Digital Digits: A Comprehensive Survey of Finger Augmentation Devices

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Finger augmentation devices, those that are worn and operated by fingers, are a rapidly growing field in the human–computer interaction domain. This field is rooted in ancient history; however, still the academic research arena is booming with new finger augmentations every year. This article strives to survey the entire body of work on finger augmentation devices and uncover the trends and the underexplored territories. We contribute a methodical classification of over 150 pieces of academic, product, patent, and concept work. We discuss the underlying sensing and feedback modalities and provide a definition, taxonomy, and reference for researchers of finger augmentation devices.

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CCS Concepts: • **Human-centered computing → Interaction paradigms**; **Interaction devices**; **Interaction techniques;**

Additional Key Words and Phrases: Wearable computing, human augmentation, finger augmentation, input methodologies, assistive technology

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1. INTRODUCTION

Wearable ubiquitous computing is no longer a dream—it is the reality we live in. It has grown from a niche field of academic research into a multi-billion-dollar industry and a booming scholarly endeavor. The advent of wearable computers gave rise to *finger augmentation*, an up-and-coming domain of devices worn primarily on a finger to add sensing and feedback and allow a new kind of manual interaction with the world. New *finger-augmenting devices* (FADs) appear annually in major academic venues of the HCI community (see Figure 1), in the consumer market as new products, and in prominent news and popular media outlets. The demand for these types of devices is

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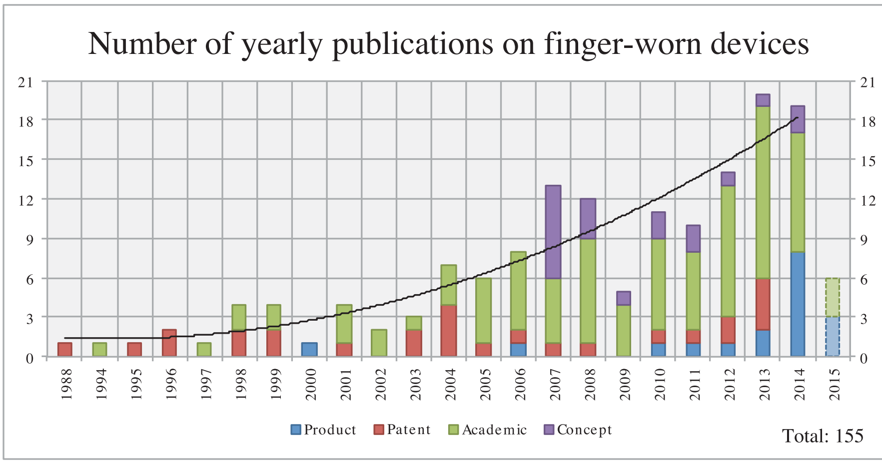


Fig. 1. The yearly account of publications on FADs suggests a growing trend. Note: (1) we do not yet have a full tally of the works published beyond 2015, and (2) in the years 1916–1987, there were four publications that are not visualized here.

increasing, which is the reason we set upon the undertaking of surveying, documenting, and defining the field.

Finger augmentation seeks to add three additional abilities to the innate human finger abilities: (1) to sense (input) beyond what the ordinary human finger senses (e.g., image, tactile, thermal), (2) to provide (output) information to the wearer, and (3) to control or output information via the finger to an external object. Such devices leverage the finger's direct interaction with proximal surfaces and the inherent focus of attention derived from pointing and touching, and build on the dream of the extended hand's reach into virtual and distal worlds. Recognizing the potential of enhancing the finger with additional I/O capabilities, researchers and inventors suggested a large number of ways to attach sensors and actuators to the finger. Readily available finger-augmenting consumer products already rely on inertial sensing with accelerometers, gyroscopes, and magnetometers and interpret their signals to recognize gestures. However, other sensing modalities such as attaching miniature cameras are on the rise.

FADs come in myriad shapes and forms, targeted at multiple audiences and applications. These FADs embed a wide range of sensors, power sources, wireless communication modules, and actuators into very small form factors. The major application domain for these devices is keyboard and mouse input for personal devices; however, applications in the medical, assistive, and industrial domains are also very prominent. From controlling a cursor to preventing injury, each application domain drives the embedded components and interaction modalities. We created a classification based on the following categories rising from previous works: input and output modalities, application domain, form factor and location on the finger, interaction scheme, and wireless capabilities (see Figure 2). While input, output, form factor, wireless capabilities, and application domain categories compare the functions or the intended use of the devices, the interaction scheme category suggests a classification around where the interaction takes place: on the device itself, on a proximal surface, external (e.g., a remote object), and so forth.

The goal of this work is to provide an encompassing survey of the existing attempts at finger-augmenting devices. Initially, we provide our definition for such devices, separating them, for example, from smart glove interfaces or from finger protectors of sorts. The discourse will center around the overarching range of technologies rising

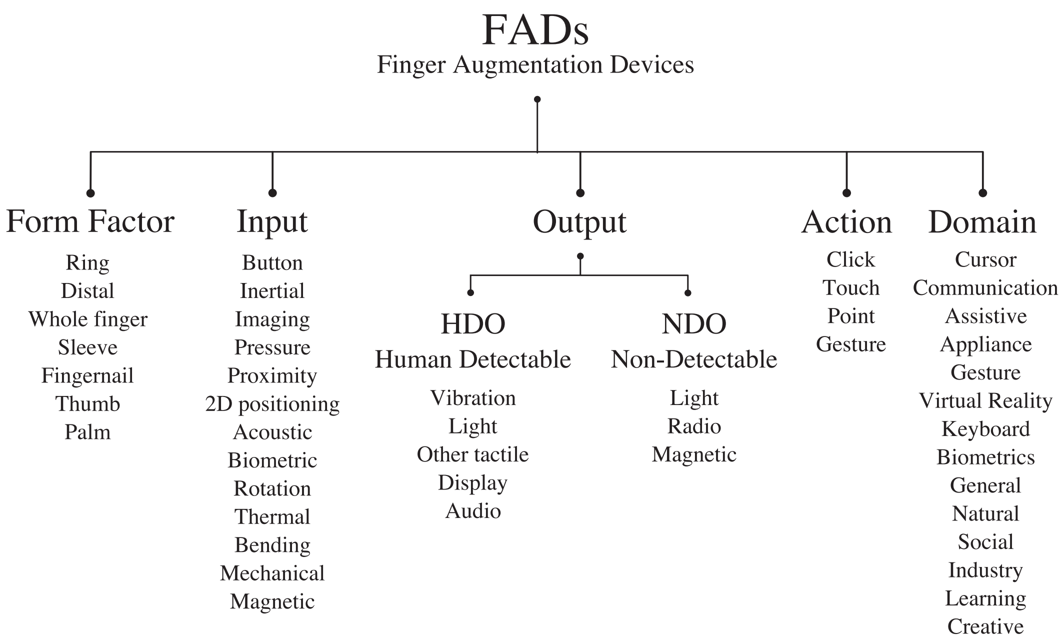


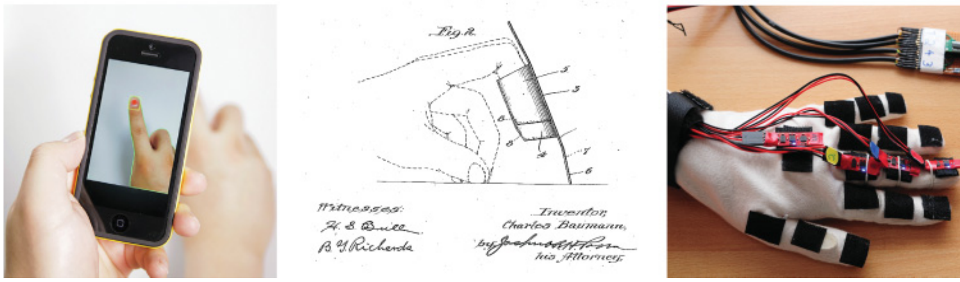
Fig. 2. Classification hierarchy for FADs.

from the whole body of work rather than focus on a specific implementation, as each instance generally has different targets, intentions, and evaluation methods. Previous surveys of finger-worn devices in standalone work or as part of a publication on a specific implementation [Nanayakkara et al. 2013] cover specific subsets of the field: Rissanen et al. [2013b] surveyed 20 works focusing on rings, surveyed 15 instances with a broader viewpoint. We therefore believe our own work (surveying nearly 160 instances) presents the most comprehensive, methodical, and up-to-date overview of the entire field.

The article starts with formative postulations on the boundaries of the field, contributing a working definition for a finger-augmenting device. A definition aids in separating other types of hand-worn devices, as well as makes ready a terminology to discuss FADs, which was not suggested to date. The second contribution is a classification hierarchy of categories and subparameters that is used to aggregate the surveyed literature and serve as an organizational framework for future surveyance. We also contribute a set of guidelines to scaffold future research into FADs arising from the surveyed body of work. To make the knowledge more accessible, the article contains information tables (Tables II, III, IV, and V) with a concise description of the merits and demerits of various approaches, which serve as bite-size pieces of advice for designers to consider. Finally, tables showing the actual classification of the work can be found in the Online Appendix.

