A 10-Year Review of the Methods and Purposes of On-Skin Interface Research in ACM SIGCHI

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ABSTRACT

This paper aims to organize research from Association for Computing Machinery Special Interest Group on Computer–Human Interaction (ACM SIGCHI) associated conferences that have significant impact on on-skin interfaces. We performed a systematic review of the ACM database and identified 68 on-skin related publications between January 2010 to May 2021. The publications are categorized, evaluated, and compared over time and by conference. Citation impact of each paper is assessed revealing trends in the field and reflected onto the general community. Through extensive data collection, we present a thorough analysis of on-skin interfaces' development in the past decade.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**.

KEYWORDS

review paper, on-skin interface

ACM Reference Format:

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1 INTRODUCTION

Since the initial boom in popularity, wearable technology has expanded to include form factors ranging from "pod"-like accessories (smartwatch and wristbands), garment-integrated wearables, to *on-skin interfaces* [3, 38]. On-skin interfaces, a young sub-field of wearable technology, are quickly gaining the interests of scholars from diverse backgrounds. Given the interest, an in-depth understanding of the domain's current state is necessary. Although several domain-specific reviews exist [1, 47, 55], none describe the current stage of the on-skin interface research. This review fills the gap in literature.

In this review, we survey papers related to on-skin interfaces presented at ACM SIGCHI associated conferences from January 2010 to May 2021. ACM SIGCHI conferences were chosen specifically because of their large influence on HCI research and practices. The papers are then classified based on the paper's research methods, purposes, and body locations. We adopt a schema method for the classification. Through this investigation, we provide a detailed analysis on research trends in the on-skin interface research domain and predict future trajectories. We describe the nature of research, pinpoint methodological approaches used, and detail a body location map for on-skin applications. This paper seeks to assist newcomers and familiarize them with the domain while benefiting current on-skin interface researchers by identifying opportunities for future research.

2 METHOD OF COMPILATION

This paper presents a classification of all of the papers (research articles), technical notes (4-6 page short papers), briefs (2-page short papers), demos, and posters (including extended abstracts) related to on-skin interfaces presented at ACM SIGCHI conferences from January, 2010 to May, 2021. Workshops proposals and position papers are not included: there is only one non-archival relevant workshop and the position papers have evolved into full papers [1]. All major conferences related to HCI and wearable technology are included: ACM International Symposium on Wearable Computers (ISWC), the ACM Conference on Human Factors in Computing Systems (CHI), ACM Symposium on User Interface Software and Technology (UIST), ACM conference on Designing Interactive Systems (DIS), ACM International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI), ACM Tangible and Embedded Interaction (TEI), Augmented Humans (AH) which has increasingly close ties to ACM SIGCHI, and ACM Journal on Interactive, Mobile, Wearable and Ubiquitous Technologies (IMWUT), with which the papers are presented in the ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp). Other ACM venues with only one or zero papers are not included.

[1] Link to workshop webpage: https://ubicomp.org/ubicomp2016/workshops/workshops.php#UnderWare

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On-skin interfaces, the most widely used term in the surveyed papers, can be defined as devices and developed systems directly applied on and/or in the skin surface. These systems typically consist of skin-conformable form factors and are temporarily affixed to the skin. This definition excludes papers that focus on accessory forms (e.g., rings, gloves, glasses) and garment-integration. An example of an excluded paper includes Touch&Fold [62], a paper that develops a smart-ring. Papers related to smart textiles or fabrics that wrap around the body (e.g., Wearable Bits [23]) are excluded. We also exclude devices without physical manifestations on the skin. For example, devices that require external non-on-skin projection devices such as Skinput [16]. On-skin devices created with the intention to interact with an additional wearable accessory are excluded, along with devices that are not in direct contact to the body such as M-hair [6]. Papers fitting the inclusion criteria include DuoSkin [29], iSkin [69], and ElectroDermis [45].

