DESIGNING TEXTILE-BASED WEARABLE
ON-BODY ELECTRONIC INTERFACES
UTILIZING VIBRO-TACTILE PROPRIOCEPTIVE DISPLAY

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DESIGNING TEXTILE-BASED WEARABLE ON-BODY ELECTRONIC INTERFACES UTILIZING VIBRO-TACTILE PROPRIOCEPTIVE DISPLAY

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For my Nana
Theola Treado
Who always told me I could do whatever I set my mind to

And

To my Husband
Delton Moore
Who loves me because I believed what my Nana said

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List of Abbreviations and Definitions

BAN – Body Area Network
HCI – Human Computer Interaction
HUD – Heads Up Display / Head Mounted Display
PDI- Proprioceptively Displayed Interfaces
WBAN – Wireless Body Area Network

"Active Touch refers to the exploratory action of touching, whereas **Passive Touch** describes a stimulation of the skin brought about by some outside agent [31]."[72]

I am defining a **Proprioceptively Displayed Interface PDI** as an interface, which is not only on-body, but also easily self-referenced. A user should be able to touch and interact with a PDI without looking, just as a user should be able to touch their nose without looking.

Summary

With the advent of commercially available heads-up-displays and other mobile information systems, there arises a need for on-body interfaces that can be used accurately and quickly without visual attention. In this dissertation, I examine methods for creating textile-based interfaces supporting effective on-body interaction and robust manufacturing techniques.

Using these textile interface techniques I created prototypes to explore the human factors and constraints surrounding methods for interacting with electronic textile touch input. Specifically I looked at how the structure of the textile interfaces can take advantage of the human body's active touch and passive touch capabilities.

In one study I examined how the addition of raised embroidery affords greater opportunities for active touch interactions. I helped test raised embroidery with both multitouch and single touch interactions to improve accuracy and speed of use.

In a second larger study of 104 participants, I explored how the addition of active touch and passive touch affect the accuracy and time-to-touch of the on-body textile-based prototype. This study shows that the combination of active touch and vibro-tactile passive touch improves the accuracy (by almost 9% overall and 17% in the center of the interface) and time to touch for non-visual on-body interfaces.

Chapter 1

Introduction

1.1   Motivation

Wearable technologies are of increasing interest for many companies and researchers excited by the potential of computing working on and with a user's body. Researchers are developing the necessary technology to bring such systems to market and are exploring human computer interaction HCI topics such as the best on-body locations for the interfaces [3] and their social acceptability [20].

There is an under-explored aspect of sensing that the body affords that could be very beneficial to the use of wearable devices. Because wearable technology systems are used on the body, it is imperative that researchers and designers endeavor to use the body's full potential for interface interaction. This potential could include the information gathered by the skin (passive touch) underneath a wearable interface; a concept I am calling *Proprioceptively Displayed Interfaces* (PDIs). For my purposes, I am defining proprioception as the human body's natural ability to understand where one part of the body is in relation to another part of the body through kinesthetic sense and the body's sense of touch. A Proprioceptively Displayed Interface PDI would consist of a vibro-tactile display, such as an array of vibration motors, placed beneath an on-body interface at the location and in the pattern of the selection points on the interactive surface of the interface. PDIs should display information about the

interface's on-body location, referencing and calibrating its location on the body with respect to the wearer's proprioception, and the interface interactions against the body using tactile sensation. Other researchers are exploring tactile feedback; however, many open research questions remain. Are interfaces placed on and easily referenced on the body more efficient and usable than interfaces simply worn without any display of on-body location? What is the most appropriate way to design an on-body interface to take advantage of the human body's proprioceptive nature? Currently, there are no systematically developed, evidence-based guidelines that researchers and designers can reference when building PDI wearable systems. Such knowledge is critical to the advancement of this domain for the full potential of wearable interfaces to be realized.

Therefore, one of the goals of this research is to combine and create guidelines for designing PDIs. I am defining a Proprioceptively Displayed Interface PDI as an interface, which is not only on-body, but also easily self-referenced. A user should be able to touch and interact with a PDI without looking, just as a user should be able to touch their nose without looking. I quantify the differences in access time and accuracy between static electronic textile on-body interfaces and PDIs, including use without visual attention.

Figure 1 - This is an example of a conductive thread embroidered interface. This interface demonstrates what a Proprioceptively Displayed Interface might look like as a commercial product.

Potential Applications of Proprioceptively Displayed Interfaces (PDIs)

PDIs could have a wide range of applications, from emergency responders and pilots/astronauts, to smart phone users accessing information as they move through the world, and even assistive technology. The inherent tactile nature and body-reference aspects of on-body interfaces could prove helpful in any environment where the user must focus their visual attention on other tasks or is unable to see or hear an interface due to disability or environment. PDIs can also be unobtrusive; the textile-based interaction points on garments do not need to draw unwanted attention; and the embroideries used to create these interfaces could double as aesthetic embellishments.

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Visual Disability

In past work, I interviewed a visually impaired PhD student and researcher at Georgia Tech about PDIs and their potential applications for visually impaired users. He presented several scenarios of use and described simple problems he is seeking to ameliorate through his research. He stated, "It has been very cold here in Atlanta for the past couple of days (single digit temperature). While walking across campus, my fingers are gloved or become numb, and I am unable to feel tangible interfaces easily with my fingers. If the interface I was using included vibration displayed on my arm and let me know where my finger was on top of the interface, I could probably still use the interface even though my fingers were numb." He then explained, "It seems ridiculous, but one of the hardest things for me to do on my smartphone is to make a telephone call. My favorite contacts are always full and changing because it is so hard to dial on the touch screen, and voice commands are not always the best solution," (quoted with permission). He agreed that the quicker access time of a wearable is a benefit, but he hypothesized that a PDI could make it more robust and still be usable for visually impaired users.
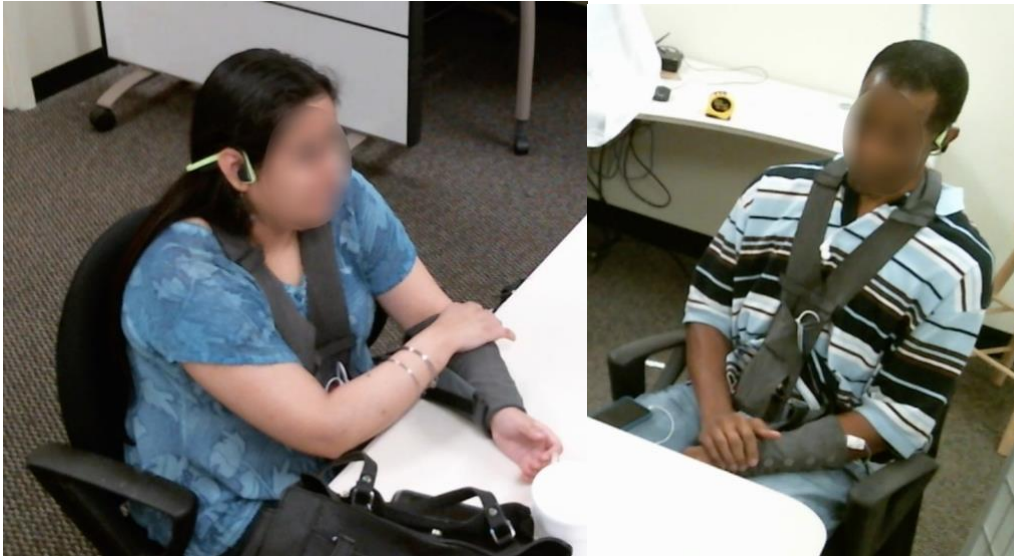
Figure 2 – People with visual impairments trying out an electronic textile based on-body input interface, and giving qualitative feedback.

Proprioceptively Displayed Interfaces have the potential to act as an accessible interface for all users. The materials and methods for construction allow designers to create interfaces that would work for everyone, and allow everyone to use the interface without visual attention. This type of universal design means that wearable technology designed with PDIs could have the added benefit of not having to be retrofitted with other technology to make the interfaces accessible to people with visual impairments.

Mainstream Applications

PDI research could also have an impact in the consumer electronic arena. With the advent of commercially viable heads-up displays such as Google Glass, it seems the perfect time to increase the amount of research regarding on-body interfaces. There is the potential for on-the-go interactions that might be more natural for input than interacting with the head mounted display itself. Wearable input interfaces allow users to access controls, such as raising or lowering the volume of music, by simply touching their clothing. Levi's Commuter X Jacquard By Google jacket is a good example of such an interface although the Commuter jacket uses gestural interaction rather than a selection point interaction [44]. Other studies suggest [3] on-body interfaces should have better access time than reaching into a pocket to pull out and unlock a carried mobile device . Also, with the addition of PDIs in garments, the interface could move across the skin of the body (in an action where the interface might be on a looser woven shirt for example) and still be easily referenced due to its ability to calibrate its orientation to the body through vibro-tactile display and defining its precise location before use.

Figure 3 - Proprioceptively Displayed Interfaces could be used in conjunction with heads-up displays as a quicker more natural interface compared to interacting with the display itself or a carried peripheral device.

Using a touch based input interface is more convenient than speech based commands in many scenarios. With a connection to a smart phone and blue tooth headsets, the possible applications of PDIs are numerous. A user could accept or decline a call without removing a phone or looking at the interface, thus making on-the-go interactions a real possibility. These types of non-visual input interactions also open up a user to real experiences, rather than walking through a city with their head down staring at a phone screen.

1.2   Thesis Statement, Research Question and Hypothesis

Most, if not all, wearable technology interface research has focused on the body location of the interface or the surface interaction with user's hand. One contribution of this research is to take this wealth of research, organize it, and make it accessible to designers creating wearable technology. The PDI research in this dissertation goes beyond previous research to gain an understanding of how the body underneath the interface might be able to gather interaction information as well. By using both the *Active Touch* (or investigative touch) [31, 59] sensation from the hand and *Passive Touch* (touch felt by the body) from the body underneath, interfaces could increase in robustness, resolution of use, and ease of use through faster access times and non-visual interactions. The resulting body of knowledge from this research informs those developing wearable interfaces in a wide range of applications, allowing them to apply tactile interfaces appropriately and effectively.

Hypothesis

My hypothesis is that an active touch / passive touch Proprioceptively Displayed Interface will be easier to find and use than an on-body textile interface without a Proprioceptively Displayed Interface. These benefits should include decreased time of touch, improved accuracy, and decreased workload.

To investigate and answer my hypothesis I created electronic textile based on-body input interfaces with varying levels of active touch and passive touch affordance. To create these input interfaces I utilized methods including both materials and techniques testing to make sure the textile input systems worked reliably at recognizing and registering touches to the fabric. I also employed user studies to find how well participants were able to use the systems. This research addresses three main research questions that address my hypothesis.

Research Questions *Detailed Research Chart APPENDIX A*

- What are effective techniques to create and design on-body textile-based interfaces that are robust, reliable and accurate?

- Can active touch affordances aid in making on-body textile interfaces more accurate and quicker to interact with than interfaces without such affordances?

- Can combining active and passive touch techniques aid in making on-body textile interfaces easier to locate and use, more accurate, and quicker than interfaces without such affordances?

The research described in the following dissertation addresses these three research questions. In investigating and responding to the research questions, I answer my hypothesis and validate my thesis.

Thesis Statement

Through the combination of active and passive touch in the form of Proprioceptively Displayed Interfaces PDIs, wearable textile-based on-body input interfaces will be faster in access time, more accurate, and easier to use than interfaces without such affordances.

In addition to providing substantial evidence to support this thesis, I have also organized my findings into a short set of guidelines and considerations for designers interested in creating Proprioceptively Display Interfaces. These guidelines can be found in Chapter 7. The results and contributions from my research to demonstrate this thesis range from material tests, to manufacturing methods, sensing techniques, and finally user studies.

1.3 Results and Contributions

Detailed Research Chart APPENDIX A

The contributions of this dissertation include:

- A set of validated techniques and processes for creating embroidered interfaces for on-body touch based interactions that create a foundation for active touch / passive touch interfaces. (Chapter 3)

- Prototype textile interface artifacts such as the Electronic Textile Interface Swatch Book, The Hood (e-textile garment music controller), and Le Monstré (an interactive participatory performance garment). (Chapter 4)

- An assessment through usability studies as to whether active touch and proprioceptive display of on-body interface PDI location through vibro-tactile stimulation aids in finding and using interfaces on the body, allowing designers to create designs with quicker and more accurate interactions. (Chapter 4 "Is it Gropable Study", Chapter 5 Preliminary Active Touch / Passive Study, Chapter 6 Final Active Touch / Passive Touch Study)

- Design considerations, guidelines and descriptions for producing textile based interfaces for on-body wearable technology interactions. (Chapter 2 Body Maps and On-Body Location Considerations, Chapter 7 Design Guidelines for Proprioceptively Displayed Interfaces)

Chapter 2

Where and Why: Considerations in

On-Body Location for Active / Passive Touch

Wearable Input Interfaces

When it comes to Proprioceptively Displayed Interfaces on-body for on-body input (most of which are meant to be used in a mobile condition), there are some clear human factor considerations for usability. For a touch based input system reachability is a key factor, along with body sensitivity at different locations. Active touch and passive touch sensitivity at different on-body locations is especially important to my research. I am hoping that through the addition of active and passive touch affordances to the interface, I can show in accuracy of use and a decrease in time to touch of interactions. The size, weight, and interference with mobility are other human factors that can have a great impact on a wearable system. When designing a wearable technology system it is also important to consider the social acceptability of interactions (even within a laboratory setting).

The set of body maps and design guidelines described in this chapter directly relate to on-body location selection for proprioceptively displayed interfaces. This information comes from a larger more inclusive literature review of human body affordances and current technology capabilities that has been synthesized in to graphical representations of what types of technology work best on what parts of the body (body maps) [111, 113]. Some of the design guidelines presented here help start to

create one of my research contributions as *guidelines and descriptions for producing textile based interfaces for on-body wearable technology interactions*.