2. DEFINITION OF FINGER-AUGMENTING DEVICES

Hand-worn and hand-held augmentation devices have been an incredibly large engineering and research endeavor for many years. Within this domain, finger-worn devices are a relatively new vector of investigation that was until recently inseparable from the larger agenda. Thus, in order to create a boundary for the body of work on FADs, it is helpful to create a definition. As a trivial exercise in finding a good boundary for FADs, consider the regular computer mouse or a touchscreen. These can be thought



(a) NailSense [Hwang et al. 2013]

(b) Finger Protector [Charles Baumann 1916]

(c) Hand pose sensor [Hrabia et al. 2013]

Fig. 3. (a) and (b) are not considered FADs based on our definition, since they do not augment the finger itself (a) or have no augmentation other than their form factor (b). On the other hand, (c) is in fact an FAD since the glove is only used for conveniently placing sensors on the fingers. Images (a) and (c) are courtesy of their respective authors.

of as FADs since they gives our fingers the abilities to move cursors on screens and perform click, drag, zoom, and many other operations that un-instrumented fingers cannot perform. However, under this possible broad definition, we should include just about any computer interface that involves a finger's touch, which accounts for most computer interfaces in existence. Since wearable computers become more popular and some also promise to provide special powers to our fingers, we tried to create a stringent rather than lenient definition for FADs using inherent qualities of the device itself rather than only its supposed function for our fingers. As a counterexample, Digits [Kim et al. 2012], the OrCam glasses [OrCam 2014], or Nailsense [Hwang et al. 2013] (see Figure 3(a)) also intend to augment the finger with capabilities, but they do not instrument the finger itself, rather the glasses or mobile device.

We define finger-augmenting devices as *finger-worn devices with an additional augmentation other than their form that provide a supplemental capability for one or more fingers using the finger itself as a central element*. Perhaps the hardest task in creating this definition was to separate the immense body of work on smart gloves [Zimmerman et al. 1987], as they are also, to a degree, FADs. This distinction is nevertheless possible to make; for example, in the work of Yamada et al. [2001], the glove itself plays a central element in the sensing, whereas in Hrabia et al. [2013], the glove only serves to provide a convenient mount for the researchers intending to augment the fingers (see Figure 3(b)).

We include "additional augmentation other than their form" in the definition for an FAD since some finger-worn objects do not provide a function beyond the affordances of their physical form. The following are examples of nonactive finger augmentations that only provide a function via their form factor: a finger-worn stylus pen [Smith 2005], a finger-worn painter's palette [Bajaj and LaVaque 2012], a basketball training instrument [Grover 2012], or even a self-defense device [Knowles 2005]. While these do provide an enhancement of the finger's inherent function, they do so only by a static supplement.

2.1. History of Finger Augmentation

The existence of finger wearables goes at least as far back as documented history. Finger rings in particular carried symbolic and mythical meaning throughout the ages of humankind, up to our own days [Roop 2011]. In ancient times, ring devices were used to represent power (e.g., signet and seal rings of rulers) and amuletic protection from evil spirits and bearing magical forces, while in more recent history they were used as ornaments and objects of remembrance and bonds (e.g., an engagement ring). The narratives of ancient times, the tale of Prometheus's memento ring from Jupiter of Greek mythology, for example, still echo through our modern-day media, where one would often see film and television scenes of couples buying and exchanging diamond wedding rings [McCarthy 1945] (although the original symbolism may have been replaced by advertising [Brinig 1990]).

Finger wearables are intrinsically intertwined in our culture; however, only "recent times" have shown functional usage for them beyond symbolism. Sewing thimbles (that date back to 206 BC [thi 2014]) are an example of an ancient utilitarian finger augmenter; however, the more recent abacus ring (from 17th-century China) and the document-sealing rings of the Middle Ages (10th to 15th centuries) are also of very practical usage, beyond being an emblem of status [McCarthy 1945]. Even more recently, with the advent of the industrialization age, finger-wearable devices started to take a much more practical role, usually as protectors, such as the finger protector for safe kitchen knife operation [Baumann 1916] (see Figure 3(b)) or a device to assist in holding a writing pen [Zazzara 1971].

Evidence from the early days of FADs, devices that operate beyond the factor of their form, is hard to pin down; however, in 1916 and 1918 two patents were filed detailing a finger-wearable electrical switch for easily operating the lights in a car [Newton 1916; Harris 1918]. In 1965, a finger-wearable switch to operate a sewing machine was patented [Samuel 1965], and since then FADs started to branch out into other input modalities such as a microphone [Murad 1979] and a cursor-controlling pad [Levine 1990].

3. CLASSIFICATION OF FADS

In preparation for this survey, we collected works from academic publications, registered patents, currently available consumer products, and concept design works. Our collection includes 91 academic publications from conference proceedings, journals, and theses; 29 patents; 20 consumer products; and 19 design concepts of FADs. We also surveyed 23 other pieces that do not fit our definition for an FAD; nevertheless, they are all relevant to the discussion. Pieces were collected using a number of methods: systematic search through conference proceedings for relevant work (in particular ACM CHI, UIST, TEI, UbiComp, ISWC), keyword search through academic and patent publication index engines, hierarchical citation-tree backtracking from existing publications, and, lastly, general queries in a web search engine.

The obvious advantage of an academic publication is that it presents the technical details in a clear fashion; however, it often reflects a research-in-progress rather than a ready-for-market product. It was therefore important to seek out products to complete the picture, as these mostly represent a mature state of work. Patents present units of knowledge that exhibit enough market potential that they needed to protected; however, they are often not in a high stage of maturity. Design concepts that are freely published online add a valuable aspect of *wishful engineering* and a futuristic outlook that brings out the needs and desires from FADs. This range spans the extent of the current research, implementation, and ideation on FADs.

Our classification considers the following dimensions: form factor, input modality, output modality, the device's action, and the application domain. The form factor, input, and output modalities prescribe the physical affordances of an FAD, as they determine how it could be appropriated to interface with the user's hand. These categories were quantized in a combined inductive and deductive process, where both preconceived and emergent subcategories were used to parameterize the surveyed work (see Figure 2). Classifying the intended action for an FAD was first indicated in Nanayakkara et al.

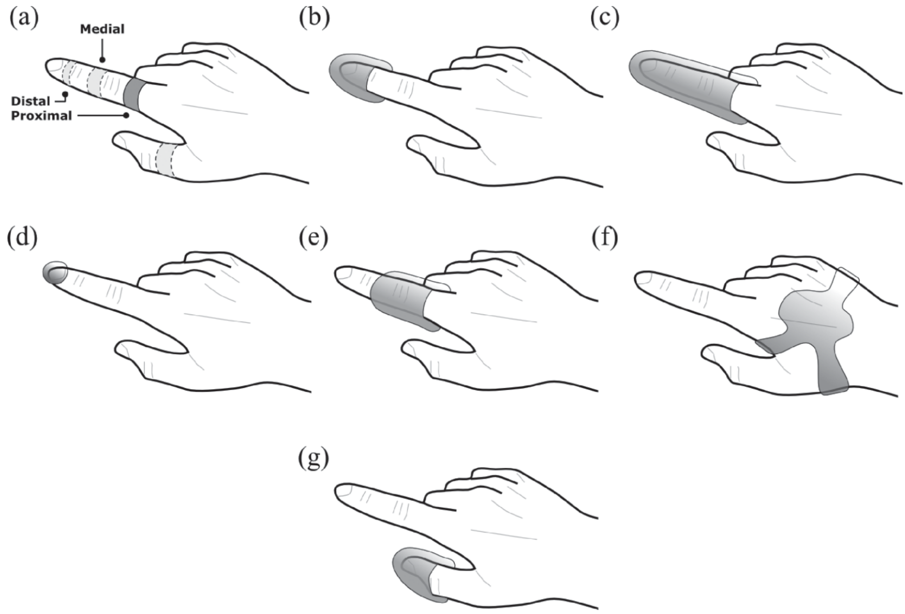


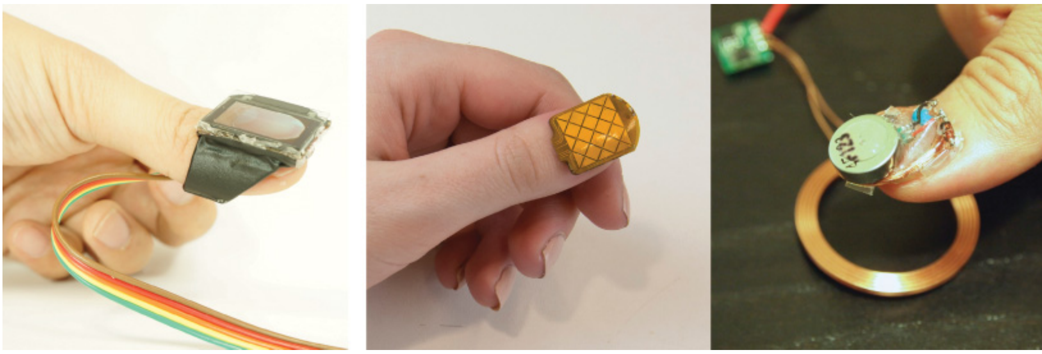
Fig. 4. FAD form factors: (a) rings, (b) distal addendum, (c) whole finger addendum, (d) fingernail addendum, (e) sleeve, (f) palm component that accompanies an FAD, and (g) thumb addendum.

