Why EMS/EMG? Of all the existing sleeve prototypes, multi-electrode EMS systems provide some of the most restrictive constraints. For one, the error tolerance of where the electrode should be placed relative to the muscle can be very low, requiring an exact fit. Then, for EMS to work, but even more so for EMG to function, the contact quality with the skin must be high. Also, the complexiy of the cabling scales directly with the number of electrodes (compared to, for example pressure sensitive sleeves [49, 68] which scale as a function of the square root of pressure points).

Through three design iterations (see Figure 1), we present lessons learned and extend upon the current literature regarding wearability. We will introduce the concept and motivation for each iteration, discuss how the sleeves were produced, and then reflect on each design.

We present reflections on the default option - using off-the shelf electrodes. We then reflect on Iteration 1, which was used for conducting research on auto-calibration [28] with a main focus on electrical functionality. We then present Iteration 2, which was designed with a stronger focus on wearability, and finally Iteration 3, which combined the focus on wearability of Iteration 2 with specialized functionality.

For each iteration we will describe the manufacturing process, and provide reflections on how it performed, structured around the identified themes of wearability from related work (See Table 1) as well as the specific design considerations we had in creating and working with the sleeves. It should be noted that, because users typically do not directly interact with skill sleeves, we do not discuss human abilities. Also this case study focuses solely on the design of the textile multi-electrode array. Considerations regarding the wearable design and connection of the electronic EMS and EMG devices will be presented in future work.

4 DESIGN ITERATIONS

DEFAULT: Placing Individual Electrodes

EMS requires anode and cathode electrodes (i.e., signal and ground). Typically, these electrodes are coupled and treated as pairs (See Figure 4.1). Many HCI EMS systems, e.g., [27, 51, 55], rely on a limited number of pairs, with 1-3 pairs covering much of the existing literature. These sticky electrodes are placed manually. For most systems, this placement process proceeds (approximately) as follows: (1) the researcher develops an expectation of electrode placement (i.e., on the lower posterior forearm, near the elbow). (2) The researcher asks the user to palpate their muscles (i.e., quickly and repeatedly tense and release), whilst they observe or feel for muscle deformations, to refine their expected starting placement. (3) The electrodes are individually peeled off their protective backing and placed in the determined location. (4) The researcher uses wires, often using alligator or snap connectors, to connect the electrodes to the stimulation circuitry. (5) Based on the observed results from sample stimulation, the electrodes may be removed and replaced (typically in small increments.) This may occur multiple times. This electrode placement process can be time consuming - see Knibbe et al. [28] for a more detailed discussion.

Default: Reflections

Technological. A primarily strength of using off-the-shelf electrodes is the convenience for robustly prototyping simple interactions. From a technological perspective, a benefit of commercial electrodes is the **functional** electrical connection made with the body.

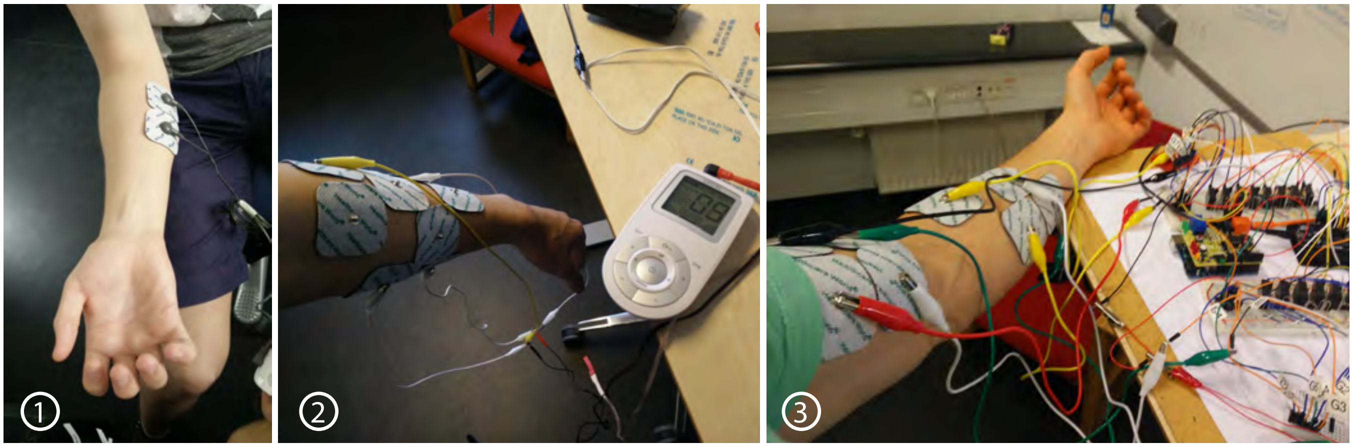

Figure 4: Placing Individual Electrodes. (1) Typically, when prototyping interactions, small numbers of electrodes are used. These are placed and connected directly to the stimulation device. (2) As electrode numbers increase, EMS users must turn to custom circuitry in order to support multiple channels of stimulation. (3) Connecting multiple channels of stimulation simultaneously becomes hard to manage.

Additionally, this approach is also inherently customizable. Electrodes are easily placed, moved, and altered at any stage. Further, though more rarely seen in HCI, off-the-shelf electrodes can be easily trimmed down (i.e., 2.5cm^2 electrodes can be comfortably trimmed to 1cm^2). This can be used to optimize **information** flow, both in terms of the achievable stimulation resolution [53] as well as optimization of data collected using EMG sensors. In principle, this approach can scale to support complex electrode arrangements and patterns. However, the time complexity associated with placement and tuning of the system is impractically large [28]. Furthermore, the scalability of the wiring and associated management quickly becomes infeasible.

Sensorimotor. These considerations similarly depend on the number of electrodes. The placed electrodes are independent from one another, and so can freely deform with the body. As the number of electrodes increases wiring can become a limiting factor – wires pull and rub on one another and so begin to constrain movement. Further, as more electrodes are employed, the arm is increasingly covered in electrodes. This makes it difficult for users to comfortably rest their arms during use, without stressing electrode connectors or uncomfortably pressing connectors into their arms (See Figure 4.3).

Social. The clear visibility of the individual electrodes hints at the system's inner workings, which is a benefit to novice EMS users, for whom revealing the system is initially important, but often overlooked [27]. However, the somewhat medical appeal of the off-the-shelf electrodes can also act as an 'accentuated social signifier' (c.f., Li et al. [33]), which can negatively affect (social) wearability by attracting pity and potentially inducing stigma: *"[...] my friends will worry whether I am sick"* [31, 33]. In addition, opportunities to tailor the aesthetics of off-the-shelf electrodes to a desired look are limited.

One of the main challenges we encountered is a lack of durability and repeatability. Both electrodes and wires can easily catch on objects, clothing, and body parts, and so become dislodged and disconnected. The system is fully dismantled when the electrodes are removed for cleaning or replacement, and repeat wearing is akin to building the electrode setup from scratch. Anecdotally, we have used ink marks on the skin to support removal and re-application of electrodes.

In summary, for many scenarios, including design concept explorations and initial lab studies, this approach to electrode configuration is simple, practicably quick, can be tuned to support sufficient complexity (for example, by trimming off-the-shelf surface electrodes down to a smaller size), and can work across all available users. However, the time requirements for configuration, the cabling complexity, and the robustness of individually connected electrodes becomes problematic before the ceiling of achievable stimulation resolution is reached. This becomes especially problematic, considering that the process must be repeated for every single use. As such, we started designing electrode sleeves, with the intention of supporting higher numbers of electrodes and effectively managing the cabling requirements, while increasing the speed of application and supporting repeated use.

