SkinLace: Freestanding Lace by Machine Embroidery for On-Skin Interface

Jeyeon Jo
Cornell University, Ithaca, USA
jj693@cornell.edu

Hsin-Liu (Cindy) Kao
Cornell University, Ithaca, USA
cindykao@cornell.edu

ABSTRACT

Freestanding lace is a method to create a lace by machine embroidery. Lace has advantages compared to the other fabrics in terms of skin-compatibility, weight, and aesthetics. In this paper, we present SkinLace, a freestanding lace by machine embroidery for on-skin interface. Conductive thread, water-soluble stabilizer, and home embroidery machine can create SkinLace, which is aesthetic, light, skin-compatible, body-conforming, durable, and inexpensive. The freestanding lace approach enables aesthetic customizable lace and patches through a combination of non-conductive and colorful threads. We propose three different applications of SkinLace; on-skin displays, capacitive touch sensing, and RFID tag antenna. Tension of the thread in the embroidery machine and the accuracy of the stitch are the main challenges, but the advantages and potential to create more complex circuitry and to enhance sensing capability present rich opportunities for further exploration.

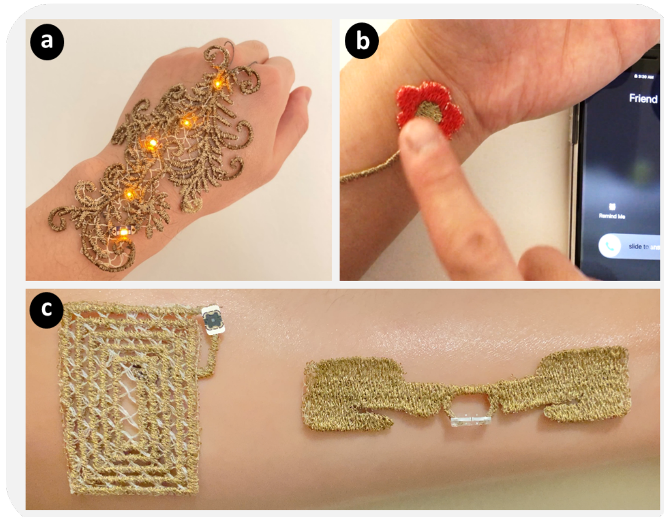

Figure 1: SkinLace is a fabrication method to create freestanding laces for on-skin interfaces such as (a) on-skin displays (b) capacitive touch electrodes, or (c) RFID tags.

CCS CONCEPTS

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

KEYWORDS

On-skin interface, lace, embroidery, e-textile, fabrication

ACM Reference Format:
Jeyeon Jo and Hsin-Liu (Cindy) Kao. 2021. SkinLace: Freestanding Lace by Machine Embroidery for On-Skin Interface. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '21 Extended Abstracts), May 08–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3411763.3451756

1 INTRODUCTION

Lace is a decorative fabric that consists of open motifs. It is semi-transparent thanks to the voids around the motif, so it often works as a home decoration fabric such as curtains creating patterned shades and moderate penetration of sunlight. It is more popular in use to make a cloth look elegant. When a panel of a garment uses lace only, it guarantees high ventilation and breathability based on its structure which does not completely cover the surface. This aesthetic, body-conforming, thread connection-based structure of lace can be beneficial for a circuitry making for on-skin devices, but it has not had a strong presence in Human-Computer Interaction (HCI) except in one instance [28]. While they focused on the fabric form factor with a fixed shape, we extended it to investigate its broad potential as on-skin applications in this work.

Among various methods to create a lace, the freestanding lace approach has distinct advantages: it does not need a big industrial lace making machine, nor does it require manufacturing in a certain shape such as a rectangle. The freestanding lace is appropriate for fabrication of an on-skin interface that affords various shapes and customization based on the user's preference and comfort. In this research-through-design [9] investigation, we explore possibilities of the freestanding lace to expand the realm of smart textile-based on-skin interface and to contribute to the HCI community as follows:

- We present SkinLace, a fabrication method to create freestanding laces based on machine embroidery for on-skin interfaces.
- We introduce water-soluble stabilizer as the key material enabling the SkinLace freestanding lace approach, which enables the fabrication of the porous structure of lace without expensive and large industrial lace making machines.
- We present initial applications of SkinLace including an on-skin display, capacitive touch electrode, and RFID tags.