[2013] and further developed here to suggest that the inherent action of fingers and hands supports four levels of FAD interaction: touching a surface, gesturing in the air, touching the finger-worn device, and pointing at a referent. Lastly, we examine the rich world of applications for FADs, as they evidently cluster together to solve or enhance manual operations in a given field.

3.1. Form Factors

To support different interactions, FADs are positioned and formed in many different ways. They attach to any of the finger sections: proximal, medial, and distal; some cover more than one section to form sleeves, and others cover the whole finger and even the palm and fingernail. We identify seven generic form factors used in FADs, which are also illustrated in Figure 4: rings, distal addendums, whole-finger addendums, fingernail addendums, sleeves, thumb addendums, and, finally, components mounted on the palm that support the FADs. Another varying parameter is the number of devices used in a single FAD. Sometimes many rings are used on multiple fingers at the same time (such as in the case of chording keyboards [Fukumoto and Suenaga 1994; Hirose and Amemiya 2003; Cho and Lee 2004; Bajer et al. 2012]) or a finger–thumb pair [Levine 1990; Chen et al. 2013]; however, we found that in more than 80% of the work, there is only a single wearable device.

The most prominent form factor is the ring (see Figure 4(a)), which is considered to be the most acceptable and practical long-term wearable device due to the long history of finger rings as jewelry. Moreover, rings present the least cumbersome form factor and leave the hands free to grasp and interact with screens and other devices. Most of the rings are worn, according to traditional custom, on the proximal phalanx section of the finger; however, unique cases show distal rings for biometric purposes [Rhee et al. 1998], medial rings for cursor control or pointing [Sibert and Gokturk 2001; Horie et al.



(a) Nail Display [Su et al. 2013]
(b) NailO [Kao et al. 2015]
(c) SmartNail [Tamaki and Iwasaki 2014]

Fig. 5. Fingernail-augmenting devices: (a) a miniature display added to the thumb, (b) a touch-sensitive pad for 2D cursor control, and (c) a radio-controlled vibration motor.

2012], and medial rings for gestural interaction [Jing et al. 2013; Kruse and Steger 2013]. In the early days of FADs, rings were strongly dominant, later to be surpassed in popularity by distal addendums and whole-finger addendums, and their applications gravitated toward input devices to augment or replace the mouse and keyboard. In recent incarnations, ring FADs are used more and more as gestural and cursor control input devices.

Distal addendums, devices that attach to the end of the finger and sometimes cover it (see Figure 4(b)), are an overall runner-up to the predominant rings; however, they distinctly differ from them in the applications they offer. Some applications are practically unique to distal addendums, such as interfaces for virtual and augmented reality [Koo et al. 2008; Prattichizzo et al. 2010; Chinello et al. 2012]. Since distal addendums are located at the fingertips in an area of heightened sensing, as discussed in the last section, they are prime candidates to create output interfaces, and indeed over 75% of distal addendum FADs we covered pack some sort of output modality: tactile [Koo et al. 2006], vibration [Zawrotny et al. 2006], light [Yang et al. 2012], or others.

Whole-finger and sleeve addendum devices cover bigger portions of the finger, and this real estate allowed creators to explore a more encompassing monitoring of the finger (such as its bending [Tsukada and Yasumura 2004; Li et al. 2010; Heo and Kim 2012]) as well as incorporate much more interaction elements, for example, buttons [Rosenberg 1998; Kenin 2004; Poznansky et al. 2013] and high-speed and -accuracy tracking [Rami Parham et al. 2014].

A new up-and-coming form factor for finger augmentation is that of the nail addendum. In spite of the appealing characteristics of the nail as a bed for adding input and output (see the following information box), there were not many cases reported. Prince [1996] was the first to postulate the usage of nail augmentation to enhance interaction with computers which was reiterated years later by Kruse and Steger [2013]. Mascaro and Asada [1999, 2001] looked into understanding how pressure affects the fingernail's appearance to allow for the creation of virtual buttons. Others experimented with different input modalities mounted on the fingernail, such as a photo detector [Ando et al. 2002], a pressure sensor [Kao et al. 2015], and a magnetometer [Liang 2013; Chan et al. 2013], while others mounted a vibrator motor [Tamaki and Iwasaki 2014] and an RFID chip [Vega and Fuks 2013].

Table I. Common FAD Form Factors: Applications, Advantages, and Disadvantages

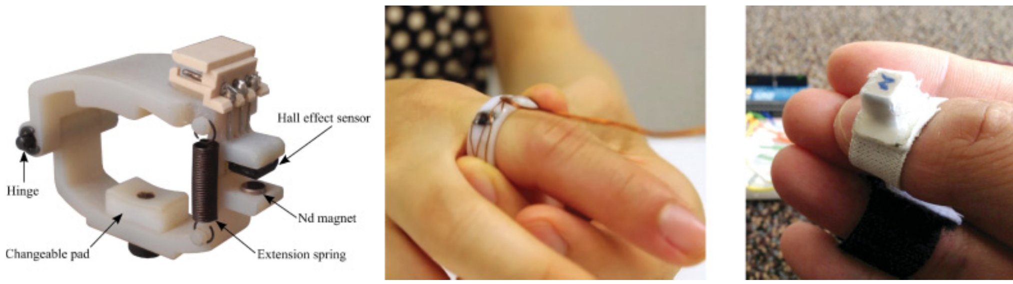
FAD Form Factors			
	Application	Advantage	Disadvantage
Rings	Commun., computer input	Socially acceptable form, with a rich cross-cultural tradition and narrative. Easily accessible for the thumb, since usually a ring rests around the proximal phalanx. Small in size, and most times easy to take off and wear.	Difficult to develop for such a small form, and using some input and output modalities is not feasible. There are social implications and preconceptions as to what is acceptable in/on a ring.
Distal add.	Virtual reality	Can output information via the sense of touch, useful for tactile simulation of virtual objects. Proximal to the touch surface, and allows for sensing it.	Obstructs the inherent sense of touch in the fingertip by covering it. Adds unnatural weight on the fingertip.
Finger-nail add.	Computer input, assistive technology	Fingernails are underutilized augmentation real estate. Very close to the touching surface, but don't obstruct the fingertip pad and the natural sense of touch. Allow using adhesives, and there are no nerve endings, which allows, for example, "tapping" with the nail.	Wearing something on the fingernail carries a social meaning. Slightly inaccessible for the other fingers or thumb of the same hand. Added weight on the tip of the finger may be uncomfortable. Difficult form to design for, although the thumbnail is often larger.
Whole finger and sleeve	Computer input	Have more room for input/output elements reachable by the thumb, suitable for creating computer input devices. Enable sensing bending, and easily lend to understanding the direction of pointing.	Big and cumbersome to wear and remove. May obstruct the natural motoric affordances of the fingers.

3.2. Embedded Input Modalities

According to our statistics, most FADs are input devices; 119 of the 159 surveyed works reported having at least one kind of input modality. Our classification of FADs revealed a wealth of commonly used input modalities, each making use of a different element of the finger. Since much of the work is not unimodal (46 out of the 119 FADs sporting any kind of input are in fact multimodal), the counting in the following list includes duplicates. To make a further distinction, we do not classify the underlying sensing technology itself but rather the outcome input signal that creators used to support the intended interaction.

The following input modalities were recorded in our survey:

—Binary-state buttons [44 instances]
—Inertial: translation (accelerometers) and rotation (gyroscopes) [39 instances]
—Imaging: cameras or other photometric detectors [28 instances]
—Pressure or force, against a surface, other fingers or objects [22 instances]
—Proximity, to other devices or limbs [15 instances]
—2D positioning: joysticks or touch-sensitive pads [13 instances]
—Acoustic: microphones or general sensing of the audible range [10 instances]
—Biometric: pulse, oximetry, blood pressure, and so forth [9 instances]
—Rotation, of the FAD device against the finger [5 instances]
—Magnetic: Hall effect sensors or other magnetometers [4 instances]
—Thermal [4 instances]
—Bending [3 instances]
—Mechanical, coded gears [3 instances]



(a) Finger flexion sensor [Heo and Kim 2012]

(b) iRing [Ogata et al. 2012a]

(c) uTrack [Chen et al. 2013]

Fig. 6. Input modalities in finger-worn devices: (a) a sensor for the flexion of finger tendons, (b) an IR reflectance sensor for different parts of the finger's skin, and (c) a magnetic sensor. Images courtesy of authors.