ITERATION 1: The Calibration Sleeve

The first design iteration was primarily intended to improve the **deployability** of Skill Sleeves. This might be done by decreasing the time it takes to **apply** the EMS electrodes and enabling **prolonged use** by repeated applications. This iteration of the sleeve was used in a study on auto-calibration for EMS by Knibbe et al. [28]. A two-fold strategy was chosen to achieve the new design goals. First, rather than placing electrodes individually, all electrodes should be applied together. Second, rather then considering where to place electrodes, a concept of a *complete electrode sleeve* was used. Instead of individually placing the electrodes at the desired location, the entire forearm was covered in electrodes. This changed the calibration problem from 'where to put electrodes', to 'which electrodes to use' (c.f. [28]). In addition to potentially reducing the time it

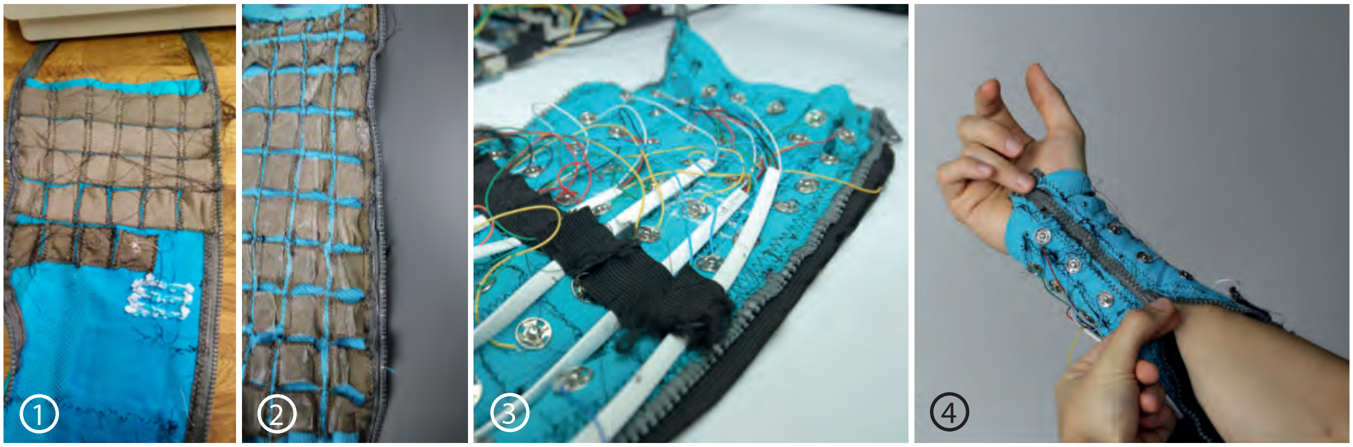

Figure 5: The Calibration Sleeve. This was the first wearable full-sleeve of electrodes for EMS for HCI. (1) The sleeve was constructed by individually sewing electrodes into the base fabric, (2) to form a dense grid of electrodes. (3) The high number of electrodes created wiring complexity. (4) The sleeve was designed to support donning and removal of the sleeve by the individual.

takes to start using a skill sleeve, this approach is also a candidate solution for increasing resolution.

Iteration 1: Fabrication

The Calibration Sleeve is fabricated into an off-the-shelf sports sleeve. The original sleeve (CompresSport compression sleeve) was designed to be tight, rolled on to the arm, and provide pressure-based support. The sleeve was cut open length-ways, and a zip was sewn into the edge. Sixty 20x20mm square electrodes were cut from conductive fabric (Statex Techniktex P130b) and then individually sewn into the sleeve, along three sides, forming a pocket (see Figure 5.1). One side of the electrode was left open, to enable a snap connector to be connected to the outer and inner side of the compress sleeve (blue fabric). This conductive snap connector would form a connection from the outside of the sleeve to the conductive fabric. On the external side of the sleeve (away from the arm), wires were individually soldered onto the snap connectors. For each row of 5-6 electrodes (the sleeve thins nearer the wrist, so the number of electrodes required is reduced), the wires came from a six-wire shielded cable (see Figure 5.3). All cables ran up the sleeve, towards the elbow, and were gathered through a strap around the users' bicep. Prior to use, squares of conductive gel (AxelGaard's AG635 'Sensing' Hydrogel), were cut and placed on the exposed side of the conductive fabric.

Iteration 1: Reflections

Technological. Conceptually, this sleeve can support a high resolution of movement control, as electrodes cover the entirety of the forearm. The sleeve was designed to be 'one size fits many' - inheriting the properties of the base compress sleeve. For users with thin arms, there were too many electrodes and not all would sit flush to the skin. For users with larger arms, the spacing between electrodes stretched awkwardly. As such, there were large differences in coverage between users. However, as the majority of the forearm was covered across all users, and through careful per person calibration [28]), it remained usable and, was able to collect both rich **information** by using the electrodes for EMG measures, as well as having high information output by its ability to induce complex movements in the user.

However, even though this functionality was present, in many ways the sleeve still was less **functional** than the individual electrodes. For example, the quality of the electrical contacts suffered from distortions in the fabric. The relatively rough craftsmanship resulted in many unwanted contacts of conductive fibres, resulting in both parasitic resistance and parasitic capacitance. This constrained the control resolution. While these problems could mostly be addressed in software and by robust electronics design, there is clear room for improvement.

Sensorimotor. To accommodate for the shape transformations that the arm undergoes when moving, the sleeve was built around an elastic sports-sleeve. The elasticity of the sleeve would then allow the final sleeve to also conform to changing shapes. However, the additional fabric, sewing, and wiring, heavily reduced the stretchability of the sleeve. Additionally, the requirement for sticky conductive gel prevents the sleeve from easily deforming with and conforming to the arm. Further, the complexity of the cabling for 60 electrodes adds a mechanical stiffness to the sleeve (i.e., from the 10 lines of 6-wire shielded cable), which hinders its use for highly dynamic arm movements (for example, it could support a user in playing piano, but could not be used for improving tennis-play). The cables are, however, kept out of the way of the hand, supporting free hand movement.

Social. This sleeve leaves the electrical nature and complexity of its workings out in the open; creating a 'cyberpunk'-like aesthetic. Like the individually placed off-the-shelf electrodes, this aesthetic is not subtle, but rather obtrusive. For (social) wearability this can pose a significant weakness, as many HCI researchers consider unobtrusiveness, i.e. not calling attention or revealing the technical nature, as crucial for social acceptability [1, 9]. Nevertheless, for more performative use cases where visibility is intended (e.g., in Stelarc's Fractal Flesh, Ping Body and Parasite performances[2]), this characteristic can also act as benefit, provoking affects and creating transparency for the spectator.

Deployability. While many of the classical factors of wearability are not well supported by this iteration, it did clearly improve on its explicit design criteria of deployability. The use of a zip enabled one-handed application and fastening (see Figure 5.4), and the zip itself proved robust to movement. While not perfect – the stickiness of the electrodes, however, made the stretching of the sleeve, in order to fasten the zip, difficult, and required the sleeve to be pealed off when removed – in terms of **application**, this iteration clearly improved over the default approach.

The sleeve also supports **prolonged use** through re-usability. One application of gel can be used two to three times, before needing replacement (as it degrades and, from our experience, begins to curl, stick to itself, etc. - Figure 5.2). And many applications of new gel can be applied before the sleeve deteriorates. (The removal of the sticky gel pulls on the conductive fabric and stresses the stitching. Should the stitching have been better, and a fabric pocket design not have been used, then the durability could have been improved). Low gauge wire was used to minimise mechanical rigidity across the sleeve resulting from the wiring. This would frequently break off from the snap connectors. Given the semi-permanent nature of the wiring, where the shielded cable was sewn into the sleeve in places, the sleeve itself could not be easily cleaned.

In terms of pure functionality and ergonomics, this iteration was not an improvement over individually placing electrodes. It was no more durable in terms of cabling, nor did it support a greater range of motion to the user. The Calibration Sleeve serves as an example of problems created by merely adding to existing garments, rather then integrating from bottom up. The garment, once layered with the necessary circuity, no longer had the desired elasticity. We note that a material with much more stretch is required as base material to counterbalance the restriction caused by the electrodes. However, the goal of making the sleeve easier to apply and enabling multi-session use was achieved. This supported a new approach to HCI-EMS research, and enabled progress towards multi-electrode, higher resolution control, not least by presenting the full 'sleeve' metaphor, and beginning to move key components to fabric.