2.1   Related Work and Human Factors

The first consideration for a study of Proprioceptively Displayed Interfaces is to decide where on the body to locate the interface. In fact, one of the first questions any researcher or designer of wearable technology has to answer in the design process is where on the body should the device be worn. It has been almost 20 years since Gemperle et al. wrote "Design for Wearability" [29] and although much of her initial guidelines on humans factors surrounding wearability still stand, devices and use cases have changed over time. I have collected literature and created an updated set of design considerations and reasons for on-body location depending on the use of the wearable technology and the affordances provided by the body at different locations. I have also included design considerations for each subject relating to wearable technology and on-body location.

I synthesized design considerations outlined in this chapter from a literature review. I also took the information from the literature and graphically presented the regions on the body that work best for each consideration. I call these body maps. While it is not necessary to go through many of the considerations here (ones having to do with biometrics, for example) the full collection of body maps with references and design / accessibility considerations can be downloaded for use [106, 111].

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An important place to start, for my purposes, will be the human body's capability to feel and sense touch. My hypothesis takes the assumption that through a combination of active touch and passive touch a user might be able to find and interact with a wearable interface more effectively.

2.1.1 Tangible / Tactile / Haptic Feedback (passive touch)

Many wearable devices use tangible feedback, or haptic feedback through the use of vibration motors, and sometimes other means such as electrical stimulation [26]. "Active touch refers to the exploratory action of touching, whereas passive touch describes a stimulation of the skin brought about by some outside agent [31]"[72]. Vibration can be felt better on some locations on the body than others. If more than one tactor (or haptic stimulator) is used to create a pattern, it is also helpful to understand the body's sensitivity to how close stimuli can be to each other and still be detected as separate stimuli. Knowing the level of sensitivity local to each area of the body can help designers develop meaningful haptic stimulations. This is especially true if aiming to represent discrete on-body locations through the display of vibro-tactile stimulation at those points on the body.

Understanding the body's level of sensation can have major impact on the choice of body-location for wearable devices using haptic feedback, or haptic displays. Schiffman's text book "Sensation and Perception" also does a great job of explaining skin sensations [81]. A popular test to determine each individual's level of skin

sensitivity to passive touch is the "two point discrimination test" [68]. Mancini et al. [61] have a great overview of whole body two-point discrimination data, that "compares 2-point discrimination (2PD) for touch, as measured by Weinstein [108], by Weber [107], with Mancini's study. Both Weinstein and Weber used simultaneous stimuli. In the Mancini's study, they used both simultaneous and successive stimuli." [61] . Body Map 1 uses Mancini's findings of two point discrimination distances to present the information graphically.
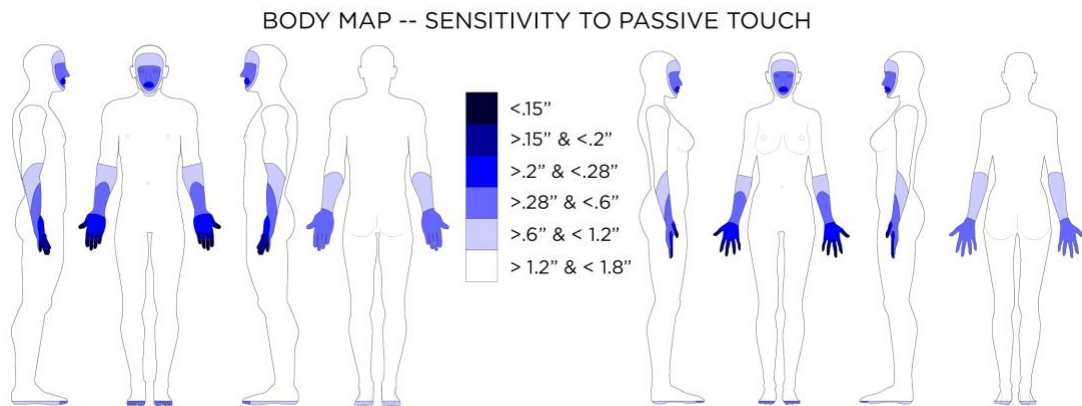
BODY MAP 1 – Body Sensitivity to Passive Touch - Average distance in two-point discrimination sensitivity test on body locations.

Aside from sensitivity with regards to static on-body location there are other factors to consider when designing wearable devices with haptic feedback. Vibration stimuli have "extra parameters" including rhythm, roughness, intensity, and frequency that can all be altered to aid in correct vibro-tactile display designs [8]. Pasquero outlines some of these factors in "Survey on Communication Through Touch" [72]. Jan van Erp also details pitfalls in the use of vibrotactile displays which can be very helpful in

the development of my research [22]. I will outline some of the key concepts that pertain to my research, and will help in the design of a Proprioceptively Displayed Interface that uses vibration to help locate discrete points on the body for input.

Vibro-tactile Masking

Masking describes when presentation of stimulus is habituated to over time. This is seen both with static and vibro-tactile stimuli. Masking can also occur when the stimulus is presented in succession and is mitigated by the extending the time between presentations. Craig and Cholewaik also describe this effect [13, 15–17]. For my purposes I am mainly interested in masking as it pertains to the dulling of sensation at a discrete on-body location thus making it hard to precisely find. Masking can also have the effect of making vibrations (of different strengths or patterns) harder to distinguish from one another [18, 102], however this type of masking can be avoided by using different locations or different frequencies [11].

Vibro-tactile Adaptation

Adaptation is different from masking in that it is not about habituation to stimuli, but misunderstanding stimuli. Certain combinations of vibration, frequency, location and timing can make a vibration display harder for the user to understand. For instance feeling a very intense vibration and then one that is less intense can have an effect on the perception of the actual intensity of those vibrations [7, 100, 101]. Another adaptation that can happen regards the effect of presenting two stimuli at the same time, if they are close to each other in body location they can have the effect of being

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perceived as one location rather than two separate locations [30]. Another example of this type of adaptation may occur if the two separate stimuli are present in close succession, where the presentation of the stimuli has the perception of a moving vibration [47, 88]. "Yet another is the tactual rabbit, in which a number of taps at distinct locations A and B results in a percept of a continuously hopping stimulus from A to B" [28].

When it comes to passive touch, there is also evidence that vibration applied to the fingers and tongue (while localized and descriptive on the individual finger and the tongue) may not help in describing the overall position of the finger or tongue. Benedetti's research shows that the vibration on a finger may not aid in describing where that finger is in respect to the other fingers [5]. For the purposes of the study I am designing, this information is helpful. An interface that uses passive touch to aid in interaction, should be placed on surface of the body that articulates and gesticulates with less variability to the rest of the body. For instance the hand and fingers would not be a good place for a Proprioceptively Displayed Interface.

The Contextual Computing Group at the Georgia Institute of Technology has shown how the use of vibro-tactile motors through a combination of body placement (on the hand) and vibration styles and techniques and work quite effectively as a passive haptic learning tool [43, 63]. This is akin to haptic guidance for training motor skill, but is completed passively rather than actively [24]. Markow found that through the use of the wearable vibro-tactile passive learning piano gloves in the Mobile Music

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Touch project, spinal injury patients were able to advance their rehabilitation (gaining more feeling and dexterity after they otherwise would have stopped improving). Seim picked up the Mobile Music Touch project and began researching the best way to use the technique for teaching braille typing [83–86]. Seim describes the process for determining where to place the vibrating tactors and how to display multiple vibrations near each other on the hand through a wave pattern of vibration [85]. She also describes what she found as the usefulness of LRA and ERM vibration motors.

Types of haptic stimulators:

- ERM Eccentric Rotating Mass Vibration Motors – The intensity of vibration is tied to the frequency of vibration. [1]

- LRA Linear Resonant Actuator 'Vibration Motor' – The intensity of vibration is not tied to the frequency, but intensity can be controlled more precisely and thus LRAs are very useful for haptic applications. [2]

- Electro-tactile / Electrical Stimulation – Electricity can also be used in low voltage to create the sensation of vibration by activating the muscles under the stimulator. This requires very good conductive connection with the skin, as the voltage needed from a resistive

connection can cause the pain threshold to be met before the electricity is felt as a vibration.[53, 56]

In many vibro-tactile displays the forearm seems to be a desired location, but the sensitivity of the forearm does not allow for very precise display [71]. Designs and evaluations have also been conducted for vibro-tactile displays placed on the shoulders [98].

Design Considerations for Tangible / Tactile / Haptic Feedback (passive touch)

- When designing haptic displays for wearable devices, the sensitivity of the on-body location where the wearable is placed is very important.

- Vibro-tactile displays should be programmed to account for masking and vibro-tactile adaptation.

- Tangible/Haptic Feedback is an important part of a multimodal display system. Multimodal feedback is important; designers need to create wearable devices that can prompt users with a variety of different abilities. Vibration and haptic alerts can aid those with visual impairments when acoustic feedback is inappropriate.

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- Vibration and haptic feedback have been seen to provide added benefit in rehabilitation of injuries (such as spinal injuries) where sensation has been degraded. Mobile Music Touch has shown that rehabilitation with the vibrating piano gloves not only taught participants to play piano, but also improved their sensation and dexterity [63].

2.1.2 Touch (Active Touch)

"Active touch represents the exploratory action of touching, which is generally involved with kinesthetic movement of the body." [56] In other words active touch is how a person investigates the world through touch. When asked to turn on a light switch in the dark, a person would use their hands and fingers to feel for the switch to find it and understand its position. This "feeling for" or "groping" is the act of active touch investigation.

"Kinesthesia relates to the relative positioning and movement of body parts with regard to muscular effort while touching or manipulating objects. When tactile perception, which includes skin stretch, vibration, pressure, and contact force, is combined with kinesthetic perception, the result generally conveys a felt object's properties such as shape [58, 59]. In this paradigm, passive touch is associated with cutaneous or tactile sensation, whereas active touch implies proprioception or haptic sensation."[56]

"When we examine an object using the sense of touch, there is nothing in our experience that would indicate the operation of two distinct sensory subsystems, each with its own functional properties. These two subsystems are the cutaneous and kinesthetic senses. In functional terms, the cutaneous sense provides an observer with information about stimulation of the skin surface; whereas, kinesthesis provides static and dynamic information about the relative positioning of the head, torso, limbs and effectors used in touching. While J. J. Gibson [31] acknowledged these two components of the sense of touch, he believed that analysis of the touching process in terms of them lost sight of the purposive nature of touch. In addition, he disdained the idea prevalent at the time and promoted by the then current research on cutaneous sensibility that perception was based on sensations. Rather, he believed that the perceiver seeks the invariant aspects of sensory stimulation over time and space that correspond to the properties of objects in the spatial field. Thus, he preferred to stress the function of the two subsystems working in concert."[59]

"Many approaches to augmenting tactile perception focus on translating stimuli through a bulky protective garment using an array of protruding stiff elements embedded in a flexible textile." [105] Thad Starner and team also looked at using vibration to aid firefighters in sensing heat through their gloves by vibration when using active touch to investigate doors in burning buildings [103].

Designing interfaces made to be "easy to find" through active touch is a tenant of human factors. Norman talks a great deal about mapping associated with physical interfaces [70], but the shape of buttons and levers offer affordances as well, and our hands find a way of using them through active touch. A cylinder with a grip on the sides affords turning the cylinder just as a textile design with raised embroidery affords active touch investigation [48].

Active touch happens almost exclusively with the hands. It is where the human body is the most sensitive, and the part of the body which humans use the most to investigate their surroundings through touch. The feet and the mouth might also be used for active touch, but less so than the hands.
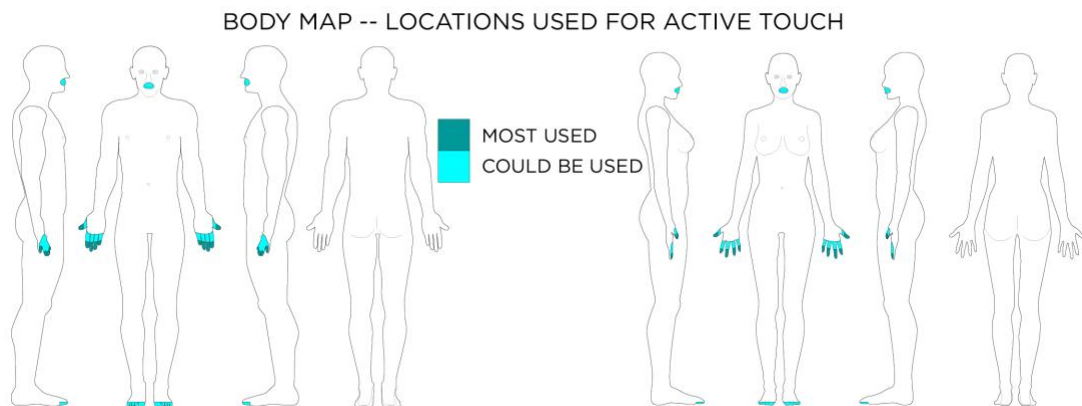
BODY MAP 2 – Body Used for Active Touch - Active touch represents the exploratory action of touching.

- Following good human factors and industrial design standards when creating physical interfaces will aid in a person's ability to use active touch to interact with objects and controls. This is also true for interfaces on the surface of wearable devices.

- Certain shapes contain certain affordances. Concavities on top of buttons might lend themselves to a pushing type active touch investigation. Ridges on the circumference of cylinders might lend themselves to turning. Expenditures at an angle to a plane might afford a flick or leverage. Dreyfus lays out shapes and sizes for controls in his book [97].

- It is important to remember that each person has a different ability to feel or sense tactile sensation. Thus, interfaces should be designed with robust multisensory feedback. Whereas one person might feel a click of a button through tactile means, others who cannot might require an audio cue or a visual cue to know that a selection has been made.

2.1.3 Reach-ability

In terms of reach-ability, it is important to know which parts of the body, and therefore wearable devices placed on those parts of the body, are reachable by a

person's hands. One way to start to qualify reachability is by looking to clothing, specifically the location of garment closures for self-donning and doffing [105]. We place buttons in the front of a shirt because we can reach them and use them, whereas dresses with back zips need long pulls or a helping hand to aid in closure. When it comes to reach-ability, there are easy to reach locations (where your hand can reach without any body movement), reachable locations (where you can move a part of your body to your hand to be able to reach it), and hard to reach locations (such as your center back).