Binary buttons are widely used in FADs for their straightforward operation and user familiarity, where the buttons are usually located on one finger (facing out or in) and operated with the thumb. As is the case in most early FAD applications, the major usage was to create finger-wearable keyboards [Rosenberg 1998; Lehikoinen and Röykkee 2001; Lee and Hong 2004; Johnson 2013; Bajer et al. 2012] and mice [Weinblatt 1999; Jarra 2003; Kenin 2004; Baughman 2005; Sun 2006; Shai 2011; Saar Shai and Efrat Barit 2012]. Other prominent usage profiles for binary buttons include communication [Fukumoto and Suenaga 1994; Marti and Schmandt 2005; SmartyRing 2013; Mota 2014] and assistive technology [Frederick et al. 2004; Hedberg and Bennett 2010; Rissanen et al. 2013a; Nanayakkara et al. 2013].

Inertial measurements units (IMUs) are implemented using accelerometers (to sense motion) and gyroscopes (to sense orientation). Much attention was given to creating keyboards by detecting finger taps [Fukumoto and Suenaga 1994; Fukumoto and Tonomura 1997; Prince 1996; Lam and Li 2002; Kim et al. 2005; Kanai et al. 2009; Kruse and Steger 2013; Logbar Inc. 2014; RHLvision Technologies Pvt.Ltd 2014] and mouse-like input [Tsukada and Yasumura 2004; Pandit et al. 2009; Zhang et al. 2011; Horie et al. 2012; Ranta et al. 2012; Liang 2013; Poznansky et al. 2013; Mycestro 2013; Thanko 2013; Nod, Inc. 2014; Chan et al. 2013] for the clear affordances these sensors provide in detecting abrupt motion or integrating it into a velocity signal. However, recently, gestural interaction has become the de facto usage scenario of inertial measurements in FADs with an abundance of recent work [Lee et al. 2007; Jing et al. 2011; Ketabdar et al. 2012; Jing et al. 2013; Su et al. 2013; Wolf et al. 2013; Logbar Inc. 2014]. However additional usage scenarios do exist, especially in the biometrics domain, where the acceleration signal is traditionally used to filter noise from arterial blood flow measurements [Asada et al. 1999; Shaltis et al. 2005; Han et al. 2007; Lee et al. 2008; Huang et al. 2014].

Finger-worn cameras (or other photoreactive elements) combine a powerful sensor with a highly sensitive body part (see Figure 7). For this reason, many researchers use them for assistive technology work, looking to recapture even a sliver of a lost sense of sight in a variety of ways: reading text or detecting patterns in print [Ando et al. 2002; Hedberg and Bennett 2010; Lee 2011; Shilkrot et al. 2014; Stearns et al. 2014], detecting objects and scenes [Rissanen et al. 2013a; Nanayakkara et al. 2013], and navigation and general sightless usage [Horvath et al. 2014]. Nevertheless, finger-worn imaging was shown to be useful for screen cursor control [Zawrotny et al. 2006; Yang et al. 2012; Thanko 2013; Shai 2013; Poznansky et al. 2013; Kienzle and Hinckley

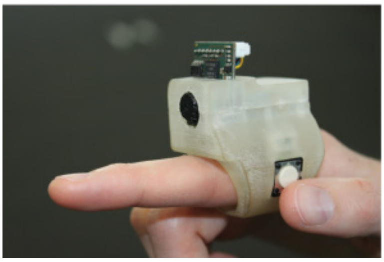
Table II. Common FAD Input Methods: Applications, Advantages, and Disadvantages

FAD Input Methods			
	Application	Advantage	Disadvantage
Button	Computer input (keyboards, mice) and commun.	*Inexpensive*, easy to *integrate,* and simple to *operate* for the user. They are relatively small, so can be placed almost anywhere on the finger.	Provide only a *simplistic binary operation* with little information for the system. If mechanical, they are not as thin as touch-sensitive surfaces (e.g., capacitive).
Inertial (IMU)	Cursor control, gesture recognition	Relatively *inexpensive*, *small*, and work very *intuitively* with finger or hand air gestures to represent the motion of a cursor or a symbolic gesture.	Sometimes require calibration, and cannot reliably measure precise translation. Gesture recognition requires *additional computation power*.
Camera or photo-sensor	Natural interaction, assistive technology	Provide *high-dimensional input* and enable object or scene recognition, complex hand gesture poses. Photodetectors are *small and cheap*. Some can work beyond the visible spectrum, e.g., in the dark.	Analyzing camera images or video requires *considerable computation* and *power*; they are also usually quite *large*. Photodetectors provide a *low-dimensional*, albeit continuous, signal. Finger-based imaging is *not intuitive* to the user.
Pres-sure sensor	Virtual reality, computer input	*Intuitive to the user*, for the natural heightened sense of touch in the fingertips, translates well for simulated and virtual environments. Usually provide a continuous signal with more information, at low power consumption.	Only support proximal activity, i.e., cannot detect gestures.

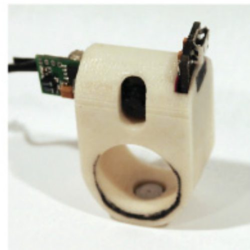
2014; Rami Parham et al. 2014], for natural interaction with objects [Merrill and Maes 2007; Yang et al. 2012; Rissanen et al. 2013a; Ransiri and Nanayakkara 2013; Hettiarachchi et al. 2013], as a wearable barcode scanner [Symbol 2000], and simply as a wearable camera [Münscher 2007]. In all recorded cases, the imaging sensors are positioned facing away from the finger and pointing forward in the direction of pointing or down in the direction of touch.

Pressure sensors were used to create virtual reality interfaces to bridge the tactile sensation gap of the virtual world by detecting the force applied to fingertips [Mascaro and Asada 2001; Prattichizzo et al. 2010; Chinello et al. 2012] or to restore a lost tactile sensation in the fingers (in people suffering from multiple sclerosis) [Jiang et al. 2008]. In the department of computer interaction, Zloof [1996] postulated a rotating ring to control cursors, Xiong [2003] used pressure sensors to create a thumb-mouse and Chatterjee and Matsuno [2006] used a finger-worn keyboard/mouse based on eight pressure sensors. While most finger-worn pressure sensors are based on layered electrodes, Ogata et al. [2012a] have created a force-sensitive ring based on infrared lighting and photodiodes, taking into account different reflectance properties of human finger skin.

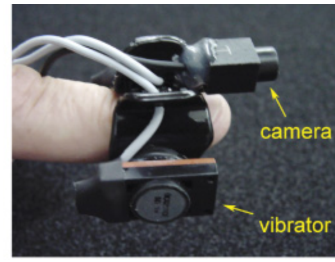
Sensing modalities such as 2D sensors (miniature joysticks, touchpads, pressure pads, or ball rollers) were mostly used to create keyboards and mice [Miner et al. 2001; Saar Shai and Efrat Barit 2012; Levine 1990; Bell 2012; Felsenstein and Wang 1998; Xiong 2003; Kent and Wentz 1998; Kenin 2004; Baughman 2005]. Sensing the bending of fingers, thermal sensors and pulse sensors showed potential in biometric applications [Li et al. 2010; Heo and Kim 2012; Asada et al. 1999; Shaltis et al. 2005; Rhee et al. 1998; Han et al. 2007; Werner et al. 2008; Lee et al. 2008; Huang et al. 2014], while mechanical fixtures attached to the hand were used to create virtual reality interfaces with sensing as well as feedback [Gosselin et al. 2005; Ooka and Fujita 2010; Solazzi et al. 2010].



(a) EyeRing [Nanayakkara et al. 2013]



(b) FingerReader [Shilkrot et al. 2014]



(c) FingerSight™ [Horvath et al. 2014]

Fig. 7. Finger-worn cameras. Images courtesy of authors.

Much of the other modalities (microphones, proximity sensors) are combined; however, Chen et al. [2013] created a finger-wearable 3D input device and Maekawa et al. [2012] a hand-held device sensor using only a single magnetic sensor.