Inductive analysis of author keywords determined key search terms: on-skin interface, skin electronics, skin interface, epidermal electronics, skin overlay, skin, on-skin, tattoo, hair, wearable, skin interface, epidermal, nail, and Flexible Wearable Sensor. We searched the ACM database using the keywords, filtering through titles, author keywords, and abstracts. Finally, the paper content determined the validity. Two researchers independently coded each publication by article title, year published, body location and application (if applicable to publication), number of citations, research method, and research purpose. Discussion about papers with classification disagreements included a third researcher, and required rereading and reclassification for consensus. After two rounds of discussion, papers were categorized. Then, the researchers re-verified the others' classifications to ensure papers were accurately coded.

3 METHOD OF CATEGORIZATION

The primary objective of this survey is to provide insight into the research methods, purposes, and trends of on-skin interfaces in HCI. We utilize a schema classification technique used in similar literature surveys [35, 47, 63]. Schema methods adopted are Basic Research (study develops theoretical creative solution), Normative Documentation (study compiles multiple sources), Applied Research (study explores a method or technique to create), Lab Experiment (study gathers data in controlled environment), Survey Research (study explores systematic sampling of population), Action Research (study consists of first hand experience), Case Study (study targets specific groups), and Field Study (study takes place in real world), consistent with previous studies [47]. Schema purposes used are Engineering (developing a system, tool, or technology), Evaluating (assessing or validating a system, tool or technology), Understanding (gaining more knowledge to better grasp content), and Describing (explaining or discussing topic). Previous schema methods [47] included Re-Engineering, however, it is excluded due to its difficulty to define which can be attributed to the domain's youth.

Chosen publications were then categorized based on body location due to location's large impact on the research question. Different

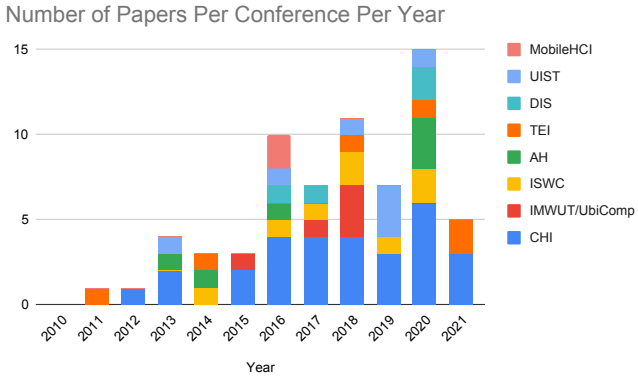


Figure 1: Number of on-skin publications per year from 2010 to 2020.

locations suggest different body movements, characteristics, attachment methods, accessibility, interactions, etc. [38]. However, some papers focus on applications of the interface rather than body location rendering location a less useful analysis. Thus, papers were also analyzed for applications which include Lifestyle & Fashion, Tech Development, Healthcare & Wellness, Gaming & Novelty, and Security & Prevention, following categorization from prior surveys [3]. Publications not classified as Engineering purpose and Applied Research method (e.g., [50]) could not be categorized and hence, not included.

4 RESULTS

4.1 Trends in the On-skin Interface Research

In total, 68 on-skin related papers were published between 2010-May 2021. Figure 1 shows number of papers published each year. One on-skin related paper was published in both 2011 and 2012. A total of 11 papers were published from 2013 to 2015. A huge spike is observed in 2016. About 80.9% of on-skin related papers are published between 2016 and May 2021.

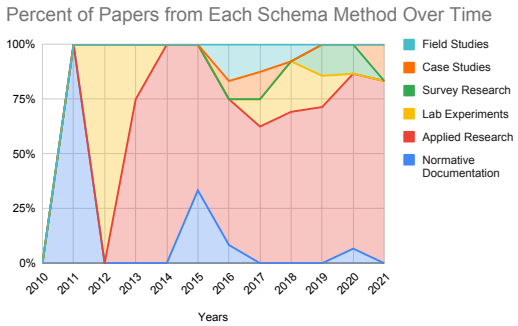


Figure 2: Research method observed over time by year.