For my purposes, I want to test interfaces in a place that is easy to reach. This means that the interface will have to be symmetrical and the same for right-handed and left-handed users.
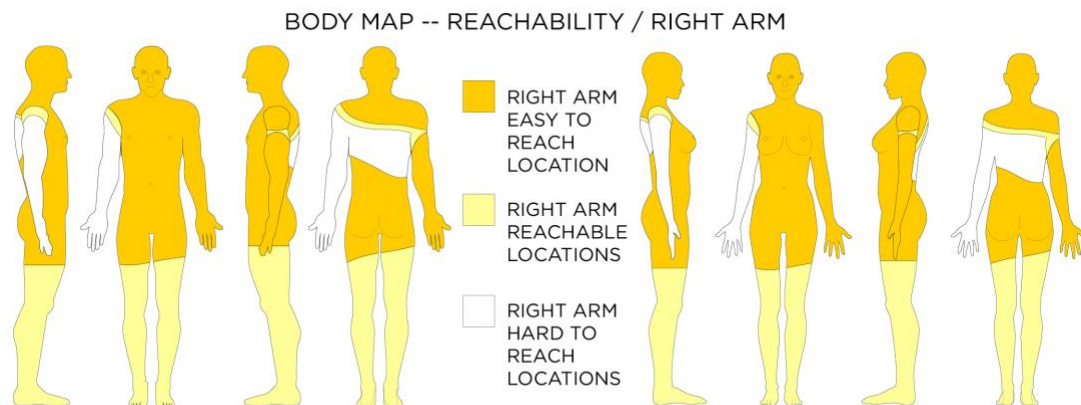
BODY MAP 3 – Map of Ease of Reach of Body Locations – Right Arm - When it comes to reach-ability there are easy to reach locations (where your hand can reach without any body movement), reachable locations (where you can move a part of your body to your hand to be able to reach it), and hard to reach locations (such as your center back).

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BODY MAP -- REACHABILITY / LEFT ARM

LEFT ARM
EASY TO
REACH
LOCATION

LEFT ARM
REACHABLE
LOCATIONS

LEFT ARM
HARD TO
REACH
LOCATIONS
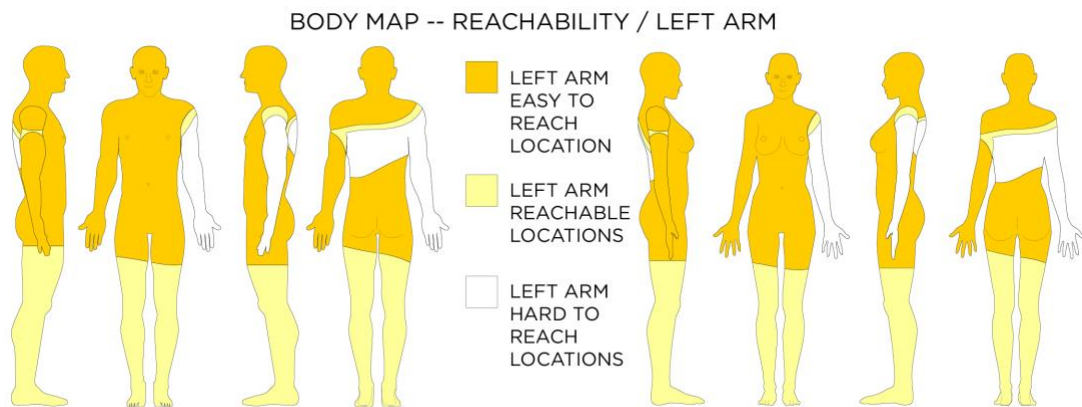
BODY MAP 4 – Map of Ease of Reach of Body Locations – Left Arm

Design Considerations for Reach-ability

- Wearable Devices should be placed in easy to reach on-body locations, especially for interfaces, but also for donning and doffing.

- Reachability is very personal as people have different physical abilities with respect to body movement.

- It is best to design a wearable device that does not cater to a dominant body side (right / left) and also is easy to reach with the hand's extension.

- Some people who spend most of their time in a seated position might be able
  to reach their upper thighs to their knees more readily. It might be better
  however to design wearable devices useful to everyone in the same way.

2.1.4 Visible Feedback

While I don't study visible feedback in this dissertation, it is important and will have
an effect on future devices designed for on-body interactions. For this reason, it is
important to consider when choosing an on-body location for the study.

When designing a wearable device with a visual display, it is important to consider
where a person can see visual feedback emitting from the body most effectively.

Chris Harrison developed such a study to find out where to locate wearable displays
[39]. Participants wore devices with LED lights and were asked to press the button on
the device when the LED blinked. The devices were placed in seven different body
locations to see if reaction time would change depending on where the light was
signaled. He and his colleagues found that the wrist and arm had the least average
reaction time of around 20 seconds.

Harrison furthered his work in on-body visual displays with OmniTouch [38] and
other projects [40], using the body as a projection surface. The projection surface he

uses is the hand and wrist, which seems obvious given his findings in on-body visual cue reaction time.

The body map for reaction time to visible feedback observes body areas from a first-person perspective also takes into account Harrison's reaction times; therefore, the map is more representative of where a designer should locate a wearable visual display rather than just locations where a user can see it.
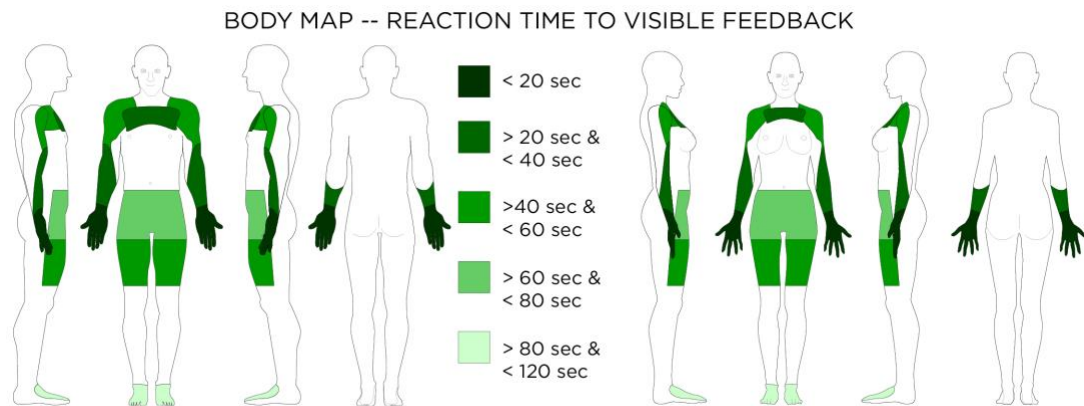
BODY MAP 5 – Visible Body Areas Map - Average reaction time to visible feedback

Design Considerations for Visible Feedback

- When designing a wearable device with a display or visual signal, it is important that the device be placed on a part of the body where the display can be seen, and also a place on the body where it will be noticed easily.

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- Visual displays should be accompanied by non-visual signals for those with visual impairments.

- The visibility of on-body locations might change from person to person depending on their mobility and means of mobility. Wheelchairs or other mobility devices might occlude some on-body locations which would otherwise be acceptable for a visual display.

2.1.5 Networking on the body

Networking on the body (specifically from the on-body to off-body) is important for my user study as my prototype use WIFI to transmit data and for console control. When mobile and communicating with an off-body network, the choice of signal and the body location of the antenna can affect data transfer.

In 2001 Thad Starner listed Networking as one of the major challenges for Wearable Computing: *For wearable computers, networking involves communication off body to the fixed network, on body among devices, and near body with objects near the user. Each of these three network types requires different design decisions. Designers must also consider possible interference between the networks.* [92]

When considering on-body location, designers need to consider the location of the antenna that communicates with the off-body fixed network. The mass

(water/muscle/tissue) of the body can block many of the lower powered high frequency wireless network signals we use for communication [36]. At a higher power, such frequencies could have the potential to cause tissue damage, which is unacceptable for wearable devices. "Wireless Body Area Networks WBANs experience high path loss due to body absorption that must be minimized through heterogeneous and multi-hop links with different types of sensors at various locations. Additionally, change in operational conditions may lead to error-prone and incomplete sensor data relative to inherent sensor limitation, human postures and motions, sensor breakdown and interference" [66]. There is a balance, and many people have researched the application of WBANs for medical and other wearable sensing systems [37, 73, 99].

While I am interested in how networking decisions can effect on-body placement, tables and content within Patel et al's 2010 work can be very useful in understanding wireless network options (including signal strength and distance) with respect to wearable technology and body area networks.
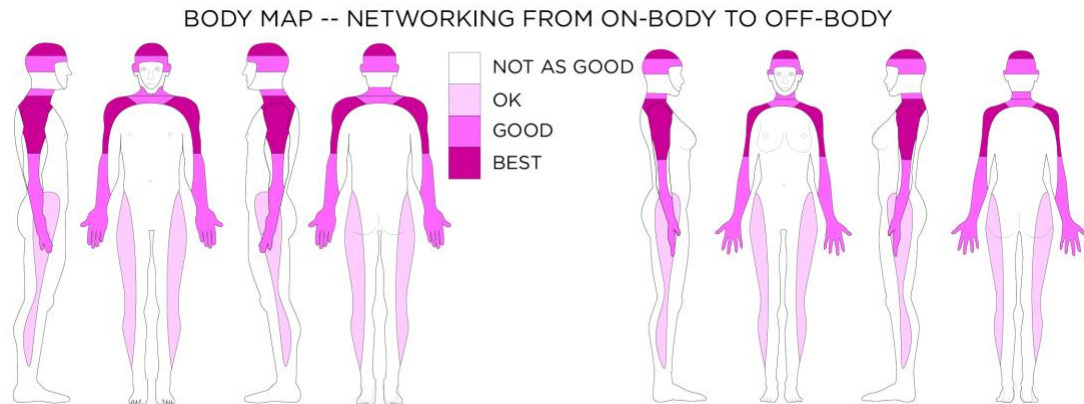
BODY MAP 6 – Networking From the Body Map - This body map shows the areas on the body where a network antenna (to communicate to the fixed off-body wireless frequencies) could be placed to have the least chance of signal interference by the mass of the body.

Design Considerations for Networking

- Antennas for wearable devices should be placed on the periphery of the body to have the best chance of having an unobstructed (by the body) connection to the fixed off-body network. This could mean the outer arms, shoulders or the head. Because of the strength and abundance of fixed off-body wireless network signal, this is not as much of a problem as it would have been in 2001.

- Body Area Networked devices using low powered wireless connections between devices on the body should also try to avoid obstruction by the body between devices. If one device on the front torso for example needs to wirelessly communicate via low powered signal to a device on the back, a third relay might be needed on the side of the body.

- All body mass compositions are unique. Outside of the general guidelines, wearable systems using wireless communication should be tested thoroughly on a variety of people and in a variety of settings.

- Health monitors or wearable sensing devices use Body Area Networks. Some people might have many different monitors all using different frequencies. It is important when designing a new device that it does not interfere with wearable health devices such as heart monitors or pace makers. It is also important that it does not interfere with wireless hearing aids and other assistive devices. Adding a new signal to a series of signals requires some standards, research, and testing.

2.1.6 Manufacturing for Garments

Understanding how garments are designed and constructed can aid tremendously in designing wearable technology, especially if it is to be integrated into clothing. This knowledge can help in making decisions about sensor location and the location of wired connections to a component placed across the body. Conversely, if a sensor needs to be placed on a specific body part, the clothing pattern can be designed to accommodate for that [45, 46, 104, 105].

While most wired connections do not stretch, most fabric does extend. Wires for connections can also be heavier than the fabric that supports them (this is especially true for light weight fabrics). These characteristics, along with the addition of rigid components, cause the hand of the fabric and the drape of a garment to alter in unwanted ways. If a garment has stretch, it is usually around the body horizontally. Designers should avoid horizontal wires connecting components and instead opt for vertical or diagonal traces. Seams are where fabric panels are sewn together to create a garment. Because seams are an edge condition and have double fabric, they are the perfect place to incorporate leads and wires if necessary. Some seams are sewn horizontal across the body and these are a better place to put horizontal traces. However, some seams are sewn in a specific way to allow stretch, so a designer should pay attention to if the fabric is a knit (stretchy) or woven (tend to not stretch) and if elastic is used to create a stretch seam. Fabric holds its own weight when cut

and sewn into a garment. If components are to be sewn onto the fabric, it is important to pick a fabric which can hold these components appropriately, both for function and for the aesthetic appeal and drape of the garment. Sometimes wires and leads can be used to support the weight of components if drape is considered during the garment design process.

Figure 4 – With proper diagonal and vertical placement, wires like these (sometimes necessary in early prototypes) can act as structural support for the garment and the components they service.