ITERATION 2: the Manufacturing Sleeve

Due to the problems related to the technological functionality, and to overcome limitations related to sensorimotor aspects of wearability present in Knibbe et al.'s [28] Calibration Sleeve, we looked to refine their design into a fully customised approach. The purpose of this design was primarily to improve our understanding of manufacturing opportunities afforded by new eTextile methods (e.g. [15]). We therefore refer to the sleeve as the *Manufacturing Sleeve*. With this design we sought to address the challenges of the Calibration Sleeve at a high level by: (1) reducing material thickness and improving elasticity, to produce a more conforming sleeve, (2) targeting electrode placement to only cover muscle bodies, (3) developing a fabrication process that could be accurately repeated at scale, and (4) increasing the robustness and manageability of the electrode wiring. A special focus was placed on creating a sleeve which was also repeatable in terms of **manufacturing**. The goal here was to enable easy customization of the designs and easy re-implementation both of individual sleeves as well as potential mass-production.

Iteration 2: Fabrication

The sleeve is constructed from three fabrics: a thin technical knit base fabric (Eurojersey Classic, which has a textural and technical quality seen in high performance sportswear, swimwear and lingerie), conductive 4-way stretch knit fabric for the electrodes and wiring (Statex TechnikTex P130b), and a fine 4-way stretch mesh fabric (PowerMesh). In this design, the wiring is replaced by conductive eTextile traces, making all electrical elements integral to the material surface of the sleeve. Further, by using fabric traces as wiring, we avoid the typical challenges around hard/soft connection points, such as where fabric meets wires[3]. The construction relies primarily on a sandwiching technique, as commonly used in high performance sportswear manufacturing, where the layers are bonded together with a stretch glue film, Bemis SewFree 3145 in .003mm. This film is washable at 40 degrees and has a low melt/flow point which allows for rapid prototyping with a domestic iron without compromising the elastic or conductive materials used.

We create a pattern for the sleeve as a vector graphic. This pattern includes the outline of the sleeve, the electrodes, and all fabric wiring. Originally, this pattern was derived through multiple manual design iterations, as seen in Figure 6.1. We started by pinning a base fabric, to derive the outline pattern of the forearm. Next, we ensured that pattern worked across multiple wearers. We then determined muscle body locations underneath the fabric pattern across multiple wearers. We positioned electrodes onto the pattern for maximum coverage across wearers (Figure 6.2). This pattern was then digitised by scanning and tracing. The pattern is then divided into layers, per the different materials (See Figure 7.1).

Next, the materials are prepared. Based on the design, some materials are simply cut to size, and others are cut to size and bonded to a glue layer with a domestic iron. The design is cut from the materials with a laser cutter. We calibrate our laser cutter per material, prior to cutting the final design, to balance effective cutting and fabric burning. We find the best performance if the fabric is attached to an off-cut backing board (e.g., spare laser plywood), and the cut is set to be fast and low power (see also [74]).

Once all of the fabric layers are cut (Figure 6.4), the final construction can begin. This involves layering the final materials and heat-bonding fabric together with an iron (Figures 6.5 and 6.6). Due to the density of electrodes and thickness of the fabric traces, masking is required in places to control when heat is applied in a multi-layered construction.

We chose to have the fabric wires free-floating from the body of the sleeve, in order to reveal some of the complexity and functionality of the sleeve to a spectator. This free floating design also served

[2]http://stelarc.org/, accessed 08/2020.

[3]For resources about hard/soft connections, see kobakant.at/DIY.

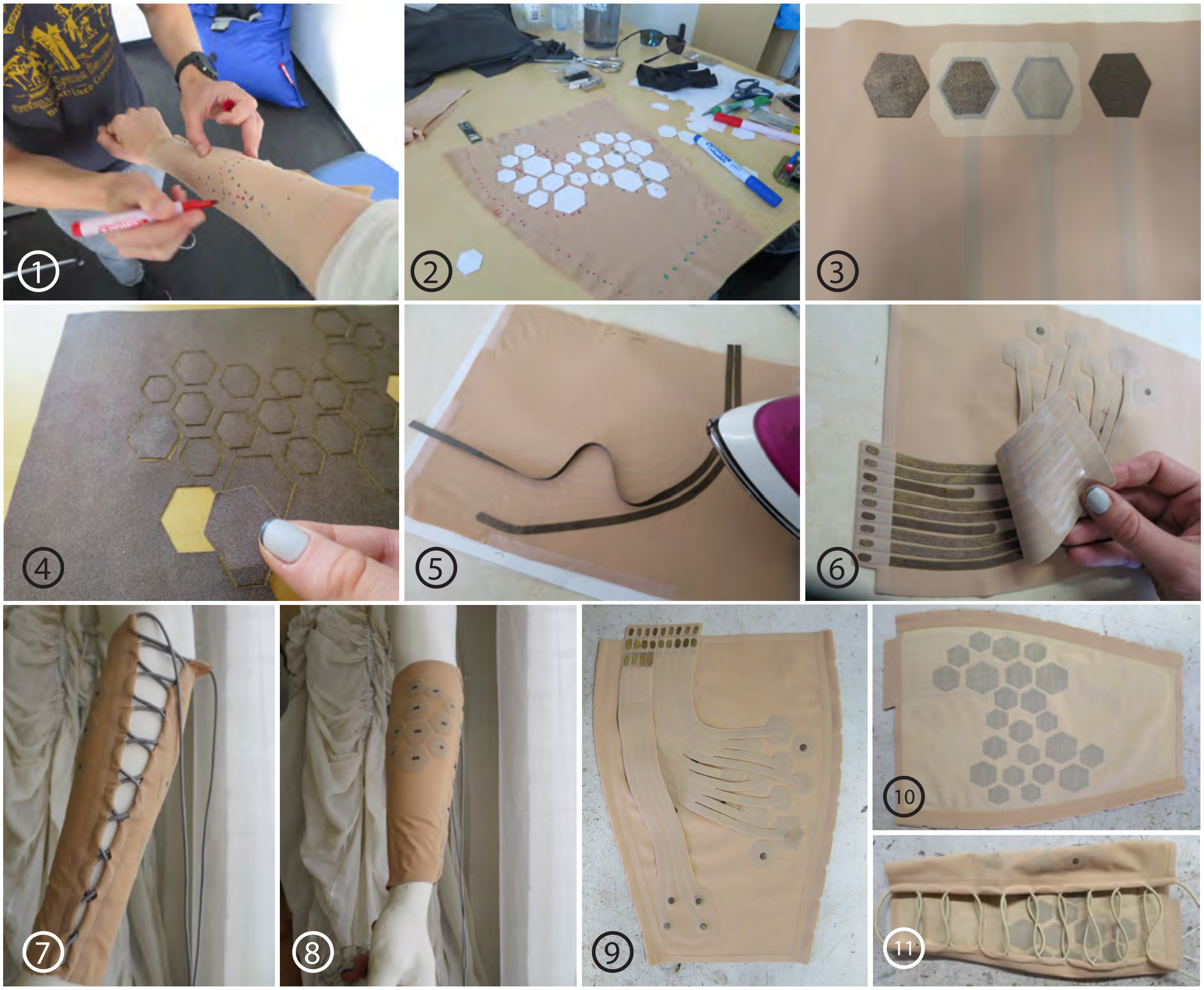

Figure 6: Producing the Manufacturing Sleeve. (1) Determining muscle locations across multiple users. (2) Planning electrode layout to cover broad range of muscle locations. (3) Testing different electrode designs. (4) Laser cutting fabric. (5) Ironing fabric layers together. (6) Layering multiple fabric layers. (7) Using a string-based, corset-esque fastening technique. (8) Showcasing electrode placement on a mannequin. (9) The final Manufacturing Sleeve (outside). (10) The inside of the Manufacturing Sleeve. (11) The final fastening configuration of the Manufacturing Sleeve.

to separate and minimise layering, reducing the glue film and therefore the restriction such layering would cause to the stretch of the garment. This required extra layers in fabrication.

The electrodes in this sleeve are still constructed from conductive fabric. However, we experimented with layers of different materials to balance robustness (as electrode gel is applied and reapplied) and best stimulation sensation. We found that covering the conductive material with a layer of fabric mesh maximised these criteria (Figure 6.3). When two conductive layers are heat-bonded together, the fabric glue seeps into both layers, and so supports a conductive connection. This means that conductive fabric traces can be bonded directly to the conductive electrodes, in order to achieve a connection. Bonding the fabric electrodes rather than stitching also means that the edges of the material were secured by the glue film and maintain a clean edge, removing any possibility of fraying which may cause electrical shorting between electrodes.