CHI '21 Extended Abstracts, May 08–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8095-9/21/05…$15.00
https://doi.org/10.1145/3411763.3451756

2 RELATED WORK

2.1 On-skin interface

On-skin interfaces can be defined as digital transformations of human skin into a device communicating with other electronic devices. It allows the user both to send and to receive a signal in the form of electronic, visual, haptic, and auditory communication. Various on-skin interfaces have emerged in the HCI community and most of them are focusing on the invention of light, thin, soft and skin-compatible on-skin devices. Epidermal electronics with micro-level thin structure based on tattoo substrates are one of the representatives of this trend [26]. Other than that, materials such as gold leaf [24], conductive thread/textile [5, 11, 38], conductive ink [31], color-changing pigment [25, 41, 43], SMA [13, 15], and polymers [21, 32, 44, 45] have shown possibilities to fabricate PCB, input sensor, and output actuator on human skin, which is appealing to the customers [49]. Nail [23, 37] and hair [6, 40] are also emerging body locations for on-skin interfaces.

2.2 E-textile

E-textile are textiles that can communicate with other components/users electronically or chemically. So far most of the commercial wearable products are using rigid PCB boards and components that do not conform to the human body surface, and most of polymer-based soft electronics does not have enough water vapor transmission to prevent skin irritation [48]. On the other hand, textiles have been the main material that covers the skin in human history and shown possibilities as soft electronics improving user experience. Fabrication of e-textile includes most textile construction methods and other methods such as conductive coating. Weaving [5, 8, 38], knitting [2, 30], felting [4], and lace [28] can integrate conductive yarns into the structure of the fabric itself. On the other hand, stitching [14, 22], embroidering [1, 10–12, 28, 34], inkjet printing [19, 36] and screen printing [3, 31] can add conductive features to the pre-manufactured fabric. The former has merits to create seamless and firm integration of the conductive material while the latter allows more dynamic circuit design on the fabric almost regardless of the fabric structure. However, textiles basically have 2D rectanglar structure (or at least a cylinder shape in case of knit) with raw edges that can get loose, so it requires darts or finishing to make it body conformal and durable, especially to be an on-skin interface.

2.3 Freestanding lace

Lace is basically an open web of yarns, but the way to do this varies. Contemporary lace mostly comes from a big industrial lace making machine using a lot of individual spools, which is the advanced version of bobbin lace [7, 18]. Another major traditional method is needlepoint lace only using a single strand of thread and a needle [39]. Main difference between embroidery and lace is the existence of a supportive fabric and the open and repetitive motifs; while lace exists alone because it is a fabric by itself, embroidery needs a supportive fabric that is embroidered. Freestanding lace is one of the chemical laces, which mostly uses a water-soluble stabilizer and embroiders on it. After embroidering, a web-like lace structure appears when the water dissolves the stabilizer [29].