Some textile manipulation techniques can lend themselves to fabric interfaces [110], and some couture sewing techniques might sometimes be used for the hand work

necessary in creating some wearable technology [87]. Many times, the type of fabric manipulation used in creating an interface might work better on some parts of the body than others. For instance, the interface in Figure 5 works by reading resistance changes in conductive materials, which touch each other. The interface Figure 5 would not work on a body location that has pressure applied to it when not in use. If a user sat on this interface, it would activate. It then also needs to be placed in a location where bending and wrinkling will not cause a false activation.
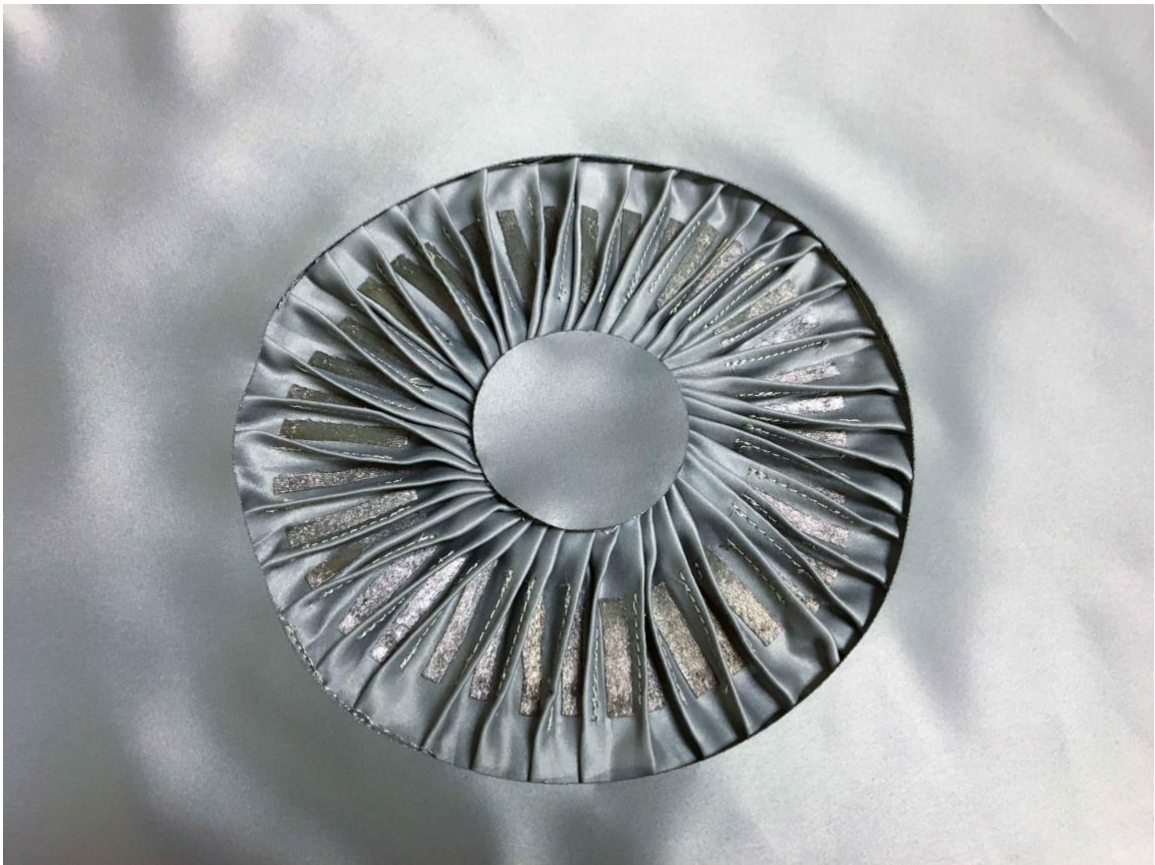
Figure 5 – A knife pleat fabric manipulation is turned here into an interactive rosette scroll wheel.

BODY MAP -- TYPICAL SEAM & GARMENT CONSTRUCTION LOCATIONS

WOVEN SEAM LOCATIONS

KNIT & WOVEN SEAM LOCATIONS
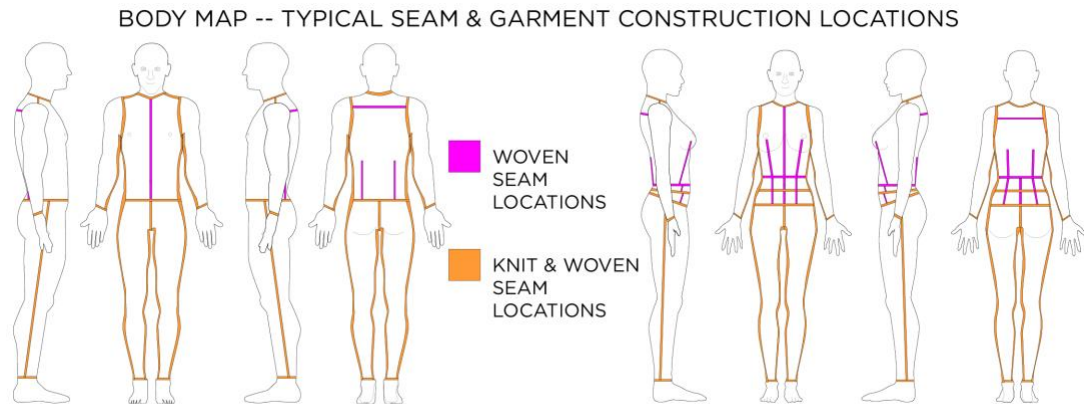
BODY MAP 7 – Typical Seam Locations and Other Garment Construction Locations

Design Considerations for Garment Manufacturing

- Wires and leads should be incorporated into seams when possible.

- Wires and leads should almost always run vertical (up and down) the body and not horizontal (around) the body.

- Look to fabric manipulation, old world textile techniques, and couture sewing techniques as inspiration for designing electronic textile fabric interfaces and sensors.

- Some garments are specifically designed to be donned and doffed by people with mobility issues [104, 105]. Designing wearable systems for incorporation with these garments should follow the same strategies as any other garment. However, if redesigning seams and closures to afford the wearable technology incorporation, it is important not to impede the donning and doffing functionality of the accessible garment.

2.1.7 Social Acceptability

A wearable product can function perfectly, but if a wearer feels socially awkward using the device, then the technology will become a failure. This is even true among health and medical devices. Wearable technology has to be socially acceptable. For this reason, it is important to consider the social acceptability of how and where I test user study interfaces as well. How people present themselves to society is a huge part of a person's identity, and is also how others are able to relate to them. Goffman would say that it is the presentation of ourselves that gives others cues as to how to interact with us [33]. He goes on to explain that most people take this inferential information as a fact of whom one is and act accordingly: "The others find, then, that the individual has informed them as to what is and as to what they ought to see as the 'is',"[33]. In 1999, Starner et al. found that wearable computers or wearable technology in general was viewed by others (interpreted by others) to be medical devices [93].

Use of wearable technology and body placement has a great deal to do with the social acceptability of a wearable system. Google Glass had an issue with its beta release because of public misunderstanding about the forward facing head mounted camera [119]. This led to a difficult release even though designers had factored in privacy by design, and there are a number of features on the device which alert the user to active filming. Other devices on the market can video and film with much more discretion, but the location of the camera on the face of the wearer (visible and noticeable during face to face social interactions) made the camera of Google Glass a touch point for discussions related to privacy [20].

The gestures and touches users make with wearable technology to interact and control devices can also cause uncomfortable situations. Social touch (a use of passive touch) can also reinforce social connections, and add social cues to digital and wearable systems [23]. The placement of interactive textiles, interfaces, and the types of gestures used to control interfaces sensed through motion detection can make a wearer/user as well as bystanders feel awkward. "For wearable devices, the social perception and comfort of worn artifacts often extends beyond the "static" aesthetic variables of the artifact (worn on the body, but not interacted with) into the social aesthetics of interacting with a body- worn device," [21]. Profita et al. look specifically at body placement of interactive electronic textiles, and how third-party viewers deem interactions socially acceptable when placed on different parts of the body [79]. Given the information collected in these studies, I have developed a body

map with regions of socially acceptable locations for wearable technology interaction and forward-facing displays of technology.

BODY MAP -- SOCIAL ACCEPTABILITY

NOT ACCEPTABLE

LESS ACCEPTABLE
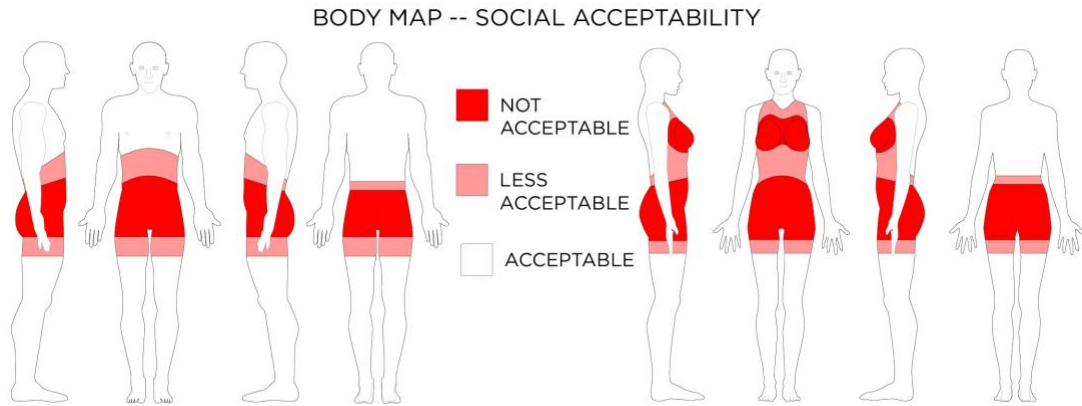
ACCEPTABLE

BODY MAP 8 – Social Acceptability Body Map - Social acceptability of on-body touch based interactions.

Design Considerations for Social Acceptability

- Body placement of wearable technology can drastically affect the social acceptability of the wearable device. In general, avoid touch-based interactions and displays within regions of the body associated with sex or elimination of body waste. An exception would be if the wearable device is specifically designed to aid in sexual stimulation.

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- In general, it is also advisable to avoid the breast and an interaction location for wearable technology (except for wearable devices specific to cis-gender males, but there are still more socially acceptable places on the body which could work better). An exception would be products designed to work with the breast (e.g. a breast milk pump).

- Sometimes users want assistive technology to be conspicuous so that others know about their needs. Other times users want assistive technology to be inconspicuous so they can go about their daily life without a disability being the focus. Designers should work with users to allow for wearing technology in ways that can throttle the visibility of wearable assistive technology.

- Wearable assistive technology should conform to the same social acceptability standards as other wearable technology. Assistive devices do not have to look like medical devices.

2.1.8 Proxemics (human perception of size)

Proxemics becomes important for the on-body location of wearable technology when the size of the items being placed on the body exceed the body's natural understanding of its perceived size. The interfaces used in the study in Chapter 6 do not cause any proxemics issues in the task the participants are asked to perform, but it

is good to understand the human body's limitations. Humans naturally have a slightly enlarged sense of their size to help them navigate the world without bumping into obstacles around them. When a young football player first puts on shoulder pads and bumps into the door on the way out to practice, this is a great example of a wearable object's size reaching beyond the body's perceived size. The distance from our actual skin we still perceive to be our size differs on different parts of the body. A designer might be able to place a larger object on the waist than on the wrist and it still feel natural to the wearer.

The concept of self-size awareness might not be as important as other design guidelines because from casual observation it seems that humans can adjust their self-size awareness. A person with a huge diamond ring might snag the ring as they reach into pockets or bags at first, but over time they account for it. The value of the ring is more important than the initial change in self-size awareness. The same might be true for a person who needs a wheel chair, navigating the world incorporating the extension of the chair into one's self-size. However, if designers are to create wearable technology for the general public striving for Weiser's [109] idea of seamless, or invisible computing, then containing the shape of wearable tech within the aura of self-awareness might be a good start.

Figure 6 – Symbol Ring Scanner (photo by Maria Wong Sala)

A great example of proxemics becoming a design issue is the development process for the Symbol Ring Scanner [95] used to scan boxes in a shipping hub. Because the device (see figure 6) extended beyond the self-perceived size of wrist / lower arm the key pad housing constantly rubbed against corrugated boxes during trial use in a shipping center. Constant abrasion caused the softer abs plastic to rub away and expose the internal electronics. Because of this, the whole system had to be 'ruggedized' for normal wear and tear. This could have been avoided if the device were smaller and within the user's proxemics (at the time this device was built, technology would have prevented this).

Gemperle talks about proxemics as a consideration for "Design for Wearability" [29], and Edward T. Hall discusses large aspect of humans' relationship to the space around them in The Hidden Dimension [35]. Gemperle uses Hall's definition of

intimate space at 0-5 inches to develop an aura around the body of self-perceived size.

I take that aura and segment it into zones on the Body Map. Using these zones, I can make suggestions of where to place wearable technology based on the distance that tech extends from the body. I also use the clothing corrections guide from Henry Dreyfuss Associates "The Measure Of Man and Woman" as a proxemics minimum guide as most humans wear clothing [97].

BODY MAP -- PROXEMICS

- <.1"
- >.1" & <.25"
- >.25" & <.5"
- >.5" & < 1"
- > 1" & < 2"
- > 2" & < 4"
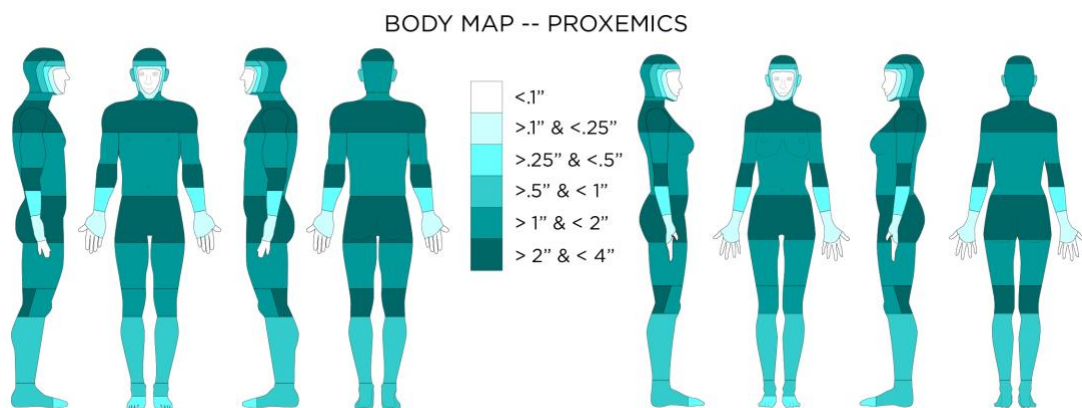
BODY MAP 9 – proxemics map – Proxemics, as defined here, is a human's perception of self-size. The distance from the body portrayed on this body map indicates how far from the body a wearable device might extend and still be naturally considered part of the person's self-size awareness. Items extending beyond this distance from the body might take a period of time for a person to adjust and account for the object within their personal self-size envelope.

Design Considerations for Proxemics

- If a wearable device or garment extends beyond the wearer's self-perceived body size, then the device or garment will obstruct natural movement within the environment. There will be a period of adjustment (through continued use) before the wearable device is incorporated into a person's perceived size of self.

- Some parts of the body can accommodate larger wearable devices without the protrusion from the body extending beyond a person's perceived size of self.