Iteration 2: Reflections

Technological. The Manufacturing Sleeve can support a similar level of complexity to the compress sleeve, as electrodes cover all muscle bodies. In this sleeve, electrodes were varying sizes, depending on

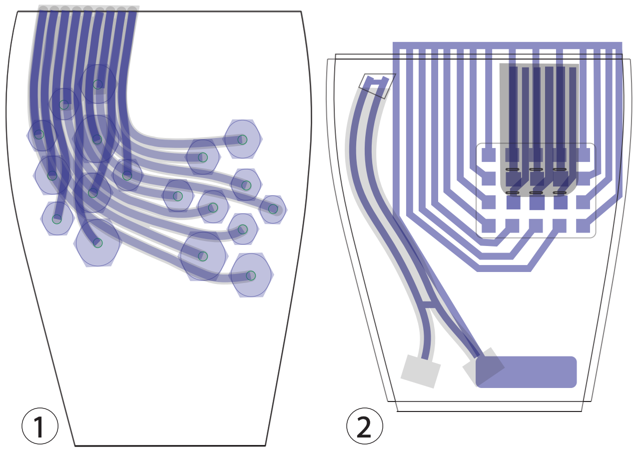

Figure 7: Design pattern for (1) the Manufacturing Sleeve and (2) the Typing Sleeve. The vector designs demonstrate differences in the sleeve's design approaches. The fluid style of the Manufacturing Sleeve, for example, were manually constructed, taking time and requiring expertise. The typing sleeve sought to remove this requirement of manual craft in production.

proximity to the center of the muscle body. This cleaner implementation however resolved many of the problems related to noise and parasitic resistance and capacitance of the previous iteration. Overall, the basic **functionality** of this sleeve clearly improved over the previous design. Also, while this design had reduced electrode count, because the arrangement of the electrodes corresponds to human physiology, the **information** which can be presented through and collected from this sleeve is similar to the previous iteration.

Sensorimotor. By constraining the electrodes to only sit on muscle bodies, as opposed to covering the whole arm in Knibbe et al.'s compress sleeves, the Manufacturing Sleeve is also better able to flex and conform to the body during movement. The requirement for sticky conductive gel remains, however, creating patches of increased stiffness within the sleeve. The novel electrode connections no longer create a mechanical rigidity within the sleeve, as the conductive traces (i.e., fabric wires) can flex and deform with the arm. As these traces are bonded onto the sleeve in at least two places, they do not risk getting in the way of the hand during expressive, complex, or dynamic movements.

Social. Due to the improved manufacturing approach, the sleeve has a clean aesthetic and low profile. This goes some way towards communicating its functionality through the use of 'wire muscles' along the outside, de-emphasizing the technical nature (c.f., Profita et al. [61]) without hiding it. As a result, it might support social acceptability by creating a 'candid' design that neither deceives nor calls for attention [13, 29]. In contrast to the earlier iteration, it can easily be adapted to appeal to different stylistic preferences and offers options for aesthetic personalization. Although the Manufacturing Sleeve's current design language follows a sports-style emphasising the functional, loose-fitting or more ornamental external layers could be added to achieve a different aesthetic, whilst keeping the electrodes on the inner layers tight to the skin.

Deployability. The zipper of the previous design reduced elasticity. To maintain the full 4-way stretch of the design, we used a hooped, corset-like fastening approach, based on an elastic cord that can be pulled tight and easily loosened. This change was not successful, as the cord needed to be very loose to populate the electrode gel and to enable the arm to fit through the sleeve, without catching on the gel. Once tightened, the sleeve became difficult and time consuming to loosen with one hand. A benefit of this approach, however, was the ability to loosen or tighten specific parts of the sleeve. For example, certain loops of chord could be left looser, or made tighter, depending on the exact desired placement of the sleeve and the users' arm size.

The entire sleeve is machine washable. The bonding film that binds the material layers together is a stretch thermoplastic polymer typically used for binding seams in high-performance sportswear, and so is designed to withstand repeat washing and structural stresses, and is formulated for repeatable stretch with optimum recovery. In our construction technique, the use of bonding film to surround the conductive material also serves to minimise the potential for the silver coating of the Techniktex to be damaged by washing[4].

Manufacturing. The primary contribution of this iteration was the simple design of the manufacturing process. The sleeve was simpler to produce, requiring three primary steps: design, laser cut, and iron.

One limiting factor within this design, however, is the spatial requirement of the electrode traces. The conductive traces were 6mm wide to conduct the signal with limited noise and resistance. With increasing number of electrodes, the surface area required for electrode traces also increases. These traces can be layered, with isolating fabric in-between, but this increases the rigidity of the sleeve. In the current prototype, a secondary floating layer of conductive traces was required to connect to all electrodes. This floating layer helped to preserve the stretch of the sleeve, though also increased the complexity of construction.

One of the intentions of the Manufacturing Sleeve was to create a fabrication process that would facilitate a more steamlined creation of personalised sleeves. The base design of the current sleeve (including the forearm pattern, fastener design, and external wiring concept), for example, fits a broad range of arm sizes. However, the electrode placement within is tailored to a small range of users, depending on their musculature. Whilst this electrode design may generalise across a broader range of users (and could further generalise depending on the adopted calibration approach), the intention is that each users' arm may be digitally scanned and a set of activities selected. The associated underlying electrode pattern required to stimulate the desired muscles might then be generated to fit the exact physiology of the user and then produced and fabricated.

[4]We see the silver coating of the Techniktex deteriorate more on the exposed electrode surface than on the traces isolated by the fabric layering.

In summary, this iteration clearly improved the functionality over its predecessor. The reduced electrode count was achieved without reduced functionality, and – together with the new fastening mechanism – improved the wearability in terms of biomechanics. Overall, the sleeve was also more comfortable to wear, improving wearability from a sensorimotor perspective. However, the fastening mechanism proved detrimental to applying the sleeve, so, even though the durability of the sleeve increased, the deployability was not as good as desired. The manufacturing technique explored proved successful and not only provides a path towards manufacturing at scale, but also opens up new opportunities for customization.

ITERATION 3: The Typing Sleeve

To explore the ability of the new design to adapt to various body shapes and activities, we embarked on an EMS project focused on typing. Together with a digital design agency, we explored the transferal of motor skill, in this instance professional gamer keyboard skills, to novice users, to convey the 'feeling and experience' of a pro. To this end, we needed a sleeve that could support finger level actuation for keyboard input (as demonstrated by [10]), but also required wearability, and especially aesthetic, considerations beyond prior sleeves. This new design was also intended to address the problem of deployability, and further explore manufacturing opportunities.

Iteration 3: Fabrication

We depart from the same fabrication technique as the manufacturing sleeve. We revisited the electrode positioning requirements for individual finger actuation. Ad hoc testing with four members of our team revealed a stable electrode configuration that could flex the fingers individually down onto the keys (figure 8.2) (note, we do not actively pull the fingers back off the keys, in this instance). This calibration process was done using the traditional individual placement technique above (this, in turn, reveals the exploration and testing quality of that approach). Our uncovered electrode pattern required two electrodes on the lower hand, and so we augmented the sleeve with a low-fitting fingerless glove. This enabled free movement for typing (including comfortable stretching for keys), whilst ensuring secure electrode attachment. The electrodes were reduced in size to 1cm^2. This enables more precise targeting, without any change in sensation. A single, large ground electrode was placed near the wrist. The sleeve was also altered to use d-rings and cummerbund buckles for fasteners.

Iteration 3: Reflections

Technological. As with the previous iteration, the **functionality** of the electrodes was satisfactory. In terms of **information** which might be conveyed through the sleeve, changes were made from generic to special purpose. This sleeve supports EMS for typing. Unlike the previous, general purpose iteration, this version had a specific target application, based on a project's requirements. To this end, the more generalised opportunities for use of this sleeve were removed in this instance. The same number of electrodes are present as in the manufacturing sleeve, however, requiring the same trace complexity.

Sensorimotor. The typing sleeve retains the comfort of the Manufacturing Sleeve. The reduced size of electrodes also reduces the quantity of electrode gel required, which adds to the flexibility of the sleeve and further improves conformability to the arm. The connection between the glove and the sleeve is specifically flexible (made of only one layer of the Eurojersey material), to better support unencumbered movement and rotation of the wrist (biomechanical design criteria). The fabric bonding glue used in this design is thicker, however, which adds some rigidity to the sleeve. To reduce the amount of glue used and improve the sleeve's flexibility, the precise placement of the glue was revisited. In the Manufacturing Sleeve, a layer of bonding glue spanned the entirety of the sleeve, bonding the eurojersey top layer to a powermesh bottom layer. Conversely, in the typing sleeve, bonding was only used to fuse traces, or for edges and seams.