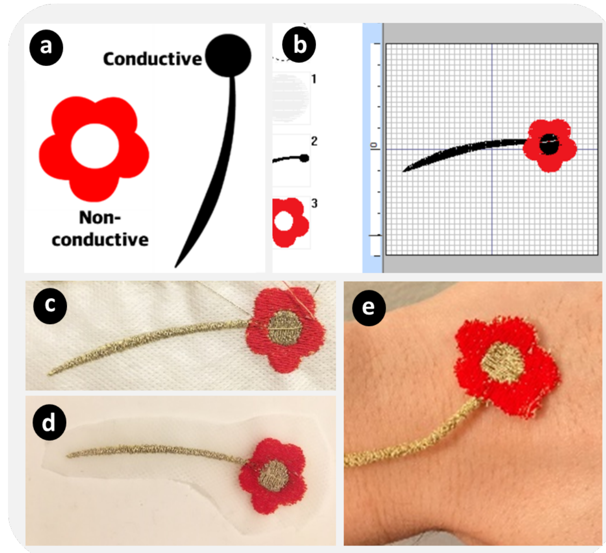

Figure 2: Fabrication process of SkinLace. (a) Lace component design, (b) import the design into embroidery software and define stitch specifications, (c) embroidery on water-soluble stabilizers, (d) dissolve the stabilizer, and (e) attach on the skin using a hairspray.

3 FABRICATION

3.1 Materials and tools

We used a commercially available conductive thread for sewing machine (Shieldex 117/17 dtex 2-ply Size 33 Highly Conductive Sewing Thread) and a normal polyester thread (Coats & Clark Dual Duty All-Purpose Thread) to fabricate SkinLace. In terms of the conductive thread, thickness and conductivity are important factors to keep the conductivity even after using an embroidery machine. Softer and more conductive thread is always better, and the resistance of the thread in this study is 2-3Ω/cm. Since this method takes advantage of machine stitching unlike conventional lace-making techniques mostly twisting yarns with various thickness, thickness of the thread matters and it is up to the machine. In this study, the thickness of the conductive thread is 252 Denier. We also used another key material, a water-soluble stabilizer (World Weidner FSL Non Woven Water Soluble Machine Embroidery Stabilizer) as a supportive fabric of the embroidery process. We embroidered on the stabilizer without any other fabric to create a web structure, so the stabilizer should be strong enough to bear repetitive needle penetrations by an embroidery machine. We used a home embroidery machine (Brother PE-770) and its bundle software (PE-DESIGN PLUS) to fabricate our designs.

3.2 Method

Fabrication process consists of the following five steps (Figure 2):

1) Design a lace using a graphic tool or the given embroidery software. A picture can work as a source for a patch-like design up to the embroidery software. The design needs

to combine the circuitry for the on-skin interface and its aesthetic features.

2) Import the design graphic into the embroidery software to set up colors of each part, to adjust the order of the filling stitches, and to define the specification such as stitch density. Stitch density corresponds proportionally to conductivity and thickness of the device and it was between 4-4.5 lines/mm in this study. If the filling stitch direction is all the same, then foundation thread, which works like a platform or a basis holding the actual filling stitches, can prevent the embroidery from being loose after dissolving the stabilizer. If there are no connected parts or weak structures in the design, a patterned foundation such as grid lines can support the whole lace panel under the actual motifs.
3) Load the water-soluble stabilizer to the embroidery hoop tightly. If there are too many filling stitches for one layer of stabilizer to bear, load more than one layer to the hoop. Adjustment of the thread tension is important, as conductive threads are mostly steep and create high tension. In this study we used the conductive thread as bobbin (bottom) thread to prevent the conductive coating peeling off in the machine. The other (non-conductive) thread (such as polyester) can work as the needle (upper) thread. We discussed this further in Section 5.1. After loading the design to the embroidery machine, let the machine do the embroidery as defined by the software.
4) Unload the finished work from the hoop and cut out the stabilizer leaving a little bit around the edge of the embroidery. We can put the cut piece on a plate with water, and leave for a while until the water fully dissolves the stabilizer. Take the lace carefully from the plate and dry out the moisture gently.
5) After connecting electronic components according to the purpose, attach the SkinLace to the skin using a strong hairspray (Got 2b Glued Blasting Freeze Spray). To attach it securely, apply the hairspray twice or more after the previous application becomes dry.