- Someone with a body limitation that requires the use of a wheel chair (or other assistive device) may have a much different self-perceived size that would include their assistive device and normal posture.

- Attachments to a required assistive device will also affect proxemics, and should be viewed as a "wearable."

2.1.9 Weight Distribution (where to carry weight and how much)

Weight does not hamper the design of my test interfaces for the study in Chapter 6 because all of the components I use are very lightweight. It is important to understand why weight maters in wearable design though, and in the case I have to use heavier test equipment for usability studies, I should make choices of where to place this weight on the body with consideration.

As a general rule, I can start with Gemperle's advice:

"The weight of a wearable should not hinder the body's movement or balance. The human body bears its own extra weight on the stomach, waist and hip area. Placing the bulk of the load there, close to the center of gravity, and minimizing as it spreads to the extremities is the rule of thumb." [29]

Figure 7 – Google Glass Pack Prototype (photo by Maria Wong Sala)

When designing the original beta Google Glass (a head mounted display /wearable computer), designers and engineers focused first on what types of features would make the device useful [119]. Early prototypes rapidly created were somewhat heavy (Figure 7) and hard to wear all day [96]. As the team worked and because of the importance of weight and comfort a separate but parallel prototype called 'Lennon' developed (Figure 8). The Lennon prototype started with a set maximum weight that the team believed a user would wear comfortably all day (45 grams), and only added features up to that weight. Lennon was the first Google Glass prototype that could be worn on the head all day without undue fatigue.
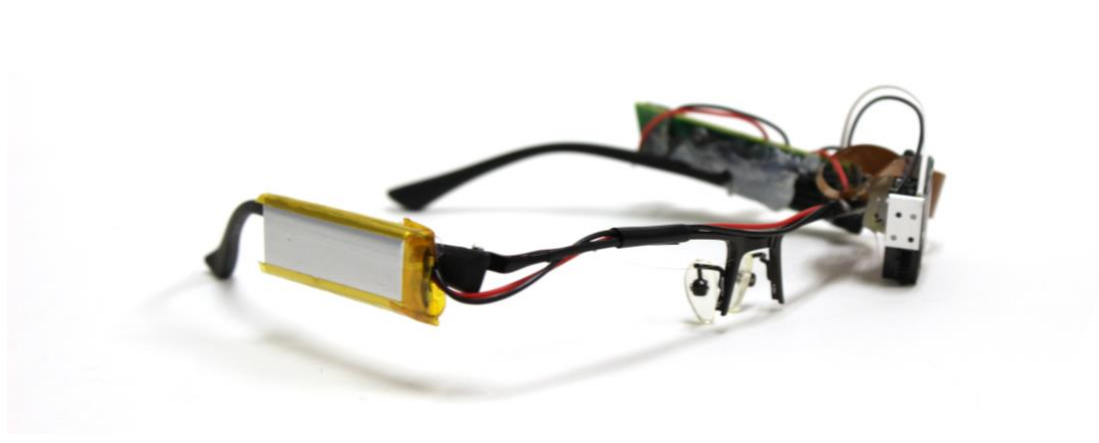
Figure 8 – Google Glass Lennon Prototype. (photo by Maria Wong Sala)

Weight of wearable objects matters, and heavier items can be carried by the body better in some locations than others. Watkins details how Scribano, Burns, and Baron were tasked with developing a system in the 1970's for finding load thresholds for discomfort in aiding to design body armor for the US Army [82, 104]. In doing so, they also described the weight thresholds for discomfort for the torso of a male.

In general, the army found that the fleshy parts of the body were more able to tolerate the pressure of weight than the bony ones, and that pressure on major nerves, arteries, and veins, particularly those that supply the brain, can affect coordination, and produce fatigue. [104]

Taking this information into account, I created a body map for possible load thresholds of discomfort. This will aid in developing wearable systems where weight can be distributed and minimalized where appropriate across the body.

BODY MAP -- WEIGHT DISTRIBUTION

<.5lb
>.5lb & < 2lb
> 2lb & < 5lb
> 5lb & < 9lb
> 9lb & < 13lb
> 13lb & < 17lb
> 17lb
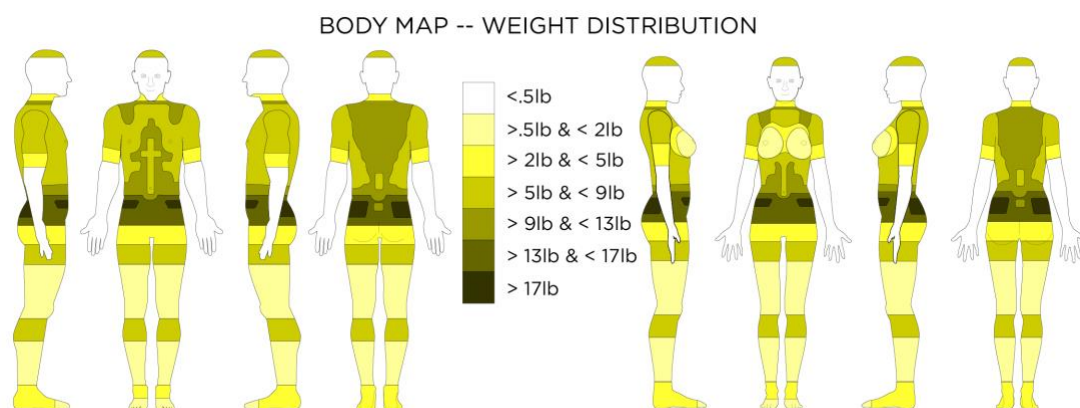
BODY MAP 10 – Weight Distribution Map - This body map shows the amount of weight or pressure that can be placed on the area before the pressure becomes a discomfort.

Design Considerations for Weight Distribution

- Weight, load, or the pressure of weight should be placed on the fleshy but non-sensitive parts of the body, avoiding boney areas.

- The lower waist is a good area for heavy loads.

- Weight should be balanced across the body evenly, and aligned to the center of gravity is possible.

- Heavy items should not be placed on the body's extremities for long periods of time.

- Batteries for a wearable device tend to be the source of most of the weight. If a device needs a large battery (to last a long time or because it needs large amounts of power to function), place the large battery on the waist. If the wearable needs to be located on a different part of the body for use then consider distributing the power from the area of use. Finally consider distributing battery cells instead of using one large battery.

- From a design perspective, weight also has a visceral quality. Density or heaviness compared to size in combination with other material aspects such as metallic textures are perceived to be luxurious. Donald Norman explains, "Physical objects have weight, texture, and surface. Physical feel matters. We are after all, biological creatures, with physical bodies, arms, and legs." [69] Use weight where appropriate to create a positive experience with the wearable technology object or garment.

- Watkins states: "*One aspect of Load Analysis to consider is that even though these tests provide data on pressure levels, not all individuals or areas of the body respond in the same way to pressure. Age, sex, medical conditions and other factors may affect the way in which pressure affects mobility*." [104]

- Of course, it is easy to assume that designers want the most light-weight wearable technology anyway, but it is also good to remember that being light weight can make the wearable technology useful to broader communities (elderly, arthritic patients, children, etc.)

2.1.10 Body Mechanics and Movement

The human body moves. As such, any wearable technology we place on the body must not impede on this movement. I have already discussed proxemics where the added size a wearable device might impede movement with the environment. In this section, I will discuss body placement of wearable objects with respect to hindering regular motion of body parts. "Consider the many elements that make up any single movement. Elements include the mechanics of joints, the shifting of flesh, and the flexing and extending of muscle and tendons beneath the skin." [29]

Again, let's start with Gemperle's observations [29]. She starts a discussion about body movement by explaining areas on the body do not actually move that much relative to the rest of the body. These areas are good locations to place wearable technology, as they will not likely obstruct body movement. The outer upper arm for instance is a better location to place an object than inside the elbow. If I designed a wearable for inside the elbow with any bulk or rigidity at all, it would hinder the arm's ability to bend.

Roebuck ran into the problem of hindering body movement when helping develop the Space Suit for NASA in the 1960s [80]. To aid in his endeavor, he created a system for annotating body movement built on what he called linkages. These linkages were joints or combinations of joints that allow the body to bend or move at a point. This simplified and codified way of finding movement points can help a designer today

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know where to avoid placing wearable technology objects which might hinder

motion.

Henry Dreyfuss and Associates also created charts with the standard range of motion

of most humans. These charts also help describe in visual detail areas where larger,

bulky, or rigid objects might get in the way of human motion [97].

I have combined the areas selected by Gemperle, the linkage areas described by

Roebuck, and the range of motion charts developed by Dreyfuss Associates to create

a third body map of locations appropriate for more rigid wearable objects.
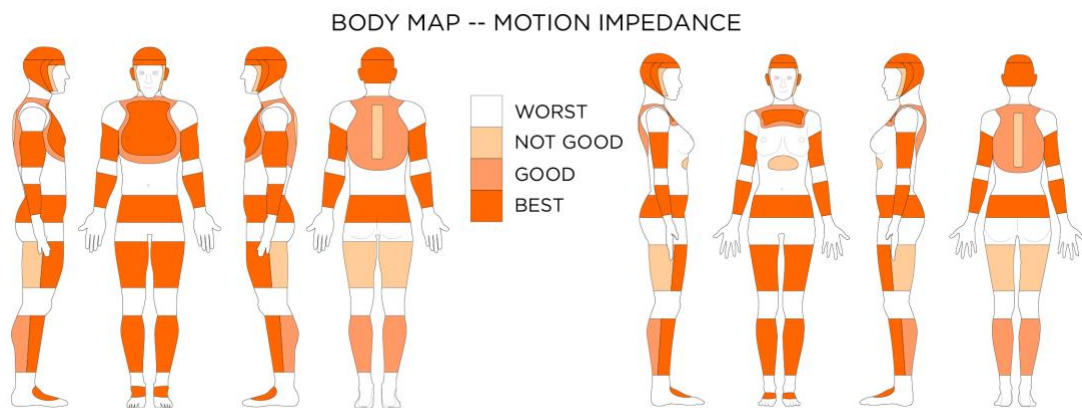
BODY MAP 11 – Zones of Motion Impedance - This body map shows the best places to put

wearable devices on the body: where they will be the least obtrusive and cause the least amount of

body motion impedance.

Other aspects of a wearable technology device affect body movement and prospective placement: the flexibility of the item, the bulk, and the weight work together in helping dictate proper on-body location. A more flexible device will have more options of body location without impeding normal movement. Watkins does a great job of describing and relaying garment construction techniques to accommodate for flexible construction [104]. Skin also stretches from motion, even within the zones where there is minimal movement and attachment of wearable devices to the body need to allow for the skin to stretch.

Design Considerations for Body Motion

- Large, bulky, or rigid objects should not be placed on the inside of joints, or the concave areas where the body bends.

- Rigid objects or flexible but non-elastic objects should be adhered to the outside of joints in a way that hinders the skin on the outside of the joint from stretching.

- Smart garments, clothing, or e-textiles should have ample room, or flexible and elastic properties to allow all parts of the body to move effectively.

- Larger or rigid objects should be located in zones on the body with relatively limited movement or linkages.

- All body movement criteria should apply the same to individuals of impaired self-movement, unless the wearable is specifically designed to stabilize the body for medical purposes.

- Individuals may be unable to feel or move parts of their body, but these body parts still have the capability of movement from outside sources. This means that a discomfort from an inappropriately placed wearable device will not be felt, and could cause harm from extended wear.