Social. The black color, along with the cummerbund buckles also create a more ready-made, game controller-like look and generate the impression of the sleeves being a professional tool – which, in turn, can have a positive effect on social acceptability [30].

Deployability. The sleeve is easy to put on and take off. When not worn, the sleeve opens up fully, making the application and removal of gel simple. The cummerbund buckles tighten with velcro straps, which supports flexibility of sizing requirements. There is one d-ring fastener on the glove, which supports a wider range of flexibility. Our experimentation found that three anchor points on the sleeve, and two on the glove, were the best trade off for fastening complexity and security to the arm. In the future, to further improve the fit and comfort of this design, elasticated velcro loop tape or velcro-backed neoprene could be used to simplify this fastening approach and support a broader range of sizing requirements.

The typing sleeve is similarly machine washable as the previous iteration. The electrode traces are attached to the sleeve, improving durability and reducing the risk of catching and tearing. The reduced quantity of glue may impact the durability in the longer term.

Manufacturing. The typing sleeves highlights the complex interplay of **specialized function** and **personalized form**. While this sleeve maintains many of the features of the previous iteration, its length is not variable (i.e., the relative distance from the forearm to the wrist) due to the addition of the glove. Previously, the sleeve could have been re-positioned up or down the arm slightly, to account for different proportions. With the addition of the glove, this is no longer possible. The special purpose application made the sleeve less generalizable to a multitude of body shapes.

Similarly to the manufacturing sleeve, the typing sleeve is easy to produce at scale, relying on the same design, laser cut, and iron workflow. For the Typing Sleeve, the speed of manufacturing was increased, as some of the manual craft in the production of the manufacturing sleeve was removed. For example, in the manufacturing sleeve, straight traces were laser cut and then manually curved for the design. This was to reduce signal noise along the traces as aligning traces with either weave or weft yields the best conductive

Figure 8: The Typing Sleeve. (1) This sleeve features an array of 20 small electrodes in a grid-like pattern, with fabric traces routing primarily between layers of base fabric. (2) The sleeve also features a large wrist ground electrode, and two palm electrodes on a half glove. (3) Cummerbund and d-ring fasteners are used to fasten the sleeve to the arm.

properties. In the typing sleeve, we opted to laser cut the specific trace design, include all bends, choosing simplicity of design over ideal electrical properties – with no noticeable detriment to EMS.

We further simplified production by creating the electrodes and traces in a single layer. We also maintained small tabular connections between traces. These support the fast placement and alignment of traces for bonding: Traces can be placed and aligned, loosely pressed into position by hand (providing a small amount of heat to begin the bonding process), the tabs can then be cut, and the final bonding can be completed with the iron. We tried many forms of glove and hand-wrap, for the palm-mounted electrodes. In our case, it was critical that biomechanical freedom be maintained, to enable fast typing speeds, and as such we settled on a minimal glove.

The typing sleeve represents the culmination of our design research practice into wearable electrode arrays for EMS. The sleeve is comfortable, durable, machine-washable, simple to produce, and easy to put on and take off. It does however highlight important design trade offs between generalizeability and specialization both in terms of personalized fit and specialised function. The speed and simplicity of production, however, enables quick iteration and creation of specific Skill Sleeves supporting exploration of these trade offs.

5 DISCUSSION

The prototypes presented in this paper highlight that there are factors which should be considered in addition to the wearability aspects commonly discussed in the literature (See Table 1).

In our case, **deployability** was a key design criteria, primarily, because it saved Knibbe et al. a lot of time in experimental work, but also, because we designed these sleeves with the vision of one day being able to deploy them in a sports context. For doing so, they must be easy to repeatedly *apply and remove*, and capable of being worn for *prolonged periods of time*. Also, we learned that there is a complex interplay between **customization** and generalized functions or generalized form. Specifically, it appears difficult to customize for a *specific application*, while keeping the form sufficiently general that it can fit a wide range of *different bodies* and vice versa. This led to an increased interest in **manufacturing methods**. We highlight that the wearability of a technology must already be considered in the manufacturing process. Here the design criteria were that the manufacturing process must, from bottom up, *serve the other wearability criteria*. For example, the biomechanics of human motion must already be considered in the choice of material, and the deployability in the choice of fastening mechanism. Additionally, due to the complex interplay of constraints between generalization and specific use cases, manufacturing processes must both be *feasible at small and large scales*, to allow both batch-production and customization. See Table 2 for an overview of identified design criteria. It should be noted that these considerations were not formalized during the prototyping process, rather the intention behind building these devices was curiosity driven, with the question of *"Can we make this?"* and *"How could we improve on this?"* driving the exploration. The above mentioned criteria were only made explicit in this retrospective analysis.

Lessons can be learned from all iterations: For example, our exploration highlights the utility of off-she-shelf electrodes for prototyping. Even with access to sophisticated Skill Sleeves, they have remained our go-to prototyping method. The main drawback of off-she-shelf electrodes is that they become difficult to manage once their numbers increase and that they must be carefully calibrated each time they are applied. The first iteration presented – the Calibration Sleeve used by Knibbe et al. [28] – solved this problem. It is easily possible to apply and remove the Calibration Sleeve. However, it proved both limited in electrical functionality as well as unsuitable for a wearable device considering the human sensorimotor system. The second iteration – the Manufacturing Sleeve – was designed as an exploration of manufacturing methods. While

Table 2: Additional Electrode Garment Design Criteria based on the design of Skill-Sleeves

Design Focus	Design Criteria	Associated Questions
Deployability	Applying and Removing	Can it be put on and removed with reasonable effort ?
	Prolonged Use	Can it be washed? Can it used multiple times?
Customization	Function	Should the device do many things, or fewer things especially well?
	Form	Should the device fit one person perfectly, or should it be used by any person, no matter what body size?
Manufactoring	Wearability	Does the method support the other wearability considerations?
	Multi-Scale	Can the method be used both for batch-production as well as creating bespoke garments?

this sleeve was clearly superior to the previous iteration in terms of functionality and sensorimotor considerations, it was flawed in terms of deployability, due to an unpractical fastening method. This was remedied in the third iteration – the Typing Sleeve. Here, a more flexible fastening method ensured that the sleeve could also be easily deployed and removed.

We also show that there is no 'ultimate' design, rather, once the more basic aspects of wearability are well implemented, one reaches a complex interplay between customization of form, specificity of application and generalization. In the present case, the specific application of the Typing Sleeve reduces its ability to generalize to a variety of body forms. Given these constraints and the broad diversity of users, we argue against a one-size-fits-all approach to eTextiles. Instead we suggest development of methods for making bespoke devices less arduous. We see our manufacturing approach as a first step in this direction; a method of developing electrode sleeves that can be adapted to work with many sensor types, and facilitate fast, cheap, robust prototype wearables[5].

We would welcome future work which investigates parametric design of on-skin electrode placement, considering a variety of tasks but also other modalities. Electrode sleeves designed with our method could also be used for collecting other physiological measures [44], or providing electrotactile output [79]. To create fully customizeable electrode sleeves, our manufacturing technique might be complimented with parametric design tools which consider body size and shape of the user, as well as the intended task, for generating optimal electrode layouts.

An outstanding problem not addressed in this work is that current sleeve designs require electrode gel. This gel is the first part of the sleeve to degrade, it adds rigidity to the sleeve, and can make application and removal of the sleeve cumbersome. In future iterations we intend to explore alternatives to electrode gel. Such solutions are emerging, for example the use of embroidered thread [70] or textiles fused to conductive silicone[6].

It should also, again, be noted that our sleeve designs focus on the placement of electrodes and their integration with the textile. Our current designs assume that the stimulation circuitry is kept separate from the sleeves, for example in an arm band akin to Nishida et al. [43]. The Manufacturing and Typing Sleeves, for example, leave connection points exposed at the top of the sleeve, for connection via crocodile clips (see Figure 6.9). Having taken steps to optimise the design of the electrodes and wiring, we could now take steps to optimise the design of the circuitry. Previous EMS research has contributed circuitry design (e.g., [28, 54]), however none have yet optimised for wearability.