With an increase in popularity, more publications are from diverse conferences, represented in the years 2016 to 2021 (Figure 1). ACM CHI credits itself to be an established source for on-skin interfaces representing a majority of the publications. ISWC is the second largest publication venue for on-skin publications.

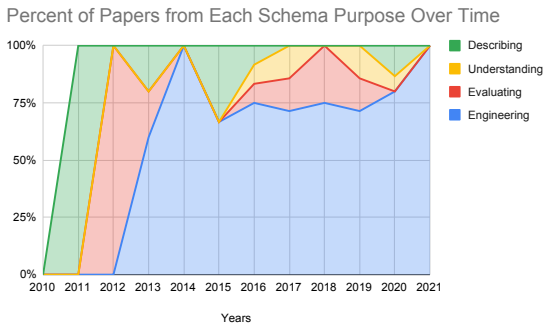
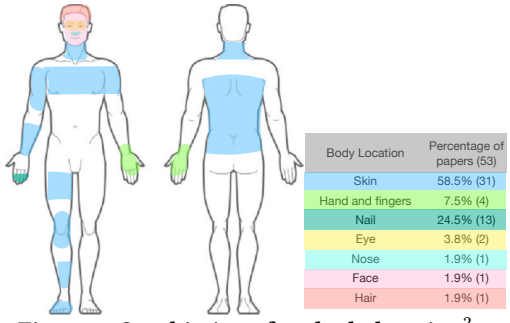


Figure 3: Research purpose observed over time by year.

4.2 Research Method and Purpose

Figure 2 shows the percentage of research method over time. Out of the 68 papers published so far, Applied Research method was the most frequently researched method (53 out of 68) followed by Lab Experiments (7). The two papers categorized under Case Studies also fall under Field Studies. No found publications were categorized as Basic Research or Action Research.

Figure 3 demonstrates the percentage of research purpose over time. In total, 54 out of the 68 papers were within the Engineering purpose category followed by Evaluating (7). Engineering publications wane towards the later half of the decade as the market focuses on improving, exploring and describing existing technologies.



Body Location	Percentage of papers (53)
Skin	58.5% (31)
Hand and fingers	7.5% (4)
Nail	24.5% (13)
Eye	3.8% (2)
Nose	1.9% (1)
Face	1.9% (1)
Hair	1.9% (1)

Figure 4: On-skin interface body location[2].

Based on the final classifications in Table 2, the most frequent classification combination is the Applied Research method and Engineering purpose (53 papers) followed by Lab Experiments method and Evaluating purpose (7). Some publications fall under multiple research methods and purposes, such as both Applied Research method with Engineering purpose and Normative Documentation method with Describing purpose [38]. These papers are those that equally demonstrated multiple schema methods/purposes [7, 17, 21, 29, 38, 52, 72, 79].

4.3 Body Location and Applications

Figure 4 displays the on-skin interface location for Applied Research method and Engineering purpose. As suggested, skin, nail, hand and fingers, eye, hair, nose, and face are commonly explored locations for on-skin application. While skin is the largest organ of the body, a large number of papers focused on the "application" of the interface (e.g., as a proof of concept of a new fabrication technique [48, 67] or novel materials [54, 70]) rather than "specific body location" (e.g., NailDisplay [58], HairIO [11]). These are categorized under "Skin" technology. Within "Skin" technology, we explore diverse body locations for on-skin applications including fingers, hands, upper arm, torso, face, etc. "Nail" technologies represent a majority of on-skin papers from 2013 to 2015. From 2016 to 2021, "Skin" technologies have been increasing in popularity. Most publications focusing on facial and sensory organs are published between 2018 and 2020.