4 CASE STUDIES

4.1 Textile-based On-skin PCB: An On-Skin Display

SkinLace can work as a textile-based on-skin PCB, which provides opportunities to enhance both functionality and aesthetics. Unlike other types of smart textile PCB, SkinLace is free from the fabric as it is not a part of another fabric structure (e.g. woven, knit, felt), nor dependent on another supportive fabric (e.g. stitch, embroidery, silkscreen). It forms its own structure with freedom in shape and porosity, and does not get loose in edges. This feature allows SkinLace to conform to the 3D shaped body surface unlike other fabrics that need darts or finishing on the edge. It also increases permeability that polymer-based on-skin devices cannot provide, and decreases weight of the device and the material/production cost. Another advantage comes from its aesthetic potential. Web-like motif pattern of lace allows a complex and elegant circuitry. Figure 1a is a simple example of SkinLace PCB inspired by a bridal lace glove. It manipulates a floral lace pattern for a soft circuit

Figure 3: SkinLace applications (a) PCB design for SkinLace (b) four letters as capacitive touch electrodes, (c1-3) image for customized SkinLace, conversion into stitches, and fabricated result with three touch points, and (d) UHF RFID tag and NFC tag.

with LEDs. Supportive grid by non-conductive thread holds two conductive floral patterns which are connected to the poles of a battery respectively (Fig. 3a). Since it consists of threads, it is soft, flexible and light enough to be on the skin, and the strong hairspray (which is also popular to attach a wig on the forehead) can hold the SkinLace for hours in a day. The resistance of a 2mm-wide line (stitch density: 4.5 lines/mm) of SkinLace is 1-1.5Ω.

4.2 Capacitive Touch Sensing

Freestanding lace approach of SkinLace enables various designs for the electrode for capacitive touch sensing. SkinLace can adopt colorful non-conductive threads with the given conductive thread, so that the color combination can create a customized design which is not only aesthetic but also indicates where to touch visually. Non-conductive thread can visually imply where to touch to the users by adopting noticeable shapes and colors. When there are many touch buttons, SkinLace can work as both touch button and wire, and a grid pattern by non-conductive thread can hold every electrode and wire where they have to be, to keep the original design and to prevent any short in the circuit (Fig. 3b).

It is also possible to create a result like an embroidered patch (Fig. 3c). Unlike usual methods which remove non-soluble supportive fabric mechanically, the freestanding lace method uses water-soluble stabilizer and it allows wider options for patch designs because it is easy to create many holes in the patch. Even though the example shown here does not have any holes, if there is one it can help the user to find the touch point easier. The freestanding lace patch can have multiple electrodes based on the design. Furthermore, many embroidery software offers picture-based embroidery for easy customization.

To prevent electrical charges on the skin from interfering with the capacitive touch signals, a thin layer of non-conductive lace can be fabricated at the bottom of the interface to shield the capacitive touch electrodes when worn on skin.

4.3 RFID Tag

We fabricated two types of RFID (Radio Frequency Identification) tag antenna using SkinLace; NFC (Near Field Communication) and UHF (Ultra High Frequency) RFID tag (Fig. 3d). Chip of each tag is attached on the SkinLace antenna by a z-axis conductive tape. The NFC tag fabricated with SkinLace antenna and MIFARE Classic 1k chip responded to a portable NFC reader (ACR1255U-J1), and an UHF RFID reader (Impinj Speedway Revolution R220) can detect the RFID tag that consists of the SkinLace antenna and Monda 4D IC from Smartrac DogBone RFID Wet Inlay. In our test, SkinLace UHF RFID tag showed a slightly lower RSSI (Received Signal Strength Indication, -44.72dB) compared to a usual wet inlay tag (-28.00dB), but there are possibilities to improve the performance by adjusting stitch density, direction and the conductive connection between the antenna and the chip [27, 35, 42]. The NFC reader does not provide the RSSI information, but it could detect the SkinLace NFC tag within 2cm distance. Based on the recent explorations to track human motions and vital signs through radio signals from a tag attached on human body [17, 20, 46], the RFID tags fabricated by SkinLace has a lot of potential not only to identify the user but also to work as a wearable and battery-less sensor [16, 47].