3.3. Embedded Output Elements

Output in an FAD is mostly geared toward the user, providing notification on a performed manual action or output from an external system, delivered to the finger for its sensitivity to many kinds of energy and bodily visibility. We consider two classes of output FADs, ones with Human-Detectable Output (HDO, i.e., energy detectable by the innate human senses) and ones with Non-Detectable Output (NDO, e.g., magnetic energy or radio). Even though HDO FADs were extensively explored, FADs in general do not have HDO—only roughly half of the works we surveyed had any kind of output modality detectable by human senses. An interesting special case is the pure-HDO (i.e., FADs without any input modality) that is prominent in creating interfaces for virtual reality, where the focus is on stimulating the fingers to feel virtual objects rather than sensing the world [Lee et al. 2006; Sarakoglou et al. 2006; Scheibe et al. 2007; Minamizawa et al. 2007; Kim et al. 2008; Koo et al. 2008; Scheggi et al. 2010; Gallotti et al. 2011]. Other prominent outlets for HDOs are, naturally, communication, in the form of a mobile phone companion device [Mota 2014], and assistive technology, in the form of wearable finger-Braille devices [Hirose and Amemiya 2003]. So far, we only encountered a single finger-worn device concept based on temperature output [Alaska Jewelry 2008].

NDO FADs are mostly used as means of input to other devices, mostly for cursor manipulation, by utilizing a companion module such as a wristwatch [Harrison and Hudson 2009], a bracelet [Cho and Lee 2004], or external light sensors [Sibert and Gokturk 2001], to pick up on the undetectable emissions (or reflections) from the FAD.

The following are the dominant output modalities we encountered in the surveyed works:

—HDO	Vibration	[30 instances]
—HDO/NDO	Light	[22 instances]
—HDO	Tactile (other than vibration, e.g., compression)	[19 instances]
—HDO	Display (complex lighting setup)	[11 instances]
—HDO	Audio	[5 instances]
—NDO	Radio	[4 instances]
—NDO	Magnet	[3 instances]

The primary HDO modality is vibration, with 30 unique publications reporting the usage of vibration capabilities in an FAD (due to the evident widespread use of vibration in FADs, we separate it from other forms of tactile feedback). Presumably, this is owing to the fact that human fingertips are highly sensitive to vibration through mechanoreceptors embedded close to the skin and deeper inside the finger, allowing one to effectively detect vibration in the 10 to 300Hz range with minuscule displacement (10 microns or less); other parts of the finger are slightly less sensitive than the fingertips as the concentration of mechanoreceptors decreases [Talbot 1968]. The two major themes in using vibration output is for assistive and communication applications. Usage of vibration in assistive applications focused on finger-Braille [Hirose and Amemiya 2003; Amemiya et al. 2004; Matsuda and Isomura 2012], sensory substitution [Ando et al. 2002; Shilkrot et al. 2014], and sensory amplification/mediation [Jiang et al. 2008; Kurita et al. 2011], and in communication we find a large number of smartphone companion devices that alert of incoming messages and allow for rudimentary response [Marti and Schmandt 2005] (in interest of brevity, we invite the reader to view the complete list in the Online Appendix). Other applications for vibration include gestural and cursor control [Shai 2013; Logbar Inc. 2014] and virtual reality interfaces [Lee et al. 2006; Ooka and Fujita 2010].

In contrast to vibration, static and near-static ($<$10Hz) tactile feeling on the skin is detected with a different set of mechanoreceptors that are distributed farther apart on the surface of the glabrous skin (that of the hand) [Johansson 79]. Nonvibratory tactile feedback via FADs is virtually dominated by applications for virtual reality, for the goal in such interfaces is to simulate the force feedback from grasping or touching virtual objects. While a great number of actuators for tactile feedback exist (electromagnetic, piezoelectric, electrostatic, and others [Benali-Khoudja et al. 2004]), their integration in a finger-wearable form is not trivial. To apply compression and shear force on the fingertips, researchers explored using miniaturized finger-mounted DC motors and strings [Prattichizzo et al. 2010; Scheggi et al. 2010; Chinello et al. 2012], wrist-mounted motors with companion finger-worn mechanical pads [Solazzi et al. 2010], motor-driven extruding nuts [Kawasaki et al. 2010], or shape-memory alloys [Kruse and Steger 2013].

Simple finger-worn light output is a trivial augmentation of the finger already available in products targeting, for example, recreational usage [Munari 2007] and the aviation industry [Lambert 1992]. However, in FADs, which require a nontrivial augmentation, light is usually intended to deliver information visible to the wearer's eye (HDO) or with sensors accompanying the light source on the FAD (NDO). Many FADs use a single light source in communication applications to indicate pending operations or messages [Miner et al. 2001; Labrune and Mackay 2006; Ringly 2014; Pradana et al. 2014]. Other uses for light output are reporting of operational status such as charge, power on/off, or internal state [Tsukada and Yasumura 2004; Jing et al. 2011; Shai 2013; Logbar Inc. 2014; Mycestro 2013]; to visualize gesture [Ketabdar et al. 2012]; or a laser to indicate pointing direction [Zawrotny et al. 2006]. NDO light was used, for example, in the iRing [Ogata et al. 2012a], where an NIR light source was used to detect different skin regions.

Displays, as opposed to discrete lighting sources, can deliver a much higher order of HDO information; despite that, the domain of wearable displays is still in its infancy and FAD packing displays are at the forefront. Usage of finger-worn displays mostly revolve around communication and organization, where they display caller ID, a message, or calendar information [Hybratech 2010; SmartyRing 2013; Mota 2014]. However, interesting examples also include a nail-worn display to overcome the finger's occlusion of touchscreen devices [Su et al. 2013] (see Figure 5(a)) and a palm-mounted screen to assist in hands-free operation, for example, while driving [Lee and Hong

Table III. Common FAD Output Modalities: Applications, Advantages, and Disadvantages

FAD Output Modalities			
	Application	Advantage	Disadvantage
Vibration	Commun., assistive technology, virtual reality	Relatively *cheap* and easy to *integrate*. Fingers *easily detect vibration* at multiple degrees of frequency and amplitude.	The entire finger is not as sensitive to vibration as the fingertips. Motors can be *large* and may draw significant *power*.
Other tactile	Virtual reality	Fingertips are very sensitive to tactile response even at very subtle levels, with good resolution and separation.	Mechanical constructs to provide pressure or compression are large and power hungry, although alternatives exist (e.g., piezoelectric, electromagnetic).
Light	Commun., lighting	Simple to integrate, cheap, has a small footprint and low power consumption. Intuitive to understand for the ubiquity of light as indication of status in electronic appliances. Can easily work as an NDO outside the visible light spectrum.	Cannot provide a large amount of information. Conspicuous, may draw public attention to the finger and reveal private information.
Display	Commun.	Can deliver a large amount of information and utilize "dead space" for augmentation or occlusion.	Large, power hungry, and require more computational power to drive. Often low resolution at small sizes. Applications are limited without touchscreen capabilities.

2004]. Additional HDO modalities in FADs also include audio, where speakers create a finger-based telephone handset [Fukumoto and Tonomura 1999; Fukumoto 2005], or as an additional feedback modality [Jing et al. 2011].

While finger-worn NDO is far surpassed by HDO in frequency of usage, some did use magnets in coordination with other wearable sensors to control cursors [Harrison and Hudson 2009], create 1D input [Ashbrook et al. 2011], or control personal devices [Vega and Fuks 2013]. Vega and Fuks [2013] also postulate finger-wearable RFID to control and communicate with devices through the finger, while others proposed to use finger-wearable RF antennas [Shimizu and Kuga 2008; Watanabe and Iwasaki 2012].

3.4. Where the Action Is

One of the most complicated classifications of FADs is based on their intended action and where it takes place. Based on the collection of works surveyed, we determined the following classification for the action (see Figure 8):

—Clicking or touching the device itself [63 instances]
—Touching a surface with the finger [34 instances]
—Pointing or external action [29 instances]
—Gesturing the device in the air [27 instances]

However, some of the instances offer more than a single action to make a combination, and the most common combination is pointing + clicking, for example, in the finger-wearable remote control from Tsukada and Yasumura [2004]. Pure output FADs without an input modality cannot fit into this model and therefore are not classified in any category.