[2]Image re-created from:https://www.pinterest.com/pin/782078291510900785/

Application	Papers
Lifestyle & Fashion	[2], [9], [10], [11], [12], [21], [22], [24], [25], [28], [29], [30], [31], [37], [39], [42], [45], [51], [52], [53], [59], [60], [64], [65], [66], [67], [68], [69], [70], [73], [75], [76]
Tech Development	[8], [9], [14], [15], [19], [20], [22], [27], [32], [42], [54], [56], [57], [58], [61], [71], [72], [74]
Healthcare & Wellness	[13], [21], [26], [36], [44], [45], [48], [65], [79]
Gaming & Novelty	[20], [73], [75]
Security & Prevention	[65]

Table 1: Classification of papers based on application.

Table 1 demonstrates the distribution of applications for chosen publications. Tech Development includes papers that choose to create sensor systems or fabrication methods. This analysis reveals more popular applications to be Lifestyle & Fashion followed by Tech Development.

4.4 Impact of Publications

Publication impact is quantified by number of citations attributed to each paper. To ensure consistency, each citation number was noted from the ACM Digital Library. Negating the age of publication is necessary due to the tendency for older publications to have more citations. To do so, we divided citation number by age (*citation number*/ *age*), resembling [47]. However, age was calculated by subtracting publication year from the numerical value of May 2021, where the year, 2021, is added to the month of May over total months in a year, (5/12), equating to 2021.416. [47] analyzes the year 2018 at its entirety contrary to our May 2021 cut off. Additional factors to consider are conference age, size, and reputation. Surveying ten different conferences contributes additional variables which affects the number of citation in relation to paper impact. This negation was utilized to analyze the paper impact in regarding schema method and purpose.

Figure 5 represents the sum of citations both non-normalized and normalized as well as the normalized average citations per year. The data highlights the growing impact of on-skin interfaces in the second half of the decade. Table 3 demonstrates impact of paper dependent on method and purpose. Sum represents total number of citations within the category. Average represents average number of citations per paper within the category. Papers classified as Engineering purpose or Applied Research method have the greatest number of citations total. However, Survey Research has approximately double the average citations per paper compared to Applied Research. Additionally, papers classified as Describing purpose have the most average citations per paper compared to Engineering purpose papers.

	Basic Research	Normative Documentation	Applied Research	Lab Experiments	Survey Research	Action Research	Case Studies	Field Studies
Engineering		[38]	[2], [8], [9], [10], [11], [12], [13], [14], [15], [19], [20], [21], [22], [25], [26], [27], [28], [29], [30], [31], [32], [36], [37], [39], [42], [43], [44], [45], [48], [51], [52], [53], [54], [56], [57], [58], [59], [60], [61], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [79]				[21]	[27], [65]
Evaluating			[52]	[4], [18], [34], [41], [43], [50], [79]				
Understanding					[77], [78]		[7], [17]	[7], [17]
Describing		[5], [38], [40], [49]	[72]		[46]			

Table 2: Research methods and purposes classification of On-Skin publications between 2010 and 2020.

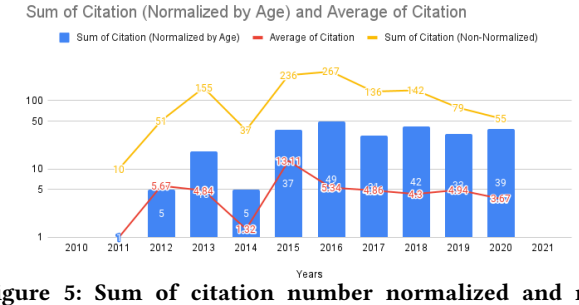


Figure 5: Sum of citation number normalized and non-normalized and average number of citations per year.

SCHEMA METHOD	SUM*	AVERAGE*
Normative Documentation	2.05	0.51
Applied Research	53.53	0.99
Lab Experiments	2.51	0.36
Survey Research	6.07	2.02
Case Studies	0.75	0.25
Field Studies	4.36	1.09
SCHEMA PURPOSE	**SUM***	**AVERAGE***
Engineering	54.58	0.99
Evaluating	2.5	0.31
Understanding	1.65	0.41
Describing	7.39	1.23

* Normalized by size of conference and age of each paper.