The criteria presented are informed by our expertise and experience as interaction and eTextile designers and tailors. In the future, these design criteria may be further refined through user evaluations and real world deployments. In turn, these future insights may reveal valuable complexities in the interplay between the criteria.

6 CONCLUSION

Many existing explorations of wearables for HCI consider functionality first and wearability second. One such example, is a recent electrode sleeve for electric muscle stimulation (EMS) by Knibbe et al. [28]. This sleeve represented technical advances for EMS (incorporating an order of magnitude more electrodes than typically seen), but lacked the general properties expected of garments (the sleeve was fragile, movement constraining, difficult to put on, etc.). Typically, as the technologies, designs, and experiential understanding develops, attention can shift towards questions of deployment and wearability. Our own prototyping work took a similar trajectory.

In this paper we have presented three electrode sleeve designs and analyzed their strengths and weaknesses. In analyzing our process, we have noted that in addition to the design criteria of wearability commonly discussed in the literature, questions considering deployability, customization, and manufacturing should be also considered central to the concept of wearability. Finally, the process first presented in iteration 2 – the *Manufacturing Sleeve* – and further developed in iteration 3 – the *Typing Sleeve* – provides a general purpose approach towards designing not only EMS sleeves, but complex and highly integrated wearables in general.

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[5]https://skillsleeves.github.io/

[6]https://statex.de/wp-content/uploads/2020/04/ShieldexSilitex_P130_V.06.pdf

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REFERENCES

[1] David Ahlström, Khalad Hasan, and Pourang Irani. 2014. Are You Comfortable Doing That?: Acceptance Studies of Around-device Gestures in and for Public Settings. In *Proceedings of the ACM International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI'14) (MobileHCI'14)*. ACM, New York, NY, USA, 193–202. https://doi.org/10.1145/2628363.2628381

[2] Daniel L. Ashbrook, James R. Clawson, Kent Lyons, Thad E. Starner, and Nirmal Patel. 2008. Quickdraw: The Impact of Mobility and on-Body Placement on Device Access Time. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 219–222. https://doi.org/10.1145/1357054.1357092

[3] Joanna Berzowska, Alex Mommersteeg, Laura Isabel Rosero Grueso, Eric Ducray, Michael Patrick Rabo, and Geneviève Moisan. 2019. Baby Tango: Electronic Textile Toys for Full-Body Interaction. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 437–442. https://doi.org/10.1145/3294109.3300973

[4] Joanna Berzowska and Maksim Skorobogatiy. 2010. Karma Chameleon: Bragg Fiber Jacquard-Woven Photonic Textiles. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 297–298. https://doi.org/10.1145/1709886.1709950

[5] Stephen Brewster, Roderick Murray-Smith, Andrew Crossan, Yolanda Vasquez-Alvarez, and Julie Rico. 2009. The GAIME Project: Gestural and Auditory Interactions for Mobile Environments. In *Whole Body Interaction Workshop*. ACM CHI 2019. http://eprints.gla.ac.uk/34242/.

[6] Audrey Briot, Cedric Honnet, and Paul Strohmeier. 2020. Stymphalian Birds - Exploring the Aesthetics of A Hybrid Textile. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS' 20 Companion)*. Association for Computing Machinery, New York, NY, USA, 437–440. https://doi.org/10.1145/3393914.3395840

[7] Jesse Burstyn, Paul Strohmeier, and Roel Vertegaal. 2015. DisplaySkin: Exploring Pose-Aware Displays on a Flexible Electrophoretic Wristband. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 165–172. https://doi.org/10.1145/2677199.2680596

[8] Ruth Casper. 2009. Guidelines for instrumentation of wild birds and mammals. *Animal Behaviour - ANIM BEHAV* 78 (12 2009), 1477–1483. https://doi.org/10.1016/j.anbehav.2009.09.023

[9] David Dobbelstein, Philipp Hock, and Enrico Rukzio. 2015. Belt: An Unobtrusive Touch Input Device for Head-Worn Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2135–2138. https://doi.org/10.1145/2702123.2702450

[10] Tim Duente, Max Pfeiffer, and Michael Rohs. 2017. Zap++: A 20-Channel Electrical Muscle Stimulation System for Fine-Grained Wearable Force Feedback. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Vienna, Austria) *(MobileHCI '17)*. Association for Computing Machinery, New York, NY, USA, Article 1, 13 pages. https://doi.org/10.1145/3098279.3098546

[11] Lucy E. Dunne, Halley Profita, Clint Zeagler, James Clawson, Scott Gilliland, Ellen Yi-Luen Do, and Jim Budd. 2014. The Social Comfort of Wearable Technology and Gestural Interaction. In *Proceedings of the IEEE Engineering in Medicine and Biology Society (EMBC'14) (EMBC'14)*. 4159–4162. https://doi.org/10.1109/EMBC.2014.6944540

[12] Lucy E. Dunne and Barry Smyth. 2007. Psychophysical Elements of Wearability. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '07)*. Association for Computing Machinery, New York, NY, USA, 299–302. https://doi.org/10.1145/1240624.1240674

[13] Barrett Ens, Tovi Grossman, Fraser Anderson, Justin Matejka, and George Fitzmaurice. 2015. Candid Interaction: Revealing Hidden Mobile and Wearable Computing Activities. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 467–476. https://doi.org/10.1145/2807442.2807449

[14] Junjun Fan, Xiangmin Fan, Feng Tian, Yang Li, Zitao Liu, Wei Sun, and Hongan Wang. 2018. What is That in Your Hand? Recognizing Grasped Objects via Forearm Electromyography Sensing. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 4, Article 161 (Dec. 2018), 24 pages. https://doi.org/10.1145/3287039

[15] Rachel Freire, Cedric Honnet, and Paul Strohmeier. 2017. Second Skin: An Exploration of ETextile Stretch Circuits on the Body. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction* (Yokohama, Japan) *(TEI '17)*. Association for Computing Machinery, New York, NY, USA, 653–658. https://doi.org/10.1145/3024969.3025054

[16] Rachel Freire, Paul Strohmeier, Cedric Honnet, Jarrod Knibbe, and Sophia Brueckner. 2018. Designing ETextiles for the Body: Shape, Volume & Motion. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 728–731. https://doi.org/10.1145/3173225.3173331

[17] Francine. Gemperle, Chris Kasabach, John Stivoric, Malcolm Bauer, and Richard Martin. 1998. Design for Wearability. In *Proceedings of the 2nd IEEE International Symposium on Wearable Computers (ISWC '98)*. IEEE Computer Society, USA, 116.

[18] Vivian Genaro Motti and Kelly Caine. 2014. Understanding the Wearability of Head-Mounted Devices from a Human-Centered Perspective. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers* (Seattle, Washington) *(ISWC '14)*. Association for Computing Machinery, New York, NY, USA, 83–86. https://doi.org/10.1145/2634317.2634340

[19] Bruna Goveia da Rocha and Oscar Tomico. 2019. Flow: Towards Communicating Directional Cues through Inflatables. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3290607.3312828

[20] Chris Harrison, Brian Y. Lim, Aubrey Shick, and Scott E. Hudson. 2009. Where to Locate Wearable Displays? Reaction Time Performance of Visual Alerts from Tip to Toe. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 941–944. https://doi.org/10.1145/1518701.1518845

[21] Mariam Hassib, Max Pfeiffer, Stefan Schneegass, Michael Rohs, and Florian Alt. 2017. Emotion Actuator: Embodied Emotional Feedback Through Electroencephalography and Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 6133–6146. https://doi.org/10.1145/3025453.3025953

[22] Sarah Homewood. 2018. Designing for the Changing Body: A Feminist Exploration of Self-Tracking Technologies. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3170427.3173031

[23] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier. 2020. PolySense: Augmenting Textiles with Electrical Functionality Using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376841

[24] Ali Israr and Ivan Poupyrev. 2011. Tactile Brush: Drawing on Skin with a Tactile Grid Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2019–2028. https://doi.org/10.1145/1978942.1979235