Pointing is a cardinal deictic gesture in our gestural language, it is cross-cultural, usage of it dates as far back as ancient cultures worldwide, and it is exhibited even in infancy [McNeill 2000]. It is therefore a very convenient platform for augmentation and was detected as such by many creators of FADs. The pointing gesture usually

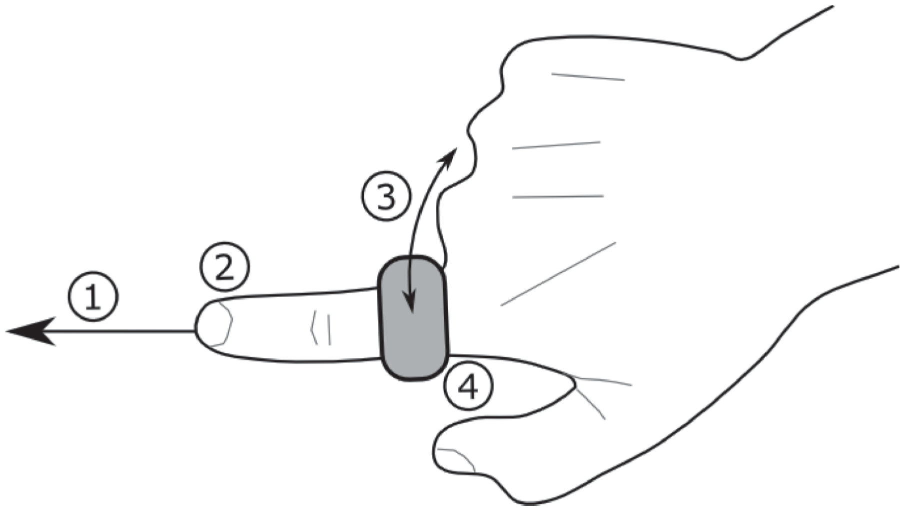


Fig. 8. Types of FAD actions: (1) pointing/external, (2) touching/on surface, (3) gesturing, and (4) clicking/touching on device.

suggests the existence of a referent in the immediate environment; thus, several pointing-direction recovery systems were suggested: global localization in the environment [Lee et al. 2007], local based on instrumented beacons or sensors (Infrared: Merrill and Maes [2007], Ultrasonic: Shaltis et al. [2005], Magnetometers: Harrison and Hudson [2009], Liang [2013], and Chan et al. [2013]), local based on fiducial markers or natural features [Yang et al. 2012; Ransiri and Nanayakkara 2013], or integrative based on accelerometers [Horie et al. 2012]. Other pointing augmentations do not make use of a localization mechanism when the interaction is oblivious to the spatial domain, simply examining the referent ahead [Zawrotny et al. 2006; Rissanen et al. 2013a; Hettiarachchi et al. 2013; Nanayakkara et al. 2013; Santiago Alfaro 2014; Horvath et al. 2014].

The most common action modality is clicking or touching the FAD, and this is most commonly done by adding a button or other interaction element to the device body. The opposing thumb easily reaches a button located on the side or bottom of the FAD (depending on the wearing finger) to support a single-handed usage, which was the goal in many recent products [Nod, Inc. 2014; Mycestro 2013; Mota 2014] and in academia [Rissanen et al. 2013b; Hettiarachchi et al. 2013; Nanayakkara et al. 2013]. More subtle input, or one that requires a gradient of values, was done via pressure sensing [Zloof 1996; Felsenstein and Wang 1998; Xiong 2003; Chatterjee and Matsuno 2006; Jiang et al. 2008; Ogata et al. 2012a; RHLvision Technologies Pvt.Ltd 2014] or a touchpad on the device [Levine 1990; Miner et al. 2001; Xiong 2003; Victor Soto 2007; Bell 2012]. Zloof et al. suggested using rotation of the FAD around the finger as an on-device input method as far back as 1996, and years later it was picked up by Ashbrook et al. [2011] and Ogata et al. [2012a].

Touching the surface when wearing an FAD was markedly used for cursor manipulation or a chording keyboard since the early days of finger augmentation [Fukumoto and Suenaga 1994; Prince 1996], and this still trends with very recent work such as Yang et al. [2012] and Kienzle and Hinckley [2014]. Leveraging the fingertip's very sensitive tactile sensation was targeted by creators of assistive FADs, guiding the process of scanning with the finger [Ando et al. 2002; Shilkrot et al. 2014; Stearns et al. 2014], for sensory substitution [Santiago Alfaro 2014] or using the body as the input

Table IV. FAD Actions: Applications, Advantages, and Disadvantages

FAD Action	Application	Advantage	Disadvantage
Pointing	Appliance control, assistive technology	Socially acceptable, cross-cultural and natural gesture, which also provides ample information for the system, as well as others, to understand the user's intent. Can leverage the finger's flex, or bend, for an additional signal.	The sensors must be aligned carefully with the finger, which presents problems of mounting, calibration, occlusion (by the nail or fingertip), and accommodation to warped fingers. May constrain the FAD to be placed on the index finger. Some pointing gestures carry negative social meanings.
Touching the device	Commun., computer input	Easily understandable for the users, mostly easy to implement, and robust. May allow for discreet, unseen function, even with a single hand. Can be placed virtually anywhere on any finger.	Many times uses a binary signal, i.e., a button. Oblivious to the environment, narrowing the interaction to the device itself.
Touching the surface	Assistive technology, virtual reality	Functions in conjunction with the sense of touch, and may also provide the system information about the touched surface or the "tapping" gesture. Lends itself easily for mixed-reality applications.	In some implementations can obstruct the inherent sense of touch, and may warrant specific positioning on the finger due to the high sensitivity of the index fingertip.
Gesture	Computer input, appliance control	Leverages on the dexterity of the fingers and the recent wave of interest in gestural interaction, which makes it fairly understandable to the user. Implementation is cheap and power efficient and can be made wireless.	Often constrained to a set of canned gestures, and otherwise may require calibration or training. Some gestures may create awkward social situations, especially as they are clearly visible to others but in fact made in private, and carry little conversational meaning.

means [Mujibiya et al. 2013]. Prattichizzo et al. explored the sense of touch in the context of a mixed-reality system [Prattichizzo et al. 2010; Chinello et al. 2012] using tactile actuators alongside pressure sensors that gauge the real versus generated force of touch. Others have explored touch as a gestural interface to enhance the interface of everyday objects [Denso Corporation 2009; Wolf et al. 2013] or displays [Liang 2013].

Using the FAD to detect gestures is a recent addition to the FAD interaction milieu, where the postulation to augment fingers to use gestures as an input was set forth in close vicinity by Soh et al. [2004], Kim et al. [2005], and Tsukada and Yasumura [2004]. Although the usage of gesture-sensing technology existed in FADs since the 1990s [Fukumoto and Suenaga 1994; Prince 1996], it was not used to detect gestural motion but rather finger taps for keyboard input [Lam and Li 2002]. In 2006, SourceAudio already introduced a product featuring a finger-wearable wireless gestural interface for adding effects to an electric guitar [SourceAudio 2006]. Following was a wave of interest in gestural interaction both in academia and in the form of patents, which culminated in a number of products released in the last 2 years [Thanko 2013; Logbar Inc. 2014; Nod, Inc. 2014; Mycestro 2013; RHLvision Technologies Pvt.Ltd 2014]. The academic front explored usage of finger gestures for appliance control [Lee et al. 2007; Jing et al. 2011], as an input device to replace a mouse or keyboard [Kanai et al. 2009; Harrison and Hudson 2009; Pandit et al. 2009; Horie et al. 2012; Chen et al. 2013; Jing et al. 2013], or for detecting gestures of a novel vocabulary [Ketabdar et al. 2012].

4. FAD APPLICATIONS

As we discussed in the last sections, FAD instances present plenty of input and output modalities with a wide span of capabilities. These instances cluster together in a number of application domains that look to achieve a common goal—enhancing or enabling a manual operation, gesture, or inherent ability. Applications for FADs trend with the eras in correspondence to the larger trends in the world of HCI. The current trend is quite clear: moving from keyboard, mouse, and/or remote control input to gestural and natural interaction. Similar trends in application were noted in the past, for example, with FADs as virtual reality interfaces, which have seen a wave of interest in the beginning of the 2000s and scaled back a few years later. This section describes the major and minor application categories that materialized from the body of work.

The following are the major application domains we recognize for FADs:

—Mouse-like cursor input [42 instances]
—Communication [22 instances]
—Assistive technology [21 instances]
—Appliance control [21 instances]
—Gestural interface [21 instances]
—Virtual reality interface [18 instances]
—Keyboard input and output [16 instances]
—Biometrics [11 instances]
—General: timewatch, jewelry, camera, etc. [11 instances]
—Natural interaction [10 instances]
—Social interaction [5 instances]
—Industry [4 instances]
—Learning [4 instances]
—Creative interaction [4 instances]

4.1. FADs as Paired Input Devices

Most FADs are input devices that work in tandem with existing electronic devices: personal computers (e.g., desktops or laptops,) mobile devices (e.g., smartphones, tablets, or wearables), and even home appliances (e.g., TVs, sound systems, or kitchen appliances). The goal of these FADs is to offer more efficient or natural interaction with paired devices through an always-on, steerable, and light finger-worn device. It appears FADs offer interaction around several recurring themes: keyboard input or mouse-like cursor input [Thanko 2013; Saar Shai and Efrat Barit 2012; Rami Parham et al. 2014], remote or gestural control [Jing et al. 2011; Nod, Inc. 2014; RHLvision Technologies Pvt.Ltd 2014; Logbar Inc. 2014], and communication [Fukumoto 2005; Marti and Schmandt 2005]. Beyond interaction with traditional personal devices, FADs are customarily used as a paired output device for virtual and mixed-reality systems offering stimulation in the hand [Sarakoglou et al. 2006; Ooka and Fujita 2010; Prattichizzo et al. 2010; Scheggi et al. 2010; Gallotti et al. 2011]. In the last few years, however, we have observed a rising prominence of the notion of natural interaction, which we define as an interface with noninstrumented everyday objects (e.g., Maekawa et al. [2012], who are using a magnetometer). Letting FADs leverage on the well-practiced pointing gesture to steer the interaction [Nanayakkara et al. 2013], the FADs can be a cursor for the main device for further action or computation.