5 DISCUSSION

5.1 Challenges

One of the main challenges is thread tension adjustment within the embroidery machine. Conductive threads mostly are stiffer than usual sewing threads, so the conductive thread can be stuck in the machine many times. Also, it sometimes pulls the needle thread too much and results in the needle thread being visible on the other side along with the conductive thread. On the other hand, if the tension of the needle is too strong, the conductive thread also can go over to the other side, which can make a short in the circuit or an unnecessary contact with the skin. Furthermore, in case of conductive-coated thread, the conductive coating can peel off under high tension, then it will increase the resistance of the device unexpectedly. The thread tension adjustment will be different by the type of embroidery machine, conductive thread, non-conductive thread, and water-soluble stabilizer. In this study, we solved the issue by using the conductive thread as a bobbin thread and the polyester one for the needle thread. It decreased the load on the conductive thread and further adjustment such as turning the screw on the bobbin case also helped, which eventually preserved the conductive coating of the thread. However, this method requires another flipped image only for the conductive part since the filling stitch from the bobbin thread is always on the bottom side.

Another challenge is the accuracy of the stitch in detailed circuit design. SkinLace approach can achieve about 2mm resolution as of now. If the design becomes more complicated and detailed, the embroidery machine can stitch on a wrong place and create a short circuit. This can also happen when the stabilizer becomes loose due to an embroidery with too many stitches. The loosen stabilizer does not hinder any further stitches on the same spot (since the embroidery that is already formed gives a support), but it can give minor effects to the accuracy of the circuit design as the stabilizer slightly moves while becoming loose. Therefore, each electrode connection needs to be confirmed after manufacturing.

5.2 Opportunities

SkinLace can achieve a higher level of complexity in circuity if the tension of the thread is thoroughly controlled. Since the conductivity exists only on the bobbin side of the SkinLace, we can create a layered circuitry simply by placing one onto another. In addition, we use conductive thread and non-conductive thread on bobbin alternatively with different widths and do the embroidery on one spot to make a layered circuitry, which will expand the area of SkinLace a lot more than now.

SkinLace is also promising as a sensor [33]. Other than RFID which can work as wearable sensors through signal processing [17, 20], SkinLace will be able to sense strain or pressure by carefully fabricating physical structure to do it. Manipulation of stitch density & direction, and combination with non-conductive thread will enable the use of SkinLace as a sensor to track many different types of input gestures.

6 CONCLUSION

In this paper, we present SkinLace, a freestanding lace by machine embroidery for on-skin interface. Conductive thread, water-soluble stabilizer, and home embroidery machine can create SkinLace, which is aesthetic, light, skin-compatible, durable, and inexpensive. Freestanding lace approach enables to make both lace and patch with aesthetically pleasing and customizable design through combination with non-conductive and colorful threads. We propose three different uses of SkinLace; on-skin PCB, capacitive touch sensing, and RFID tag antenna. Tension of the thread in the embroidery machine and the accuracy of the stitch are the main challenges, but the advantages and potential to create more complex circuitry and to enhance sensing capability present numerous opportunities for on-skin interfaces.

ACKNOWLEDGMENTS

We thank other members of the DEA 6040 Future Body Craft course: TAs Md Tahmid Islam Molla and Kim Baum, as well as other course members for their help and thoughtful feedback. We also thank the anonymous reviewers for their comments to improve the manuscript.

REFERENCES

[1] Roland Aigner, Andreas Pointner, Thomas Preindl, Patrick Parzer, and Michael Haller. 2020. Embroidered Resistive Pressure Sensors: A Novel Approach for Textile Interfaces. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 1–13. https://doi.org/10.1145/3313831.3376305

[2] Ozgur Atalay, Asli Atalay, Joshua Gafford, and Conor Walsh. 2018. A highly sensitive capacitive-based soft pressure sensor based on a conductive fabric and a microporous dielectric layer. Advanced materials technologies 3, 1: 1700237.