2.2   Choosing On-Body Location for Active / Passive Touch On-Body Interactions, and Subsequent User Studies

I can apply the knowledge gained from the robust literature review and creation of the body maps to decide where to place my interfaces on the body for testing. I divided the body into on-body locations relative to the needs surrounding wearable technology. I can do this by overlaying all the body maps I have created, and finding the distinct segments currently important for wearable on-body technology.
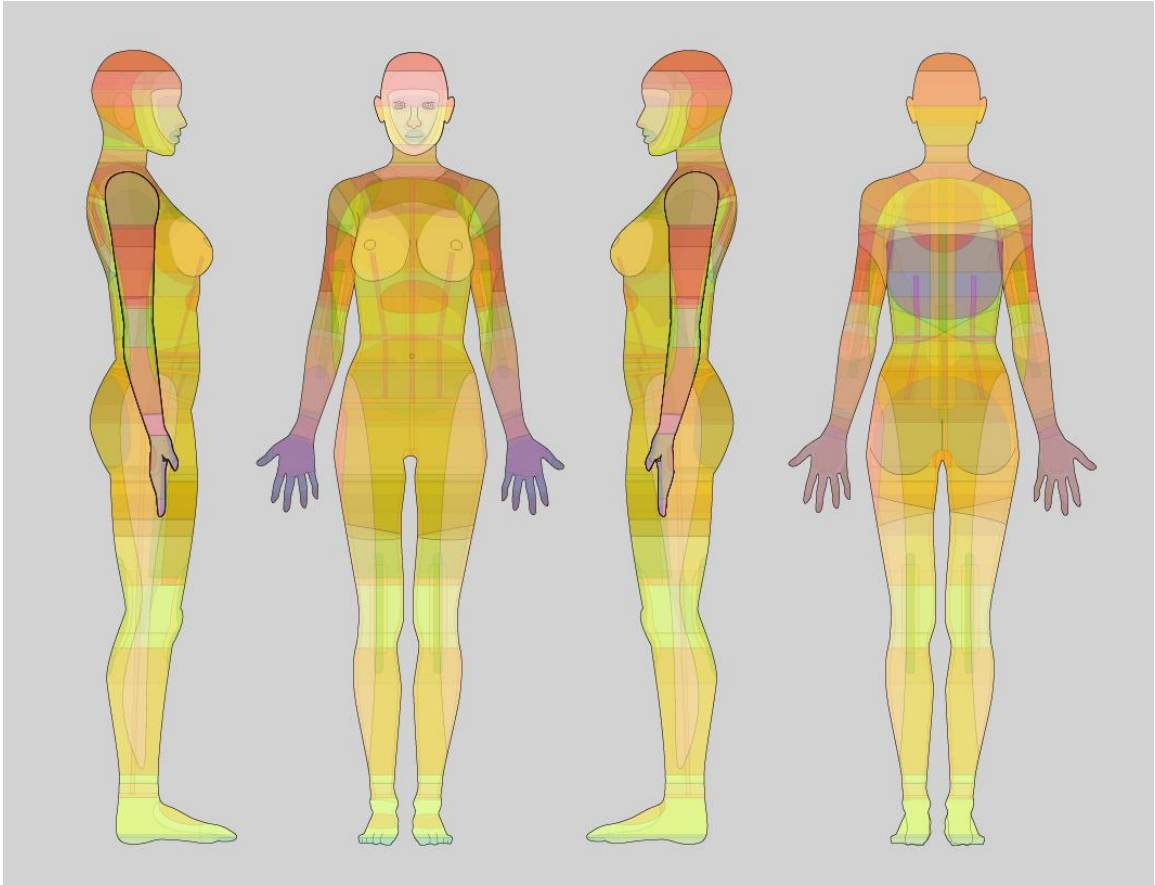
Figure 9 – Female form with combined body map overlays. The simplified intersections of all the overlays will produce a segmented map of the body for wearable technology locations.
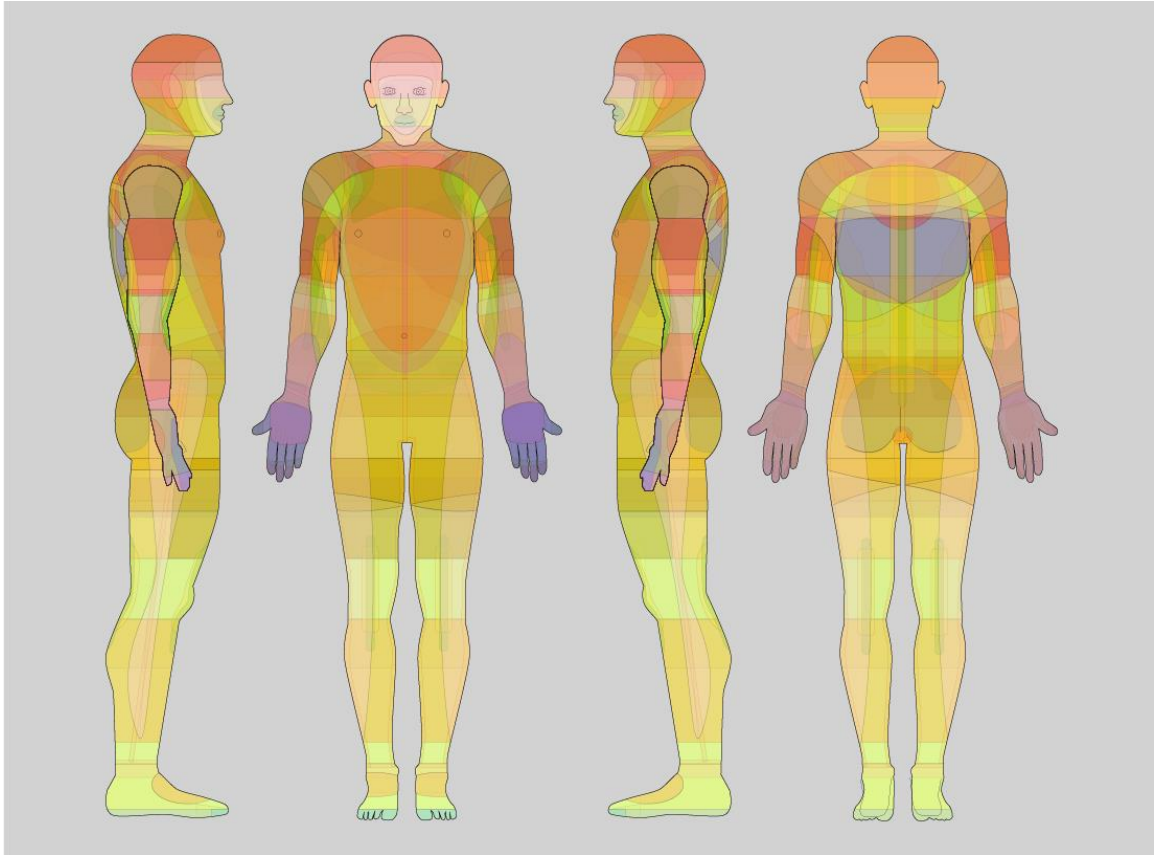
Figure 10 – Male form with combined body map overlays. The simplified intersections of all the overlays will produce a segmented map of the body for wearable technology locations.
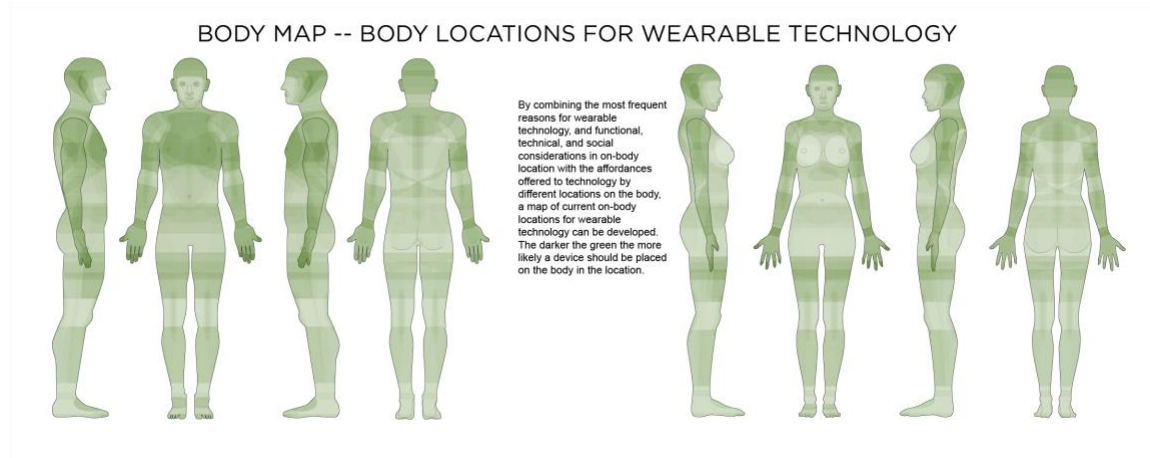
BODY MAP 12 – Map of Body Locations

Each consideration listed has a corresponding body map (along with other body maps created but not relevant to my thesis) created from synthesizing the affordances found in literature. The full collection of body maps with references and design considerations can be downloaded for use [106, 111]. A description of how the body maps and accessibility considerations might be used in the design process is also available [113]. Overlaying all of the individual body maps illuminates the areas on the body where a designer should most likely place a wearable device (Body Map 21). Body map 21 only shows where a device should be located if all design considerations are given equal weight. The body map shows that the most likely locations for wearable technology to be successful are the hand, wrist, forearm, upper arm, upper chest above the breast, forehead, ear, and mid-thigh. Of course, specific use cases and designs will place more weight on some considerations than others. For my interest, there are some locations that work better than others.

2.2.1 On-Body location needs for Active / Passive Touch PDI Interface

- Easy to reach. For active touch interfaces where investigation of the interface by the dominant hand is important.

- Easy to be felt. For passive touch to be effective it is important that the interface be located at a place on the body with some level of high sensation.

- Socially acceptable. The placement of the interface needs to be socially acceptable and aesthetically pleasing (or at least not ugly or embarrassing as perceived by the wearer). The placement of the interface can also not cause awkward moments during user gestures or interactions.

- Light weight and does not get in the way. The interface should not cause discomfort.

After a review of the requirements I have chosen the **Forearm** as the on-body location for my future user studies surround the creation and use of PDIs. The forearm seems like a likely location for future commercial devices as well, when viewed against all the requirements, body maps, and design considerations.

Chapter 3

Constructing Electronic Textile-Based

On-Body Input Interfaces

This chapter describes **effective techniques to create and design on-body textile-based interfaces that are robust, reliable and accurate**. These are *a set of validated techniques and processes for creating embroidered interfaces for on-body touch based interactions that create a foundation for active touch / passive touch interfaces. (contribution).*

There are some specific necessities for successful on-body electronic textile-based input interfaces. First, for touch based input the textile must be able to recognize touch. Second, the textile interface must withstand use, and possibly washing, for the interface to be feasible. Third, the interface and technology need the ability to be incorporated through methods similar and familiar to garment manufacturing.

3.1   Related Work on Wearable Technology and

Electronic Textiles

Post and Orth introduced the wearable computing community to interfaces embroidered using conductive thread [76]. Touches to the conductive thread interfaces could be sensed using simple capacitive circuits. Soon many other textile interface widgets like keyboards and sliders were explored [77]. Their design for the Firefly Dress used organza fabric with metal woven in for aesthetic effect but also

provided conductive properties. This gave way to embroidery and prints made from conductive materials, which then allowed designers to create interfaces on the fabric. Post recently has even looked at using conductive materials to harvest static electricity produced by fabrics for use in powering LEDs [78]. Marculecu et. al describe electronic textiles as a platform for pervasive computing, and in doing so, outline a number of methods for producing e-textiles [62]. Jayaraman and colleagues also worked on incorporating technology with fabric to produce their "wearable motherboard" smart t-shirt [34]. This t-shirt was created originally to detect injured solders in the battlefield and relay vital signs and GPS coordinates.

Buechley has focused much of her e-textile work on the democratization of technology within education, and using wearable tech as a way to make inroads with typically non-tech-enthusiast communities [9]. Buechley's work has led to the very popular Lilypad Arduino microcontroller, making designing and working on wearable technology easier and more inviting (Buechley and SparkFund.).

3.2 Construction Techniques for

Electronic Textile-Based On-Body Interfaces

Much of my research has focused on creating and testing electronic textile interface construction techniques [10, 48, 55, 115, 117, 118]. These textile interface techniques include both sensing and manufacturing techniques. I use these techniques to create the on-body interface prototypes for usability testing, interaction research, and for case studies about their design and acceptability. I used conductive thread, materials,

and some of these construction techniques to create the prototype for my final study detailed in Chapter 6.

3.2.1 Hybrid Resistive-Capacitive Sensing Technique

Part of my early work helped to develop and test techniques to create conductive thread touch sensors using a hybrid capacitive resistive sensing techniques which allowed me and other designers to place the microprocessor for the sensing some distance from the sensing location and maintain accurate touch readings. This technique allows the sensing of a discrete touch on a specific location on the fabric, such as a touch point.

The microprocessor sensed by detecting leakage current across the textile finger pads. This was done by charging up the capacitor formed between ground and one side of the touch pad, examining the time taken for it to discharge through a known resistor. By driving the other side of the touch pad to ground or power, the leakage current through a finger would vary the time needed for the capacitor to discharge. Thus, by measuring the discharge time twice, we can use the difference in times to determine the leaked current through the fingertip. Any constant capacitance in the pad gets canceled out. Once the microprocessor had determined how much current was able to leak through the touch pad, it then relayed this value to the palmtop computer via a USB-to-RS232 converter, where the software could process the data. [48]
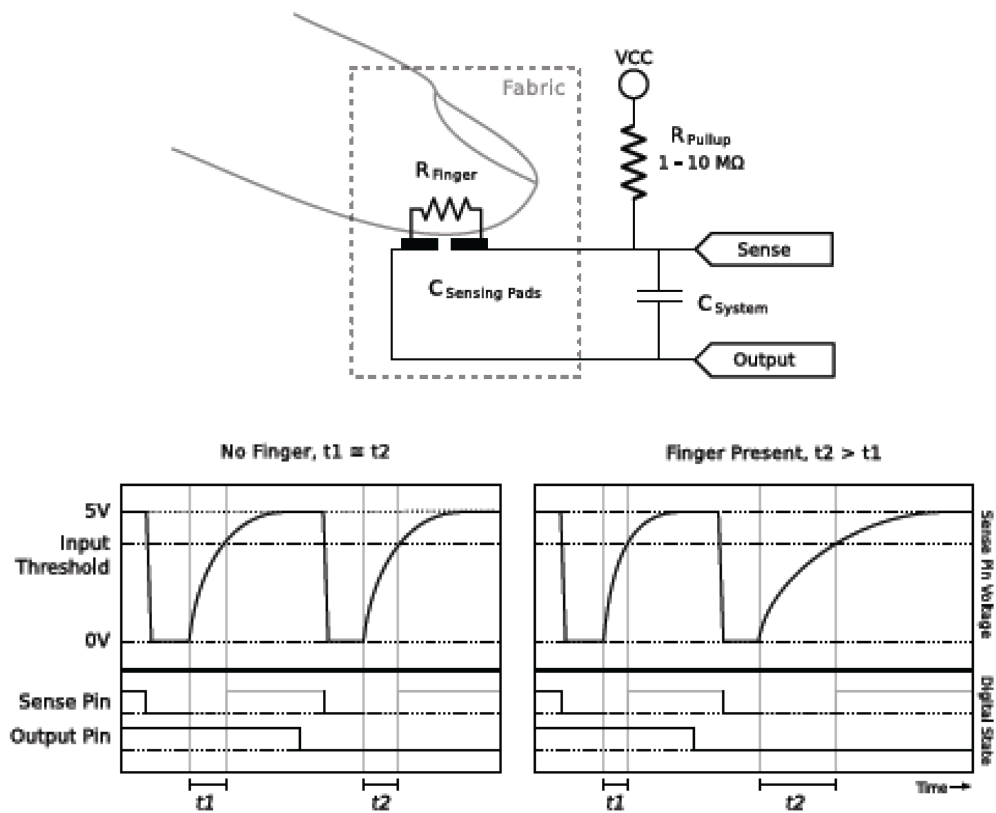
Figure 11 - Hybrid resistive-capacitive sensing method used on embroidered touch pads to improve accuracy of selections. When the fingertip is not present, t1 = t2 (left). Otherwise, t2 > t1 (right).

This is the sensing technique used to sense touches on the embroidered touch points in the testing prototypes in Chapter 6.