4.2. Assistive Applications

The assistive technologies domain presents its own set of challenges for FADs, arising from the special needs of the target audience [Velázquez 2010]. This may also be the reason concept designers are drawn to this type of user interface, to present a wishful and critical outlook on the possible role of FADs as assistive technology. Hedberg and Bennett [2010] envision a whole finger augmentor with multiple sensors and capabilities: Braille tactile screen, camera for text recognition, buttons, microphone, and wireless connectivity. Lee brings a more modest vision of a fingertip augmentor that reads barcodes and wirelessly delivers useful information to an earpiece [Lee 2011]. In the engineering world, some work was dedicated to creating a wearable form of finger-Braille (an adaptation of the Braille to three- or five-finger coded sensations instead of the usual printed raised dots [Hirose and Amemiya 2003; Amemiya et al. 2004]), while others focused on accessing visual information, in particular printed text [Shilkrot et al. 2014; Nanayakkara et al. 2013; Stearns et al. 2014]. More attention was given to tactile displays [Koo et al. 2006, 2008] and enhancing the tactile sensation in the fingers in cases where this sense was impaired, for example, helping persons with multiple sclerosis [Jiang et al. 2008] or helping people whose work demands high dexterity (such as surgeons or assembly) [Kurita et al. 2011].

4.3. Biometric Applications

In the biometrics domain, the most prominent examples of finger augmentation are the ubiquitous pulse oximeters that are donned by hospital patients to monitor their vitals. These have been in existence for many decades and recently have reached wide usage in medical facilities with a range of available products [Nonin Medical Inc. 2015]. Their central mode of sensing is photometric and relies on the different light reflection and absorption properties of oxygen saturated and unsaturated hemoglobin within the bloodstream. As the field of finger-worn pulse oximeters seems to have moved out of the academic world, we will not review its history but rather new explorations of these types of devices. Some of the challenges recent implementations try to cope with are sensing pulse while in motion [Lee et al. 2008; Huang et al. 2014], wireless and low-power operation for long-term sensing [Rhee et al. 1998; Han et al. 2007], or additional sensing modalities such as temperature [Asada et al. 1999; Shaltis et al. 2005], proximity [Perlman 2007], posture of the hand and fingers [Hrabia et al. 2013], and recently sleep quality [OURA 2015].

4.4. Industrial Applications

The industrial domain seems to remain somewhat indifferent to the outburst of finger-worn devices except for solving very specific needs in manufacturing and operations. Nevertheless, we could find a wearable controller for a sewing machine [Samuel 1965], an industrial-grade finger-worn barcode scanner [Symbol 2000], a ring to prevent the misfire of firearms [Bennett 1995], a human–robot interaction and guidance device [Mascaro and Asada 1999], and a device that enhances the tactile sense in finger-inhospitable environments such as cold and dampness [Kurita et al. 2011]. Notwithstanding, we can clearly see how most of the FADs in other application domains potentially have an impact on the industrial world with trivial adaptation.

4.5. General Usage and Fringe Applications

Looking away from the major augmentation theme, we find an interesting set of applications for various types of augmentation: a finger watch [Frederick et al. 2004; Charles Windlin 2007; Meng Fandi 2007; SmartyRing 2013], a finger camera [Münscher 2007; Furuyama 2012], and jewelry [Ringly 2014; Miner et al. 2001]. We also recorded interest in the social aspect of using an FAD, with researchers creating a discreet interaction application [Ashbrook et al. 2011; Kienzle and Hinckley 2014] and applications to stay connected with loved ones [Lee et al. 2007; Brewer et al. 2008; Werner et al. 2008]. Another interesting minor line of applications for FADs is for learning and creativity,

Table V. Problems in Interaction and the Opportunities FADs Offer to Scaffold Them

Interaction Challenges and Opportunities		
	Challenge	Opportunity
Immediate	An interface the user can operate at any time with minimal effort.	FADs are worn on the body's most dextrous limbs, the fingers, and bring the point of interaction literally to the user's fingertips. They can reduce the reliance on external setup, and sense at a very high resolution.
Close-up	Sensing at close proximity to the user, utilizing fine motoric skills.	FADs can be placed on the index finger for minuscule yet very precise motion. Utilizing the fingertips for more than close-up tactile sensing is underexplored.
Discreet	An interface that is private to the user, can be made unobtrusive and inconspicuous.	Placing I/O elements on the inside of the FAD, facing the palm where the thumb can easily operate, creates a private interaction space. Using small and weak tactile response actuators can output information strictly to the wearer and maintain the natural function of the finger. Ring FADs can be perceived as socially acceptable and not raise attention.
Subtle, efficient	An interface that outputs in low magnitude, low power, and high resolution.	The fingers are highly sensitive in frequency, magnitude, and phase (separation or translation of stimuli), especially around the fingertips, allowing one to use a weak and efficient form of output (e.g., tactile). The hands are also very visible to the user, allowing for visual feedback.
Assistive, augmenting	An interface that assists in the case of impaired senses or limiting situations, or to augment the inherent human capabilities.	The fingers are already used as substitute eyes, ears, and mouths, which makes FADs a prime candidate for assistive applications. FADs can translate from one modality to another in high fidelity, bringing the input and output together on one body part.
Gestural	An interface that works by natural gestures.	Starting at a very young age, hands and fingers serve as one of the central means of gestural language. This makes gesturing with a FAD easily understandable to the wearer, and less awkward.
Bio-sensing	An interface that monitors biological signals from the body.	The fingers have a dense network of nerves and blood vessels, allowing one to externally inspect some aspects of the bloodstream (e.g., photoplethysmography), the sympathetic nervous system (e.g., galvanic skin response), and others.
Multipurpose, repeatable	An interface with a broad range of utility, application, and reusability.	Fingers are naturally used for a wide range of both day-to-day and special activities; thus, FADs may be used to sense and augment them using the same form factor.

for example, in playing the piano [Huang et al. 2008; Kohlsdorf and Starner 2010] or the guitar [SourceAudio 2006].

5. CHALLENGES AND OPPORTUNITIES IN DESIGNING USEFUL FADS

FADs are relative newcomers to the world of wearable computing, where much was already tried and tested. Nevertheless, their unique traits help designers approach old problems with a new toolkit. In Table V, we list a number of challenging problems in interaction for which FADs offer unique support. The rest of this section is devoted to design considerations one could follow when thinking up new FADs. Both of these lists are partial but cover the most parts of the factors.

5.1. Design Considerations

Designing useful FADs depends greatly on how the creators incorporate the finger's senses and actions into the interaction. We compiled a list of considerations to contemplate when designing a new FAD, which also exposes new opportunities to seek out underexplored territories. With this list, we also stress the wholesome approach one should take when designing for the finger, for the many and intricate aspects of the finger as a living limb and an object of meaning. The list emerged both from the surveyed body of work and our own explorations in creating FADs. One should note that the most trivial of considerations in creating an FAD—making sure it achieves the intended operation—is not discussed in this list; we chose to rather focus on the more latent and underserved design aspects. These aspects have nevertheless resonated with many FAD creators, and we regularly point to the relevant works; however, we wish to put them in a single instantiation that can serve as a guideline.

5.1.1. Using the Anatomy of the Finger. Fingers are incredibly sensitive to a number of types of energy, they are the most dexterous and strategically positioned limb, and they are highly represented in the primary somatosensory and motor cortices in our brain. These and other anatomical properties, widely researched outside the HCI community, make fingers a boon of interaction and augmentation potential. Researchers of novel interaction methods discovered some anatomical traits in the exploration of the finger and fingertip's highly dense mechanoreceptors [Jiang et al. 2008; Kurita et al. 2011], the flexion of finger tendons [Heo and Kim 2012], bone conduction [Fukumoto 2005], and compression properties of the soft tissue [Mascaro and Asada 2001; Ogata et al. 2012a]; however, the vast majority plainly use the tactile sense via vibration. The finger is also highly sensitive to changes in temperature via thermoreceptors; however, only Felsenstein and Wang [1998], Asada et al. [1999], Shaltis et al. [2005], and Ketabdar et al. [2012] have discussed it as an input modality and Alaska Jewelry [2008] for output. Established usage of the finger's anatomy in FADs was recorded for pose detection (via a mechanical [Gosselin et al. 2005] or other sensing modality [Hrabia et al. 2013]) and for photoplethysmography [Lee et al. 2008]; however, an interesting yet somewhat underexplored territory is that of proprioception or sightless action [Ashbrook et al. 2011; Oh and Findlater 2014]. Large areas of design for the finger's anatomy remain at large for exploration: thermal, nociception (pain), irritation, perspiration and humidity, and more. This evident gap poses an immense opportunity for designers to deepen the understanding of the finger's physiology for usage in augmentation.