[3] Ran Cao, Xianjie Pu, Xinyu Du, Wei Yang, Jiaona Wang, Hengyu Guo, Shuyu Zhao, Zuqing Yuan, Chi Zhang, Congju Li, and Zhong Lin Wang. 2018. Screen-Printed Washable Electronic Textiles as Self-Powered Touch/Gesture Tribo-Sensors for

Intelligent Human–Machine Interaction. ACS Nano 12, 6: 5190–5196. https://doi.org/10.1021/acsnano.8b02477

[4] Matthew J. Catenacci, Christopher Reyes, Mutya A. Cruz, and Benjamin J. Wiley. 2018. Stretchable conductive composites from Cu–Ag nanowire felt. ACS nano 12, 4: 3689–3698.

[5] Laura Devendorf and Chad Di Lauro. 2019. Adapting Double Weaving and Yarn Plying Techniques for Smart Textiles Applications. In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction, 77–85.

[6] Christine Dierk, Sarah Sterman, Molly Jane Pearce Nicholas, and Eric Paulos. 2018. HäirIÖ: Human Hair as Interactive Material. In Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction, 148–157. https://doi.org/10.1145/3173225.3173232

[7] Pat Earnshaw. 1995. How to recognise machine laces. Gorse Publications, Guildford, England. Retrieved January 6, 2021 from https://newcatalog.library.cornell.edu/catalog/2751747

[8] Mikhaila Friske, Shanel Wu, and Laura Devendorf. 2019. Adacad: Crafting software for smart textiles design. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1–13.

[9] William Gaver. 2012. What should we expect from research through design? In Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12, 937. https://doi.org/10.1145/2207676.2208538

[10] S Gilliland, N Komor, T Starner, and C Zeagler. 2010. The Textile Interface Swatchbook: Creating graphical user interface-like widgets with conductive embroidery. In International Symposium on Wearable Computers (ISWC) 2010, 1–8. https://doi.org/10.1109/ISWC.2010.5665876

[11] Maas Goudswaard, Abel Abraham, Bruna Goveia da Rocha, Kristina Andersen, and Rong-Hao Liang. 2020. FabriClick: Interweaving Pushbuttons into Fabrics Using 3D Printing and Digital Embroidery. In Proceedings of the 2020 ACM Designing Interactive Systems Conference, 379–393. https://doi.org/10.1145/3357236.3395569

[12] Bruna Goveia da Rocha, Oscar Tomico, Panos Markopoulos, and Daniel Tetteroo. 2020. Crafting Research Products through Digital Machine Embroidery. In Proceedings of the 2020 ACM Designing Interactive Systems Conference, 341–350. https://doi.org/10.1145/3357236.3395443

[13] Rachael Granberry, Kevin Eschen, Brad Holschuh, and Julianna Abel. 2019. Functionally Graded Knitted Actuators with NiTi-Based Shape Memory Alloys for Topographically Self-Fitting Wearables. Advanced materials technologies 4, 11: 1900548.

[14] Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. 2018. Sketch&Stitch: Interactive Embroidery for E-textiles. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, 1–13. https://doi.org/10.1145/3173574.3173656

[15] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers. 2019. Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1–14. https://doi.org/10.1145/3290605.3300718

[16] M. Hasani, A. Vena, L. Sydänheimo, L. Ukkonen, and M. M. Tentzeris. 2013. Implementation of a Dual-Interrogation-Mode Embroidered RFID-Enabled Strain Sensor. IEEE Antennas and Wireless Propagation Letters 12: 1272–1275. https://doi.org/10.1109/LAWP.2013.2283539

[17] Xiaonan Hui and Edwin C. Kan. 2018. Monitoring vital signs over multiplexed radio by near-field coherent sensing. Nature Electronics 1, 1: 74–78.

[18] Veronika Irvine and Frank Ruskey. 2014. Developing a mathematical model for bobbin lace. Journal of Mathematics and the Arts 8, 3–4: 95–110.