3.2.2 Thread and Materials

There two main types of conductive thread used for the interactive embroideries: A silver coated thread and a 2 ply stainless steel and polyester thread [89]. The advantage of the silver coated thread is that it can be sewn over itself creating more conductive surface area and lowering the resistance of traces. The silver coated thread is also somewhat more durable than the 2-ply thread after it is sewn. The drawback is that the 2-ply thread works much better with the embroidery machine's tensioning system and has less thread breakage during manufacture.

As mentioned aside from being able to sense the touches, the materials used must also stand up to some use and perhaps washing. To determine the robustness of materials I am using to create my testing prototype I developed and ran a wash durability test of the electronic textile techniques [115]. Washing and drying might be the the greatest durability challenge to an interactive textile, so this is the test I decided to run.

For the purpose of the wash test I decided to use a standard upright agitator washing machine GE Spacemaker Model WSM2700 HAWWW and a standard detergent. One ounce of All 2x Ultra detergent is used each wash cycle. By using the same water fill level and same cycle time, I tried to standardize the mechanical aspects of the washing cycle as much as possible. All washes were made in warm water, at medium load, and a regular wash cycle. I chose to wash on the warm cycle because I wanted to use a harsher condition, hoping that if the conductive materials withstood a warm

wash cycle they would be more likely to withstand a cold wash cycle. I also chose the regular agitation and wash cycle because these would be harsher conditions than a gentle cycle.

I tested two types of conductive threads; the first is a coated conductive thread. The Shieldex size 33 thread is completely conductive on the outside surface of the thread and is very useful when embroidering interfaces because, as the thread sews over itself, it increases the conductive surface and lowers electrical resistance. One downside to the Shieldex size 33 thread is that the conductive coating on the thread makes it hard to regulate the tension of sewing and embroidery machines properly, and it is more difficult to use within industrial machines. I the second type of conductive thread I tested is Shieldex's size 40 thread, which is a 2 ply mixed yarn consisting of both conductive and nonconductive polyester. The advantage of the Shieldex size 40 yarn is that it runs much better through sewing and embroidery machines, but it cannot be sewn over itself to reduce resistance. As I also wished to explore how to best combine conductive ink and conductive embroidery to create the most robust interfaces, I also tested the effects of washing on combinations of conductive materials.

Each test condition was applied onto a cotton twill swatch. The swatches were washed for 10 wash cycles. The graph (Figure 13) shows the average resistance change from each test condition over 10 wash cycles. Where the test condition lines on the graph terminate indicate that at that wash cycle either the trace was broken or

the resistance became so high as to effectively render the trace useless. As this is an average graph, some traces might still have been working, but the majority of the traces failed where the lines terminate.

I examined the following 12 test conditions:

Less Conductive Thread (Shieldex size 40 22/7 PET sewing thread)
1. Single trace*
2. Double trace**
3. Single trace under conductive ink (sewn first and ink printed on top of trace and then cured)
4. Single trace on top of conductive ink (ink printed first and thread sewn on top of cured ink)
5. Double trace under conductive ink

More Conductive Thread (Shieldex size 33 117/17 sewing thread)
6. Single trace
7. Double trace
8. Single trace under conductive ink
9. Single trace on top of conductive ink
10. Double trace under conductive ink Conductive Ink
11. Ink alone
12. Ink covered with Plastisol***

* Single trace = A single straight sewn line of thread
** Double trace = A single straight sewn line of thread double back over itself
*** Plastisol Ink is a standard type of screen printing ink. It is a pigment suspended in a binder which cures into a plastic after being heated.
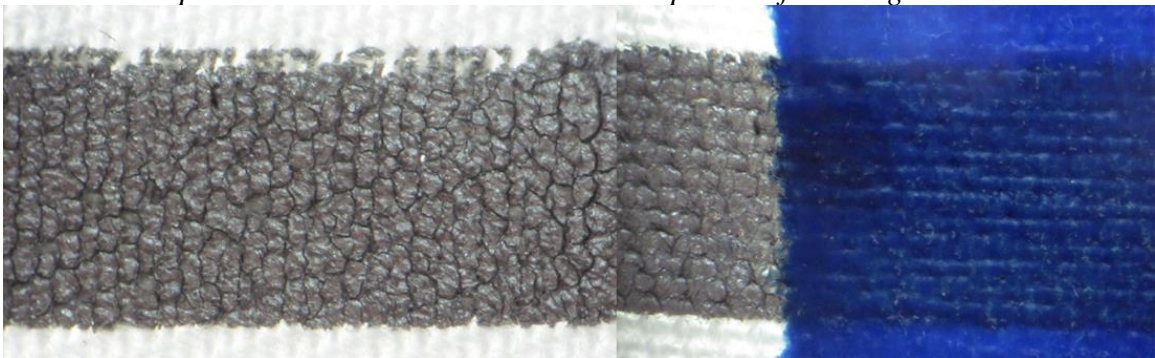
Figure 12 - Example of printed traces after wash test. With and without blue plastisol coating.

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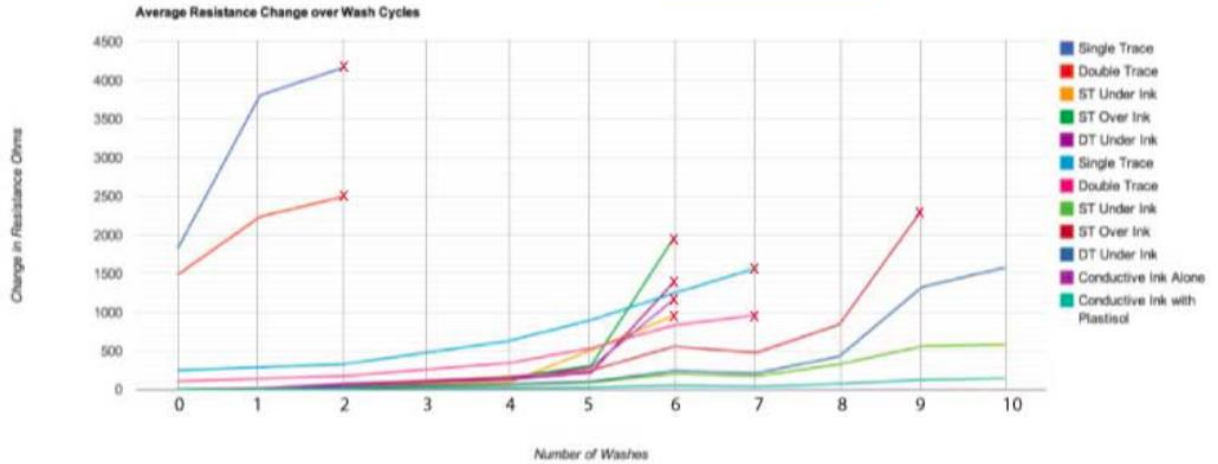
Figure 13 – Averaged results of resistance changes on 10 traces of each type over each of ten wash cycles. Red X denotes where the trace failed or the resistance became so high to render the trace ineffective. [115]

Aside from this wash test there are some other observations I can make from using these conductive threads for the past 10 years. I have found that the 2 ply thread also oxidizes and fails much faster than the coated thread. I chose to use coated thread embroidery for my final testing prototype. I did this for a couple of reasons. Printing on top of stitching is not a normal garment manufacturing technique and the 2 ply thread is too fragile, not standing up to oxidation over time. It is important to note that even though I used the coated thread, that between every day of testing, the final prototype sleeves in Chapter 6 were stored in an air tight plastic bag with "silver saver" sacrificial oxidation paper. This step I thought would be important to keep that resistance of the traces close to the same over the course of the final study.

3.2.3 Textile Interface Construction Techniques

Sometimes it is necessary to run long traces on fabric across the body using conductive thread to connect a textile interface to the microcontroller that runs the sensing. With body movement, large amounts of capacitive change can be produced along a pair of parallel conductive traces. To combat the noise generated in such a long trace, I created a textile based twisted pair ribbon [55, 118]. The creation and subsequent testing of the textile twisted pair ribbon also allows for the conductive leads to be incorporated into clothing through methods similar and familiar to garment manufacturing. As described in Chapter 2 a good place to run leads from one part of the body to another is within the seams of the garment. The twisted pair ribbon I designed can also act as bias tape. Bias tape is a material used in clothing construction to seal the edges of seams. The twisted pair ribbon is also very flexible and when placed at the seams of a garment it has much less effect on the drape of a design than wires would.
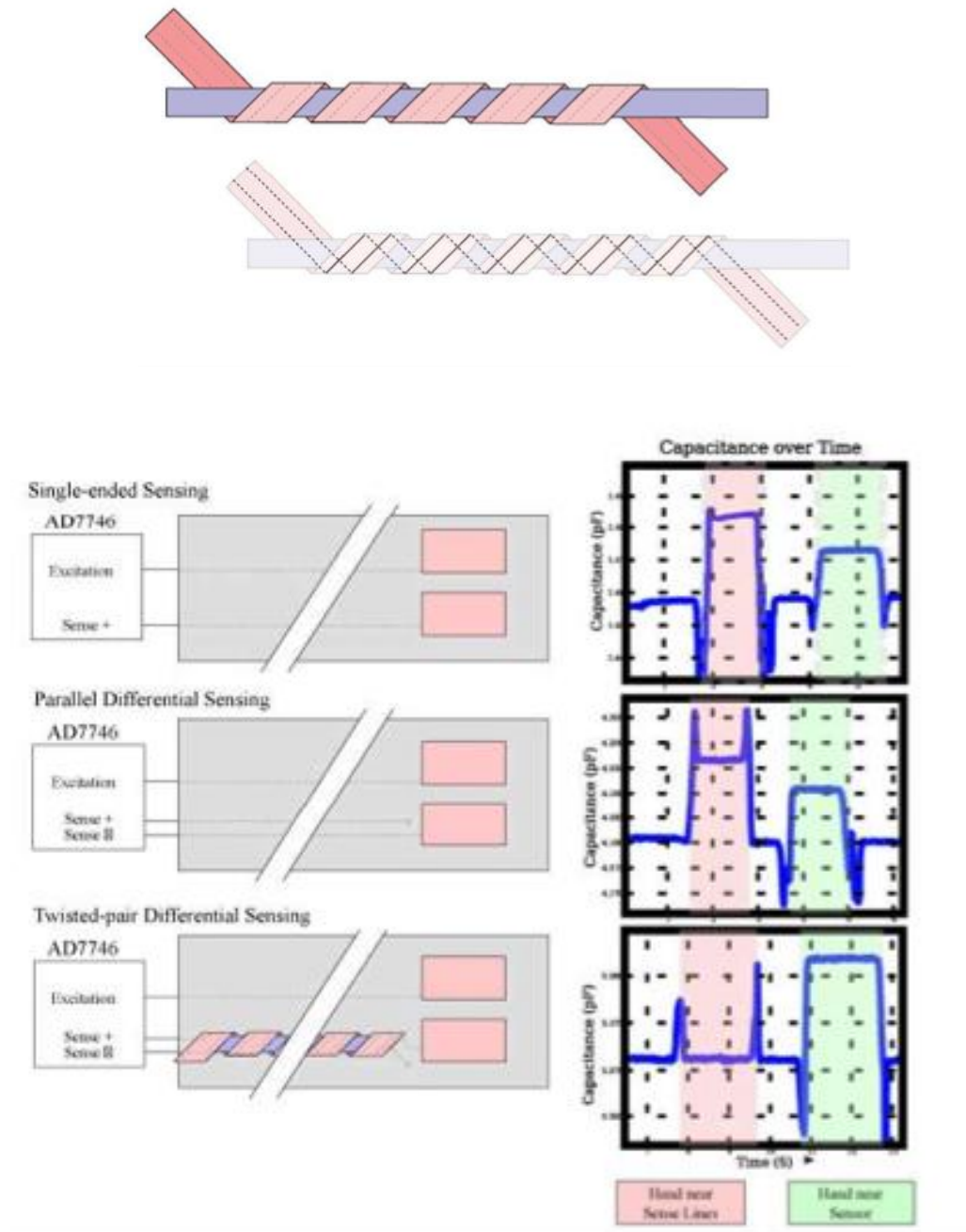
Figure 14 - Conductive Thread Twisted Pair Ribbon and three test conditions used to evaluate different methods of running capacitive sensing lines across textiles, along with data collected from a test apparatus. Each was tested for response to proximity near the sensing line and near the intended conductive pads at the end of the sensing line.

I also aided in developing some interesting fabric based interfaces using simple circuit closures and a knowledge of old world textile manipulation techniques. The knife pleat interface is a good example.

This sensing is performed by embroidering several rows of conductive thread between the pleats. The first electrode is sewn as rows on the base piece of cloth between the pleats. These rows are electrically connected as a single electrode. Importantly, the conductive thread we use has a noticeable resistance which increases as the embroidered path gets longer. Another electrode is sewn onto the left side of each pleat. All the left sides of the pleats are electrically connected in this fashion. Finally, a third electrode is sewn on the right-hand side of each pleat. All right sides of the pleats are electrically connected as one electrode.

Note that since the pleats are sewn on to the base fabric with a 180-degree twist, the pleats stand up distinctly and avoid shorting either the left or right sides of the pleats with the electrode on the base cloth. However, as the user runs his finger along the pleats left to right, the right side of the pleats short against the base electrode. Thus, a computer or consumer electronic device hooked to this interface senses that the user is stroking the pleats left to right. Since the circuit's resistance increases with the length of conductive thread, the system also detects the nearest pleat being de-pressed at any given moment. If the user strokes the pleats right to left, the left side of the pleats makes electrical con- tact, and, again, the sensed resistance indicates which pleat is being depressed. Since the left facing and right facing conductive threads

form distinct circuits, a pinch gesture (e.g. where the thumb moves right across the surface and the index finger moves left) can also be sensed precisely.

Note that the circuit required is relatively simple, consisting of the 3 electrodes, a microcontroller with analog to digital converters (or the construction of several 1-bit capacitive DACs), and a few known resistors for a variation of a Wheatstone bridge to compare the sensed resistance values in the circuit precisely. [32]

Figure 15 - Pleat: This knife-edge pleat is constructed with three electrodes. Depending on in which direction the pleat is crushed, different circuits are completed [32]

It is also important to note that I explored creating touched based interfaces with other traditional textile methods outside of embroidery. I designed and created printed versions of some of the e-textile embroidery using silver ink and a screen printing process (Figure 16 & 17). The inks available at the time could not stand up to

repeated washing, and were also not flexible enough to bend with a fabric substrate without cracking (and thus breaking trace lines). For my purposes printed interfaces also do not afford a raised surface for active touch investigative interactions. I did find that using normal screen printing plastisol ink worked quite well as an insulator, and this made it into some of the durability techniques I tested in the wash test.