5.1.2. Using Well-Practiced Behavior. The importance of the finger as a primary tool for sensing and interacting with the world is uncontested and heavily relied on by UI designers. However, often designers neglect the fact that fingers play a central role in our gestural and behavioral language from the very moment we are born, and such practiced behaviors carry deep meaning [McNeill 2000]. Deliberately leveraging practiced behavior played a minor role in finger augmentation so far, with works augmenting the pointing gesture [Tsukada and Yasumura 2004; Merrill and Maes 2007; Lee et al. 2007; Nanayakkara et al. 2013], other common gestures (the "phone" [Fukumoto 2005], stroking [Lee et al. 2006], scratching [Perlman 2007]), daily activities [Jing et al. 2013], or holding an object [Wolf et al. 2013]. Still different kinds of gestures and behaviors remain to be explored in the context of FADs, for example, iconic gestures (representing an operation, such as "cutting" or "chopping") and metaphorical gestures (such as a "speaking mouth"). In the work we surveyed, there is evidence that finger augmentation could benefit from using practiced behaviors of the hand and fingers to invite the users into a recognized interaction with the world, rather than introduce a new manual operation. On the other hand, augmenting the fingers could impede a routine operation, such as washing hands, handling a manual tool, or playing a musical instrument.

5.1.3. Using the Ring as a Fashionable Traditional Object. Finger rings are objects of tremendous tradition as jewelry and symbols of stature, power, and bond. Their history is believed to date back to the beginning of mankind; however, the concrete evidence of finger-worn fashion dates to only a number of millennia ago. Rings of significance appear throughout the narratives of ancient cultures (Egyptian, Greek, Roman, Israelite, Persian, and Chinese) and are aptly represented even in the narratives of today [McCarthy 1945]. This rich backdrop to our interest in finger augmentation is lightly touched upon in the realm of engineering; however, it is starting to take a more prominent stance with the rise of commonly used wearable computers. A new project named Ringly [2014] is specifically designed as a smart finger jewelry; however, concept designers of finger augmentors already discussed the aspect of finger-worn fashion in the past [Miner et al. 2001; Kim et al. 2005; Charles Windlin 2007; Vega and Fuks 2013]. Beyond fashion, rings hold a variety of symbolic meanings, such as engagement or belonging to a group. Building on such symbolic meaning is practically nonexistent (although not unheard of [Werner et al. 2008]) in the field of finger augmentation and presents one of the most exciting areas for investigation.

5.1.4. Creating a Comfortable Usable Design. Comfort and an appealing form factor are cornerstones for successful design for the body. In augmenting fingers with devices, this is of highest importance, since fingers and hands are very sensitive and very visible body parts. Naturally, no two fingers are the same size (girth, length) or shape; however, generalizations for these aspects were proposed in the form of finger size charts. Less standardized are the wearing and removing mechanisms, which are equally important and disregarded by the majority of FAD designers. Wearing and removing mechanisms come in a range of types: simple rings [Mota 2014], clasps [Saar Shai and Efrat Barit 2012], unclosed rings [RHLvision Technologies Pvt.Ltd 2014], flexible or rubber fastening [Shilkrot et al. 2014], and more; however, unfortunately, it seems the prolific way of mounting components to the finger is to do so without care. Placing components should also work to the function of the device; for example, buttons for the thumb should be placed on the side [Nanayakkara et al. 2013] and light output will be most successful on a line of sight to the eye, that is, on top [Ketabdar et al. 2012].

5.1.5. Using a Companion Device or the FAD as a Companion Device. Often FADs are not the only device the user would wear to perform the intended action; rather, it works in tandem with an external device, or the FAD itself is made from more than a single finger-worn device. Many cases display rings that are wired to a device on the palm [Kim et al. 2005], wrist [Fukumoto and Tonomura 1997; Zhang et al. 2011], or more commonly a connection to an external nonwearable device [Kienzle and Hinckley 2014; Shilkrot et al. 2014]. Wireless FADs are found in abundance; however, this does not mean they are used solo, as in some cases two FADs are required: on the thumb and another finger [Choi Hyong-Suk et al. 2010; Chen et al. 2013] or one on each hand [Horie et al. 2012]. A wireless single FAD would be the least cumbersome, but it poses both a technical and an interaction challenge to fit the components in a tight space and achieve an action requiring more than a single augmented finger. Using a companion device (e.g., a smartphone) may circumvent these obstacles.

5.1.6. Assistive Augmenting Technology. While a formidable amount of work was devoted to creating assistive finger-worn devices, it is not the mainstream agenda in finger augmentation, which creates ample opportunity. One important aspect to notice is that fingers are traditionally more than just fingers for people with different impairments; they often are substitute eyes, ears, and mouths. This introduces a dual challenge: not obstructing the inherent function of the finger as a substitute sense, and adding a meaningful assistive augmentation. These considerations were discussed briefly in the context of finger augmentation [Nanayakkara et al. 2013] and naturally much deeper outside of it [Velázquez 2010], with the major lesson being that assistive devices should be useful and unencumbering to become successfully adopted. The majority of the work surveyed was geared toward assisting people with a visual impairment [Shilkrot et al. 2014; Stearns et al. 2014] and only little to other impaired senses or conditions [Perlman 2007; Jiang et al. 2008]. To expand the reach of finger assistive augmentation, it is useful to observe the wider range of assistance, as one particular technology could also be practical outside its intended domain of application and target audience.

6. CONCLUSIONS

6.1. The Rise of FADs

Finger augmentation is on the rise as a domain of user interface, as well as a new branch of wearable computers that taps into new types of sensing and signaling. Recently FADs attracted considerable interest in academia but also as a commodity through products and projects, with new work contributed to the pool yearly. This success can be attributed to the rediscovery of fingers as a comfortable space for augmentation via electronics, building on past traditions. Fingers, as a driver of focus, the sense of touch, and both deictic and iconic gestures, offer easy access for user interface developers to the body language and manual actions of the wearer. With wireless sensor technology becoming ever smaller, more efficient, and simpler to integrate, the small form factor of a finger wearable is no longer a deterrent to creators.

The tradition of finger wearables reinforces the belief that FADs could be mainstream devices of interaction and have a mass-market feasibility. The prominent recent application domains of FADs are user input to a computer system (personal computer, mobile device, or smart environment), suggesting that the future lies in discreet, fashionable immediate-control devices that target end-users as their audience. Sleek design and omni-connectivity articulate the timeless narrative of jewelry doubling as objects of power or function, which is a central theme in contemporary user interfaces.

6.2. Avenues for Future Research into FADs

While it is hard to predict the future of FADs, the current trend is showing a promising outlook. Wearable computers are becoming a commodity, contributing to public interest in finger-worn devices, especially around complementing personal mobile computers such as smartphone. While products are already going to market [SmartyRing 2013], this enterprise is far from complete since the technology (input, output, power, and connectivity) for the ring form factor is immature and can benefit from further research.

Assistive technology with finger-wearable devices is still in its infancy; however, progress is being made [Shilkrot et al. 2015; Stearns et al. 2014]. This domain also presents a wide range of opportunity to prototype and research (see Table V), particularly in the areas of sensory substitution, enhancement, and recovery.

Also in evident need is deeper research into leveraging the anatomy and the natural behavior of the fingers, as currently these considerations are somewhat overlooked. This may be another effect of a vertical research agenda that gives less attention to cross-pollination between disciplines. Knowledge of finger anatomy is extraordinary rich in the traditional disciplines of medicine and physiology; however, it is fairly unreachable from the human–computer interaction perspective. An integration of this knowledge, in the form of demonstrated guidelines and prototypes, will certainly be a gift to both courses of research.

6.3. Contributions and Conclusions

Over the past years we carried out a comprehensive survey and overview of the work on FADs and we have presented it in this article. We created a categorization framework that distinguishes FADs based on their key elements: form factor, input modality, output modality, interaction, and application domain, where each element was further scrutinized to subcategories.

Our methodological review also resulted in a list of challenges FAD designers face and opportunities to overcome them. Nevertheless, we believe further inquiry into understanding the holistic nature of FADs as personal devices is required, attributed to the rich history of finger-worn objects of utility, meaning, and fashion. Research into the symbolism of rings and fingers is paramount in wearable artifact design (jewelry, for instance), but it did not yet percolate into engineering of augmenting devices. To achieve this integration, more guidelines that bring ergonomics and fashionable design factors into technological prototyping must emerge.

ELECTRONIC APPENDIX

The electronic appendix for this article can be accessed in the ACM Digital Library.

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