[19] Hanbit Jin, Naoji Matsuhisa, Sungwon Lee, Mohammad Abbas, Tomoyuki Yokota, and Takao Someya. 2017. Enhancing the Performance of Stretchable Conductors for E-Textiles by Controlled Ink Permeation. Advanced Materials 29, 21: 1605848. https://doi.org/10.1002/adma.201605848

[20] Haojian Jin, Zhijian Yang, Swarun Kumar, and Jason I. Hong. 2018. Towards Wearable Everyday Body-Frame Tracking using Passive RFIDs. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 1, 4: 1–23. https://doi.org/10.1145/3161199

[21] Hsin-Liu (Cindy) Kao, Miren Bamforth, David Kim, and Chris Schmandt. 2018. Skinmorph: texture-tunable on-skin interface through thin, programmable gel. In Proceedings of the 2018 ACM International Symposium on Wearable Computers, 196–203. https://doi.org/10.1145/3267242.3267262

[22] Hsin-Liu Cindy Kao, Abdelkareem Bedri, and Kent Lyons. 2018. SkinWire: Fabricating a Self-Contained On-Skin PCB for the Hand. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 2, 3: 1–23. https://doi.org/10.1145/3264926

[23] Hsin-Liu (Cindy) Kao, Artem Dementyev, Joseph A. Paradiso, and Chris Schmandt. 2015. NailO: Fingernails as an Input Surface. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, 3015–3018. https://doi.org/10.1145/2702123.2702572

[24] Hsin-Liu Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. 2016. DuoSkin: rapidly prototyping on-skin user interfaces using skin-friendly materials. In Proceedings of the 2016 ACM International Symposium on Wearable Computers, 16–23.

[25] Hsin-Liu Kao, Manisha Mohan, Chris Schmandt, Joseph A. Paradiso, and Katia Vega. 2016. Chromoskin: Towards interactive cosmetics using thermochromic pigments. In Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems, 3703–3706.

[26] Dae-Hyeong Kim, Nanshu Lu, Rui Ma, Yun-Soung Kim, Rak-Hwan Kim, Shuodao Wang, Jian Wu, Sang Min Won, Hu Tao, and Ahmad Islam. 2011. Epidermal electronics. science 333, 6044: 838–843.

[27] Asimina Kiourti and John L. Volakis. 2015. High-accuracy conductive textiles for embroidered antennas and circuits. In 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 1194–1194. https://doi.org/10.1109/APS.2015.7304985

[28] Kristi Kuusk, Marjan Kooroshnia, and Jussi Mikkonen. 2015. Crafting butterfly lace: conductive multi-color sensor-actuator structure. In Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers - UbiComp '15, 595–600. https://doi.org/10.1145/2800835.2801669

[29] Bonnie Landsberger. 2014. Punching sense: freestanding lace basics. Stitches, 36.

[30] Li Li, Wai Man Au, Kam Man Wan, Sai Ho Wan, Wai Yee Chung, and Kwok Shing Wong. 2010. A resistive network model for conductive knitting stitches. Textile research journal 80, 10: 935–947.

[31] Joanne Lo, Doris Jung Lin Lee, Nathan Wong, David Bui, and Eric Paulos. 2016. Skintillates: Designing and creating epidermal interactions. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems, 853–864.

[32] Eric Markvicka, Guanyun Wang, Yi-Chin Lee, Gierad Laput, Carmel Majidi, and Lining Yao. 2019. ElectroDermis: Fully Untethered, Stretchable, and Highly-Customizable Electronic Bandages. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1–10. https://doi.org/10.1145/3290605.3300862

[33] Marc Martínez-Estrada, Bahareh Moradi, Raúl Fernández-Garcia, and Ignacio Gil. 2019. Impact of Conductive Yarns on an Embroidery Textile Moisture Sensor. Sensors 19, 5: 1004. https://doi.org/10.3390/s19051004

[34] Sara Mlakar and Michael Haller. 2020. Design Investigation of Embroidered Interactive Elements on Non-Wearable Textile Interfaces. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 1–10. https://doi.org/10.1145/3313831.3376692