[25] Shunichi Kasahara, Jun Nishida, and Pedro Lopes. 2019. Preemptive Action: Accelerating Human Reaction Using Electrical Muscle Stimulation Without Compromising Agency. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3290605.3300873

[26] Norene Kelly. 2017. All the World's a Stage: What Makes a Wearable Socially Acceptable. *Interactions* 24, 6 (Oct. 2017), 56–60. https://doi.org/10.1145/3137093

[27] Jarrod Knibbe, Adrian Alsmith, and Kasper Hornbæk. 2018. Experiencing Electrical Muscle Stimulation. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3, Article 118 (Sept. 2018), 14 pages. https://doi.org/10.1145/3264928

[28] Jarrod Knibbe, Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. 2017. Automatic Calibration of High Density Electric Muscle Stimulation. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3, Article 68 (Sept. 2017), 17 pages. https://doi.org/10.1145/3130933

[29] Marion Koelle, Swamy Ananthanarayan, and Susanne Boll. 2020. Social Acceptability in HCI: A Survey of Methods, Measures, and Design Strategies. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI'20)*. ACM, New York, NY, USA, 1–19. https://doi.org/10.1145/3313831.3376162

[30] Marion Koelle, Matthias Kranz, and Andreas Möller. 2015. Don't Look at Me That Way! Understanding User Attitudes Towards Data Glasses Usage. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Copenhagen, Denmark) *(MobileHCI '15)*. Association for Computing Machinery, New York, NY, USA, 362–372. https://doi.org/10.1145/2785830.2785842

[31] Marion Koelle, Torben Wallbaum, Wilko Heuten, and Susanne Boll. 2019. Evaluating a Wearable Camera's Social Acceptability In-the-Wild. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3290607.3312837

[32] Marion Koelle, Katrin Wolf, and Susanne Boll. 2018. Beyond LED Status Lights - Design Requirements of Privacy Notices for Body-Worn Cameras. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 177–187. https://doi.org/10.1145/3173225.3173234

[33] Chen Li, Chang-Franw Lee, and Song Xu. 2020. Stigma Threat in Design for Older Adults: Exploring Design Factors that Induce Stigma Perception. *International Journal of Design* 14, 1 (2020).

[34] Ruibo Liu, Qijia Shao, Siqi Wang, Christina Ru, Devin Balkcom, and Xia Zhou. 2019. Reconstructing Human Joint Motion with Computational Fabrics. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 3, 1, Article 19 (March 2019), 26 pages. https://doi.org/10.1145/3314406

[35] Xin Liu, Katia Vega, Pattie Maes, and Joe A. Paradiso. 2016. Wearability Factors for Skin Interfaces. In *Proceedings of the 7th Augmented Human International Conference 2016* (Geneva, Switzerland) *(AH '16)*. Association for Computing Machinery, New York, NY, USA, Article 21, 8 pages. https://doi.org/10.1145/2875194.2875248

[36] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 939–948. https://doi.org/10.1145/2702123.2702461

[37] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++: Allowing Objects to Communicate Dynamic Use. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2515–2524. https://doi.org/10.1145/2702123.2702128

[38] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600

[39] Pedro Lopes, Doăa Yüksel, François Guimbretière, and Patrick Baudisch. 2016. Muscle-Plotter: An Interactive System Based on Electrical Muscle Stimulation That Produces Spatial Output. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 207–217. https://doi.org/10.1145/2984511.2984530

[40] Jess McIntosh, Charlie McNeill, Mike Fraser, Frederic Kerber, Markus Löchtefeld, and Antonio Krüger. 2016. EMPress: Practical Hand Gesture Classification with Wrist-Mounted EMG and Pressure Sensing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 2332–2342. https://doi.org/10.1145/2858036.2858093

[41] Calkin S. Montero, Jason Alexander, Mark T. Marshall, and Sriram Subramanian. 2010. Would you do that?: Understanding Social Acceptance of Gestural Interfaces.. In *Proceedings of the ACM International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileCHI'10) (MobileHCI'10)*. ACM Press, New York, New York, USA, 275. https://doi.org/10.1145/1851600.1851647

[42] Florian Floyd Mueller, Pedro Lopes, Paul Strohmeier, Wendy Ju, Caitlyn Seim, Martin Weigel, Suranga Nanayakkara, Marianna Obrist, Zhuying Li, Joseph Delfa, Jun Nishida, Elizabeth M. Gerber, Dag Svanaes, Jonathan Grudin, Stefan Greuter, Kai Kunze, Thomas Erickson, Steven Greenspan, Masahiko Inami, Joe Marshall, Harald Reiterer, Katrin Wolf, Jochen Meyer, Thecla Schiphorst, Dakuo Wang, and Pattie Maes. 2020. Next Steps for Human-Computer Integration. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3313831.3376242

[43] Jun Nishida and Kenji Suzuki. 2017. BioSync: A Paired Wearable Device for Blending Kinesthetic Experience. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3316–3327. https://doi.org/10.1145/3025453.3025829

[44] Aditya Shekhar Nittala, Arshad Khan, Klaus Kruttwig, Tobias Kraus, and Jürgen Steimle. 2020. PhysioSkin: Rapid Fabrication of Skin-Conformal Physiological Interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3313831.3376366

[45] Alex Olwal, Jon Moeller, Greg Priest-Dorman, Thad Starner, and Ben Carroll. 2018. I/O Braid: Scalable Touch-Sensitive Lighted Cords Using Spiraling, Repeating Sensing Textiles and Fiber Optics. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings* (Berlin, Germany) *(UIST '18 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 203–207. https://doi.org/10.1145/3266037.3271651

[46] Simon Ozbek. 2018. Novel Manufacturing of Advanced Smart Garment Knitting with Spatially-Varying, Multi-Material Monofilament. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers* (Singapore, Singapore) *(UbiComp '18)*. Association for Computing Machinery, New York, NY, USA, 1851–1854. https://doi.org/10.1145/3267305.3277842

[47] Patrizia Paci, Clara Mancini, and Blaine A. Price. 2019. Designing for Wearability: An Animal-Centred Framework. In *Proceedings of the Sixth International Conference on Animal-Computer Interaction* (Haifa, Israel) *(ACI'19)*. Association for Computing Machinery, New York, NY, USA, Article 8, 12 pages. https://doi.org/10.1145/3371049.3371051

[48] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 745–756. https://doi.org/10.1145/3242587.3242664

[49] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal, and Michael Haller. 2017. SmartSleeve: Real-Time Sensing of Surface and Deformation Gestures on Flexible, Interactive Textiles, Using a Hybrid Gesture Detection Pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 565–577. https://doi.org/10.1145/3126594.3126652

[50] Max Pfeiffer, Tim Duente, and Michael Rohs. 2016. Let Your Body Move: A Prototyping Toolkit for Wearable Force Feedback with Electrical Muscle Stimulation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Florence, Italy) *(MobileHCI '16)*. Association for Computing Machinery, New York, NY, USA, 418–427. https://doi.org/10.1145/2935334.2935348

[51] Max Pfeiffer, Tim Dünte, Stefan Schneegass, Florian Alt, and Michael Rohs. 2015. Cruise Control for Pedestrians: Controlling Walking Direction Using Electrical Muscle Stimulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2505–2514. https://doi.org/10.1145/2702123.2702190

[52] Max Pfeiffer and Michael Rohs. 2017. *Haptic Feedback for Wearables and Textiles Based on Electrical Muscle Stimulation.* Springer International Publishing, Cham, 103–137. https://doi.org/10.1007/978-3-319-50124-6_6

[53] Max Pfeiffer and Michael Rohs. 2017. *Haptic Feedback for Wearables and Textiles Based on Electrical Muscle Stimulation.* Springer International Publishing, Cham, 103–137. https://doi.org/10.1007/978-3-319-50124-6_6

[54] Max Pfeiffer, Stefan Schneegass, Florian Alt, and Michael Rohs. 2014. Let Me Grab This: A Comparison of EMS and Vibration for Haptic Feedback in Free-hand Interaction. In *Proceedings of the 5th Augmented Human International Conference (AH '14)*. ACM, New York, NY, USA, 48:1–48:8. https://doi.org/10.1145/2582051.2582099

[55] Henning Pohl, Kasper Hornbæk, and Jarrod Knibbe. 2018. Wanding Through Space: Interactive Calibration for Electric Muscle Stimulation. In *Proceedings of the 9th Augmented Human International Conference (AH '18)*. ACM, New York, NY, USA, 19:1–19:5. https://doi.org/10.1145/3174910.3174948

[56] Andreas Pointner, Thomas Preindl, Sara Mlakar, Roland Aigner, and Haller Michael. 2020. Knitted RESi: A Highly Flexible, Force-Sensitive Knitted Textile Based on Resistive Yarns *(SIGGRAPH)*.