Table 3: Impact of papers based on schema method and schema purpose.

5 DISCUSSION

The "Epidermal Electronics" paper [33] published by Kim et al. from the Material Science field in 2011 served as a important paper that introduced and inspired HCI researchers to explore on-skin interfaces, as evident by early HCI papers which cite this work [9, 26, 27, 29, 39, 69, 70, 73]. However, we observe that HCI research has taken an unique angle in tackling this space. Contrary to fabrication approaches adopted in Material Science [33], which are highly sophisticated but requires expensive materials and proprietary equipment, HCI research focuses on developing on-skin interfaces and their fabrication methods to be more user-friendly [14, 29, 70, 73], inexpensive [44, 54], and accessible [22, 59]. HCI research is more concerned and attuned to issues around user experience, social perceptions [77, 78], and enabling device customization for self-expression [29, 39, 69]. It has also evolved on-skin interface applications beyond Healthcare & Wellness, which is a prime focus in Material Science [33], to Lifestyle & Fashion, Tech Development, Gaming & Novelty, and Security & Prevention. While only a handful of HCI researchers were involved in this domain in 2010 and 2011, the field has witnessed significant growth, with 80.9% of on-skin papers published from 2016 to 2021.

In terms of research methods and purposes of the on-skin interface research domain, most publications focus on Engineering and Applied Research. There is a rise in Applied Research papers current peaking at 2020 (see Figure 2) correlating with the increase in commercial smart watches and fitness devices. Engineering is the most popular purpose as Evaluating, Describing, and Understanding papers emerge in the later half of the decade due to its dependence on pre-existing technology. Analyzing Table 3, there is a necessity for Survey Research. The high average number of citations per paper implies a consistent high impact Survey Research have on the field. We expect that other research methods and purposes will be more visible over time when the domain itself matures.

Regarding body location, the initial popularity of nail devices can be attributed to its rigid and static surface. Prototypes of nail devices are easier to test and wear compared to on-skin devices due to the skin surface's dynamic and elastic characteristics. Later, this was overcome with fabrication approaches which blend the use of slim and novel materials with electronics [29, 39, 69]. In recent years, researchers began exploring more specific and challenging body locations such as fingers [27], hair [11], eye [31, 42], nose [36], and face [25, 66]. These body locations have little surface area and can be highly dynamic. Most papers published before 2015 primarily focus on developing single function devices [58]. Post 2015, researchers began researching a wide range of novel and existing low cost materials e.g., tattoos [29, 69], film [71]; and fabrication techniques e.g., printing circuits [9, 32]. More recently, there is a trend in developing fully-integrated on-skin interfaces which are durable enough to deployed in the wild [27, 45]. A few recent studies also focus on social perception towards on-skin interfaces [77, 78]. We expect to see similar trends in the next few years.

6 LIMITATIONS

The publications found were from the limited pool conferences associated with ACM SIGCHI in the last decade. There are many on-skin wearable papers from major venues in other fields and/or prior to 2010. There is room for future exploration of other databases including IEEE, Web of Science, etc. Moreover, the May 2021 publications are not indicative of 2021 in its entirety. Some conferences included in this survey have not yet released their 2021 proceedings. Additionally, the publications were not published with this paper's specific schema in mind. Therefore, some classifications were more subjective, and chosen based on pre-defined schema methods and purposes for consistency.

7 CONCLUSION

This survey is a snapshot of current trends in the on-skin interface research in the field of Human Computer Interaction in 2021. In this paper, a total of 68 on-skin related papers were surveyed that were published in major ACM SIGCHI conferences between Jan 2010 and May 2021. After finding and classifying all on-skin related papers, trends were analyzed. Results the growing interest in on-skin interface research among the HCI community. Analysis on the research methods, purposes, and body location used in the on-skin research in the past decade provide valuable insights for future research. While we intended to provide a comprehensive and informative analysis of the current state of the on-skin interface research, we encourage fellow researchers to expand our work to gain more insights on the domain.

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