[35] Elham Moradi, Toni Bjorninen, Leena Ukkonen, and Yahya Rahmat-Samii. 2012. Characterization of embroidered dipole-type RFID tag antennas. In 2012 IEEE International Conference on RFID-Technologies and Applications (RFID-TA), 248–253. https://doi.org/10.1109/RFID-TA.2012.6404522

[36] 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, 1–10. https://doi.org/10.1145/3313831.3376366

[37] Chao-Huai Su, Liwei Chan, Chien-Ting Weng, Rong-Hao Liang, Kai-Yin Cheng, and Bing-Yu Chen. 2013. NailDisplay: bringing an always available visual display to fingertips. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 1461–1464. https://doi.org/10.1145/2470654.2466193

[38] Ruojia Sun, Ryosuke Onose, Margaret Dunne, Andrea Ling, Amanda Denham, and Hsin-Liu (Cindy) Kao. 2020. Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving. In Proceedings of the 2020 ACM Designing Interactive Systems Conference, 365–377. https://doi.org/10.1145/3357236.3395548

[39] Heather Toomer. 2001. Antique lace: identifying types and techniques. Schiffer Pub., Atglen, PA. Retrieved January 6, 2021 from https://babel.hathitrust.org/cgi/pt?id=coo.31924089566974;page=root;seq=7;view=1up;size=100;orient=0

[40] Katia Vega and Hugo Fuks. 2014. Beauty technology: body surface computing. Computer 47, 4: 71–75.

[41] Katia Vega, Nan Jiang, Xin Liu, Viirj Kan, Nick Barry, Pattie Maes, Ali Yetisen, and Joe Paradiso. 2017. The dermal abyss: interfacing with the skin by tattooing biosensors. In Proceedings of the 2017 ACM International Symposium on Wearable Computers, 138–145. https://doi.org/10.1145/3123021.3123039

[42] Dieff Vital, Jingni Zhong, Shubhendu Bhardwaj, and John L. Volakis. 2018. Loss-Characterization and Guidelines for Embroidery of Conductive Textiles. In 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 1301–1302. https://doi.org/10.1109/APUSNCURSINRSM.2018.8609304

[43] Yanan Wang, Shijian Luo, Yujia Lu, Hebo Gong, Yexing Zhou, Shuai Liu, and Preben Hansen. 2017. AnimSkin: fabricating epidermis with interactive, functional and aesthetic color animation. In Proceedings of the 2017 Conference on Designing Interactive Systems, 397–401.

[44] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. 2015. Iskin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, 2991–3000.

[45] Martin Weigel, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. 2017. SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics. In Proceedings of the 2017 CHI Conference on Human Factors in

Computing Systems, 3095–3105. https://doi.org/10.1145/3025453.3025704

[46] Te-Yen Wu, Shutong Qi, Junchi Chen, MuJie Shang, Jun Gong, Teddy Seyed, and Xing-Dong Yang. 2020. Fabriccio: Touchless Gestural Input on Interactive Fabrics. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 1–14. https://doi.org/10.1145/3313831.3376681

[47] L. Xu, X. Chen, S. Tan, Z. Hu, B. Ying, T. T. Ye, and Y. Li. 2020. Characterization and Modeling of Embroidered NFC Coil Antennas for Wearable Applications. IEEE Sensors Journal 20, 23: 14501–14513. https://doi.org/10.1109/JSEN.2020.3008594

[48] Sunghyun Yoon, Minho Seok, Mookyum Kim, and Young-Ho Cho. 2021. Wearable porous PDMS layer of high moisture permeability for skin trouble reduction. Scientific Reports 11, 1: 938. https://doi.org/10.1038/s41598-020-78580-z

[49] Chuang-Wen You, Ya-Fang Lin, Elle Luo, Hung-Yeh Lin, and Hsin-Liu (Cindy) Kao. 2019. Understanding social perceptions towards interacting with on-skin interfaces in public. In Proceedings of the 23rd International Symposium on Wearable Computers, 244–253. https://doi.org/10.1145/3341163.3347751