[57] Dejan B. Popović and Mirjana B. Popović. 2011. Chapter 16 - Advances in the use of electrical stimulation for the recovery of motor function. In *Brain Machine Interfaces: Implications for Science, Clinical Practice and Society*, Jens Schouenborg, Martin Garwicz, and Nils Danielsen (Eds.). Progress in Brain Research, Vol. 194. Elsevier, 215 – 225. https://doi.org/10.1016/B978-0-444-53815-4.00005-4

[58] Ana Popović-Bijelić, Goran Bijelić, Nikola Jorgovanović, Dubravka Bojanić, Mirjana B. Popović, and Dejan B. Popović. 2005. Multi-Field Surface Electrode for Selective Electrical Stimulation. *Artificial Organs* 29, 6 (2005), 448–452. https://doi.org/10.1111/j.1525-1594.2005.29075.x arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1525-1594.2005.29075.x

[59] Ernest Rehmi Post, M. Orth, P. R. Russo, and N. Gershenfeld. 2000. E-Broidery: Design and Fabrication of Textile-Based Computing. *IBM Syst. J.* 39, 3–4 (July 2000), 840–860. https://doi.org/10.1147/sj.393.0840

[60] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227. https://doi.org/10.1145/2858036.2858176

[61] Halley Profita, Nicholas Farrow, and Nikolaus Correll. 2015. Flutter: An Exploration of an Assistive Garment Using Distributed Sensing, Computation and Actuation. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 359–362. https://doi.org/10.1145/2677199.2680586

[62] Halley P. Profita, James Clawson, Scott Gilliland, Clint Zeagler, Thad Starner, Jim Budd, and Ellen Yi-Luen Do. 2013. Don't Mind Me Touching My Wrist: A Case Study of Interacting with on-Body Technology in Public. In *Proceedings of*

the 2013 International Symposium on Wearable Computers (Zurich, Switzerland) *(ISWC '13)*. Association for Computing Machinery, New York, NY, USA, 89–96. https://doi.org/10.1145/2493988.2494331

[63] Halley P Profita, Asta Roseway, and Mary Czerwinski. 2016. Personal and Social Considerations of Wearable Light Therapy for Seasonal Affective Disorder. In *Proceedings of the 10th EAI International Conference on Pervasive Computing Technologies for Healthcare* (Cancun, Mexico) *(PervasiveHealth '16)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), Brussels, BEL, 194–201.

[64] Afroditi Psarra and Audrey Briot. 2019. Listening Space: Satellite Ikats. In *Proceedings of the 23rd International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 318–321. https://doi.org/10.1145/3341163.3346932

[65] Luis Miguel Salvado and Artur Arsenio. 2016. Sleeve Sensing Technologies and Haptic Feedback Patterns for Posture Sensing and Correction. In *Companion Publication of the 21st International Conference on Intelligent User Interfaces* (Sonoma, California, USA) *(IUI '16 Companion)*. Association for Computing Machinery, New York, NY, USA, 74–78. https://doi.org/10.1145/2876456.2879489

[66] Albrecht Schmidt. 2015. Following or Leading? The HCI Community and New Interaction Technologies. *Interactions* 22, 1 (Jan. 2015), 74–77. https://doi.org/10.1145/2692980

[67] Richard Allen Schmidt, Timothy D Lee, Carolee J Winstein, Gabriele Wulf, and Howard Zelaznik. 2019. *Motor Control and Learning: A Behavioral Emphasis* (sixth edition ed.). Vol. 51. Human Kinetics. 226 pages. https://doi.org/10.1249/01.mss.0000550736.00894.1f

[68] Stefan Schneegass and Alexandra Voit. 2016. GestureSleeve: Using Touch Sensitive Fabrics for Gestural Input on the Forearm for Controlling Smartwatches. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 108–115. https://doi.org/10.1145/2971763.2971797

[69] Valentin Schwind, Niklas Deierlein, Romina Poguntke, and Niels Henze. 2019. Understanding the Social Acceptability of Mobile Devices Using the Stereotype Content Model. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'19)* (Glasgow, Scotland Uk) *(CHI'19)*. ACM, New York, NY, USA, Article 361, 12 pages. https://doi.org/10.1145/3290605.3300591

[70] Ali Shafti, Roger Manero, Amanda Borg, Kaspar Althoefer, and Matthew Howard. 2016. Embroidered Electromyography: A Systematic Design Guide. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* PP (10 2016). https://doi.org/10.1109/TNSRE.2016.2633506

[71] Kristen Shinohara and Jacob O. Wobbrock. 2011. In the Shadow of Misperception: Assistive Technology Use and Social Interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'11) (CHI'11)*. ACM, New York, NY, 705–714. https://doi.org/10.1145/1978942.1979044

[72] Sophie Skach, Rebecca Stewart, and Patrick G. T. Healey. 2018. Smart Arse: Posture Classification with Textile Sensors in Trousers. In *Proceedings of the 20th ACM International Conference on Multimodal Interaction* (Boulder, CO, USA) *(ICMI '18)*. Association for Computing Machinery, New York, NY, USA, 116–124. https://doi.org/10.1145/3242969.3242977

[73] Erin Treacy Solovey, Francine Lalooses, Krysta Chauncey, Douglas Weaver, Margarita Parasi, Matthias Scheutz, Angelo Sassaroli, Sergio Fantini, Paul Schermerhorn, Audrey Girouard, and Robert J.K. Jacob. 2011. Sensing Cognitive Multitasking for a Brain-Based Adaptive User Interface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 383–392. https://doi.org/10.1145/1978942.1978997

[74] Paul Strohmeier, Jarrod Knibbe, Sebastian Boring, and Kasper Hornbæk. 2018. ZPatch: Hybrid Resistive/Capacitive ETextile Input. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 188–198. https://doi.org/10.1145/3173225.3173242

[75] Emi Tamaki, Takashi Miyaki, and Jun Rekimoto. 2011. PossessedHand: Techniques for Controlling Human Hands Using Electrical Muscles Stimuli. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 543–552. https://doi.org/10.1145/1978942.1979018

[76] Sakari Tamminen and Elisabet Holmgren. 2016. The anthropology of wearables: The self, the social, and the autobiographical. In *Ethnographic Praxis in Industry Conference Proceedings*, Vol. 2016. Wiley Online Library, 154–174.

[77] Aaron Toney, Barrie Mulley, Bruce H. Thomas, and Wayne Piekarski. 2003. Social Weight: Designing to Minimise the Social Consequences arising from Technology Use by the Mobile Professional. *PERS UBIQUIT COMPUT* 7, 5 (2003), 309–320. https://doi.org/10.1007/s00779-003-0245-8

[78] Frederik Wiehr, Felix Kosmalla, Florian Daiber, and Antonio Krüger. 2017. FootStriker: An EMS-based Foot Strike Assistant for Running. In *Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers* (Maui, Hawaii) *(UbiComp '17)*. ACM, New York, NY, USA, 317–320. https://doi.org/10.1145/3123024.3123191

[79] Anusha Withana, Daniel Groeger, and Jürgen Steimle. 2018. Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 365–378. https://doi.org/10.1145/3242587.3242645

[80] Clint Zeagler. 2017. Where to Wear It: Functional, Technical, and Social Considerations in on-Body Location for Wearable Technology 20 Years of Designing for Wearability. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (Maui, Hawaii) *(ISWC '17)*. Association for Computing Machinery, New York, NY, USA, 150–157. https://doi.org/10.1145/3123021.3123042

[81] Mengjia Zhu, Amirhossein H. Memar, Aakar Gupta, Majed Samad, Priyanshu Agarwal, Yon Visell, Sean J. Keller, and Nicholas Colonnese. 2020. PneuSleeve: In-Fabric Multimodal Actuation and Sensing in a Soft, Compact, and Expressive Haptic Sleeve. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376333