Figure 16 - Silver Ink Printed Interface.
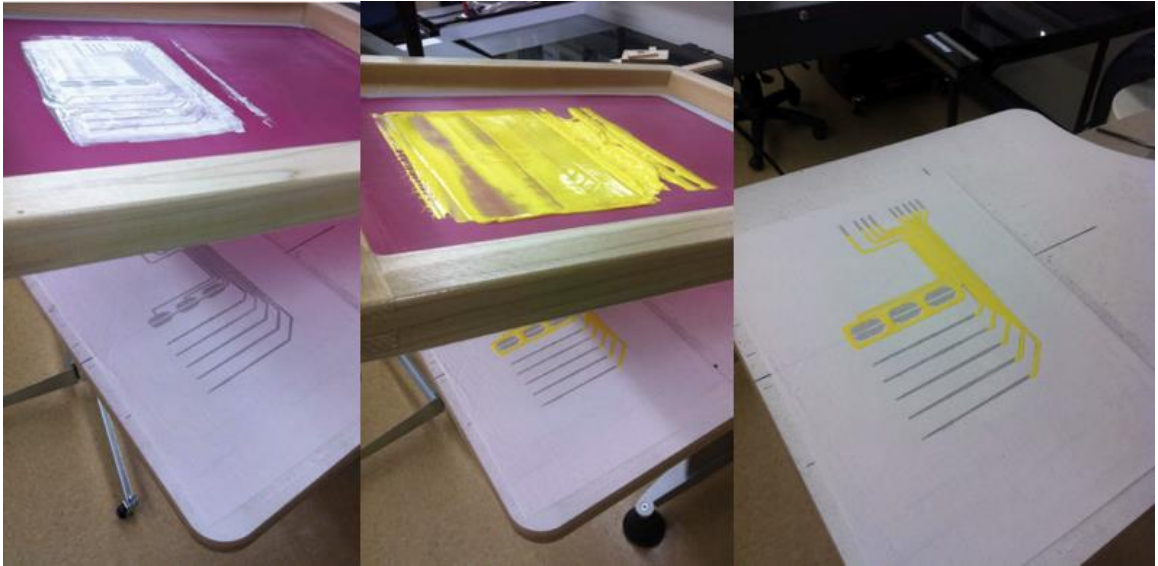
Figure 17 - Conductive screen printing process.

3.3 Impact of Electronic Textile Interface Construction Techniques

The research here makes progress toward answering my first research question. ***What are effective techniques to create and design on-body textile-based interfaces that are robust, reliable and accurate?***

Using these *validated techniques and processes for creating embroidered interfaces for on-body touch based interactions (contribution from research)* I created an embroidered electronic textile on-body interface to test the potential of Proprioceptively Displayed Interfaces as outlined in Chapter 6.

Chapter 4

Active Touch Electronic

Textile-Based Interfaces

This chapter details how ***active touch aids in making on-body textile interfaces more accurate and quicker to interact with than interfaces without such affordances.*** The description of both a user study centered around using active touch afforded input interfaces and *prototype textile interface artifacts such as the Electronic Textile Interface Swatch Book, The Hood (e-textile garment music controller), and Le Monstré (an interactive participatory performance garment) (contribution)* support the use of active touch affordance in on-body input interface design.

4.1   Related Work in Active Touch

Electronic Textile-Based Interfaces

There is a clear description of active touch in Chapter 2.1.2 Touch (active touch) [31]. All physical interfaces use active touch interactions for interfacing with systems (be they mechanical or digital). Both trusted industrial design standards [97] and trusted HCI principles such as Fitts' law [25, 60, 90] stem from human ability to reach out and touch objects. Our use of active touch to investigate and manipulate the world around us is so great that there are research efforts to figure out how to make flat touchscreen interfaces more tangible for interaction [8, 41, 52, 54]

One application of aiding active touch is Thad Starner and team's research into using vibration to aid firefighters in sensing heat through their gloves by vibration when using active touch to investigate doors in burning buildings [103]. These types of active touch aids could also be very beneficial for wearable robot control. Konyo et al presented a paper entitled Tactile Feel Display for Virtual Active Touch at the International Conference for Intelligent Robots and Systems in 2003. This paper outlined methods and usability tests of those methods for creating a haptic system to aid in remote active touch investigation virtually [49–51].

For making and testing on-body textile based input interfaces, where the interaction happens on the body, this type of active touch enhancing research is interesting but perhaps not as useful as the design standards of physical interfaces. I am more interested in how an input interface can afford active touch (rather than how augmenting a hand can aid in active touch investigation). This type of information can come from ergonomic and industrial design standards such as the "The Measure of a Man and Woman" [97] that outlines shapes and textures of interfaces for input interaction.

When thinking about how on-body interfaces might help with our everyday interactions, it is also important to think about how we interact with our most ubiquitous computer: the mobile phone. Patel et al. examined people's perceptions about how often they have their mobile phone nearby. Their data show that people routinely overestimate the physical availability of their mobile phones [74]. Even

when the mobile phone is with its user, it may not be quickly accessible. Cui et al. found that 40% of women and 30% of men miss phone calls simply due to the manner in which they carry the mobile phone on their person [12, 19]. Similarly, Starner et al. found correlations between an individual's decision to use or not use a mobile scheduling device (such as a day planner or PDA) and the amount of time and effort required to access and make ready the device [94]. Together, these studies suggest that the time required to access a device might be an important property affecting mobile use.

An important predecessor to the study described in Chapter 6 is one completed in our lab on the impact of mobility and on-body placement to access time. This earlier study on access time compared these conditions using the same mobile phone carried or attached to the body in different locations. It did not compare different interfaces such as a textile based interface with a hardware based interface. The findings from this study show that the access time from a body mounted wrist location is much better than the access time from a carried position in the pocket [3]. I build on this information with study in Chapter 6 to look at access time, among other metrics, compared against differing interfaces which are textile based.

4.2 Making and Testing Active Touch Wearable and

Gropable Electronic Textile-Based Interfaces

To test the advantages of active touch affordances designed within an interface I and my colleagues developed a user study. The study tested the ability of using a conductive thread embroidered interface to make selections while seated and walking [48]. The premise being that when thread is embroidered with a raised surface from the face of the fabric, the user will be able to feel or grope the interface and interact with it without visual attention. I created the initial embroidery for this 'gropability' study using a domestic one-needle embroidery machine; however, I have replicated the embroidery using a 15-needle commercial embroidery machine. The commercial embroidery machine used to create the current embroidered textile swatches is an automated machine and runs from computer designs I create on embroidery software. The designs are embroidered with a coated conductive thread [89], and polyester thread used for both insulation to cover traces and to create raised mounds of thread.
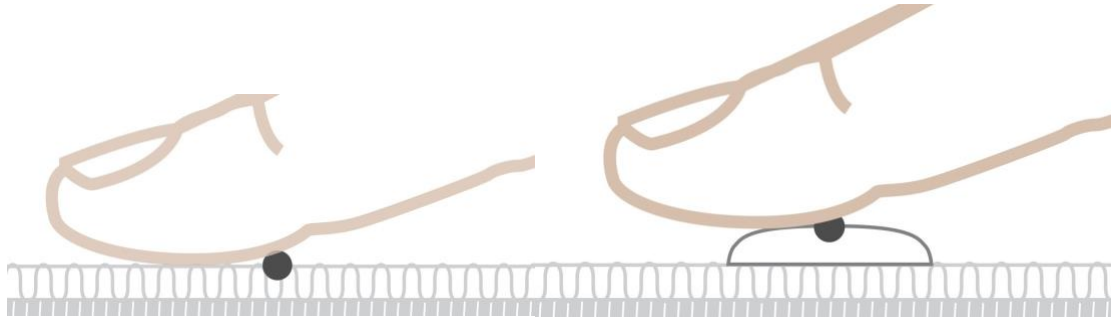
Figure 18 - Conductive thread used to create touch sensors could be sewn flat to the surface of the fabric, but with an embroidered non-conductive thread acting to raise the surface of the touch point, it can more easily be found without looking at the fabric. Illustration by Nicholas Komor

Figure 19 - The previous study on gropability [48] *utilized audio prompts to ask for specific touch pad selections*

Using these embroidery techniques and sensing techniques described in Chapter 3, I oversaw a study to compare multi-touch and single touch interactions when prompted with an audio cue. Capacitance in an on-body system can change drastically due to the movement of the lead threads required to connect the textile touch points. Instead of using just capacitance, I used a hybrid resistive-capacitive sensing method (Figure 11) allowing sensing at the location of the touch point rather than the changes in the

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system due to body movement. I also used this hybrid technique to create the embroidered textile interfaces for the on-body prototypes used in *Proprioceptive Interface Displays* study detailed in Chapter 6. The study was structured as a 2 x 2 within-subjects design. The researcher presented the participants two mobile conditions (seated and walking) and two embroidered tactile fabric interfaces (one with an anchor pad and one without). With each trial lasting approximately 10 minutes, the entirety of the study took about one hour to complete. The sessions were separated by a brief two minute break to enable the participants to rest and prepare for the next trial. Each trial consisted of 30 selections (ten for each position). The order of conditions was randomized across participants as was the order of the 30 selections within a trial. The participants were compensated at a rate of $10/hour rounded to the nearest half hour for their time. 16 individuals participated in this study. the participants ranged in ages from 18 to 36 with an average age of 23. Seven participants were female and five were left–handed. Before the first session, each participant was given verbal instructions explaining the task and goals of the experiment. The researcher described the two different prototypes and the mobile conditions to the participants. The participants were instructed to respond as quickly and as accurately as possible to the voice commands which indicated which position to touch. The participants were then led through a series of training exercises in which they interacted twice with each target on both the three-button and four-button prototype. They performed this training exercise while seated and again while mobile.

The experimental software was implemented in Python on a Sony Vaio palmtop running the GNU/Linux operating system. During each condition, the operation of the software was the same. At random intervals between 10 and 20 seconds (selected from a uniform random distribution), the software generated a synthetic audio voice prompt instructing the participant to touch either the "top," "middle," or "bottom" button. To respond to the prompt, participants felt (used active touch) the interface, located the touch points, and attempted to press the touch point indicated by the alert. If the participants were in a 3-touch point condition, they simply had to press and hold the indicated button. If they were in a 4-touch point condition, they needed to press and hold both the "anchor" pad and the indicated button. The software waited for the user to press a button for 2 seconds and played an audio tone through the headset. In the event that the participant was not successful, the software would timeout a trial at the end of six seconds. At this point the trial was complete and a timer was set to generate the next voice prompt. The software logged the timestamps of each prompt, as well as every touch event that occurred during a trial. No feedback was given to the participants to indicate if a trial was a success or a failure. The sound simply indicated the conclusion of one trial and the beginning of the next.

The 16 participants engaged in 480 total trials (30 trials per participant or 10 trials per button per participant) resulting in 80 trials per button on each interface. The participants on average pressed the correct button on either the 3-touch point or 4-touch point interface over 23 times while stationary and over 25 times while mobile. There was no statistically significant difference in the number of correct touch point

selections between the prototypes while stationary or while mobile. The time required to press the correct pad was longer for the 4-touch point interface for both the mobile and stationary situation (p<0.01). Figure 20 shows the dwell time needed to ensure acceptable selection accuracy in the various conditions.

The 4-touch point prototype had slightly better accuracy (due to the addition of the multitouch anchor) than the 3-touch point design but required more time for selection. However, examining Figure 20 reveals that the 4-touch point design requires less hold time than the 3-touch point design when mobile to get the maximum accuracy. Interestingly, accuracies fall with longer hold times for all conditions, but the 4-touch point interface accuracy decays less than the 3-touc point. Accuracy seems to peak at approximately a third of a second dwell time for all conditions.
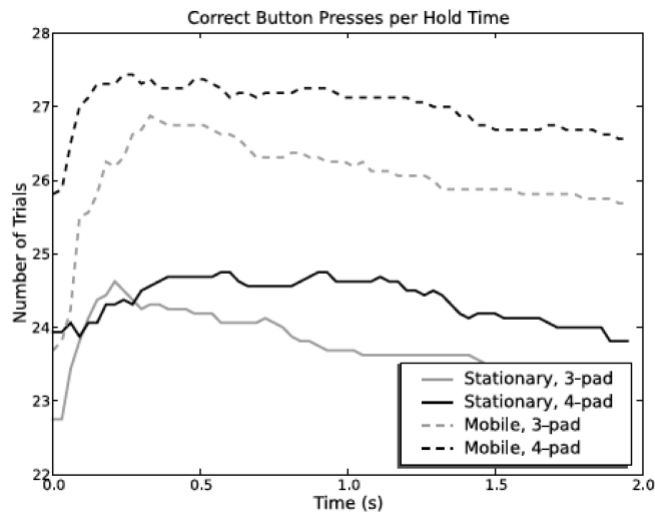
Figure 20 - Hold time versus selection accuracy (30 trials)

4.3 Designing and Using Active Touch

Wearable Electronic Textile-Based Interfaces

4.3.1 Designing Active Touch Wearable Electronic Textile-Based Interfaces

A good portion of my work has been exploring ways to help transdisciplinary design teams work more effectively together on wearable technology. Research exploring how policy and imagining futures can help create more inclusive and productive project teams [4, 27]. The disparate distant disciplines and varied skills needed for true innovation in wearable computing means it is sometimes difficult for project team members to understand one another and work together. Martin et al. speak to both the need for transdisciplinary teams while working on wearable technology projects and the nature of the current educational system producing engineers and designers: *"Practitioners in these fields gain their interdisciplinary team experience by trial-and-error and sheer luck, if at all. The deeply disciplinary nature of universities does not prepare students for working on the types of design teams that are required for successful wearable computing systems,"* [64].
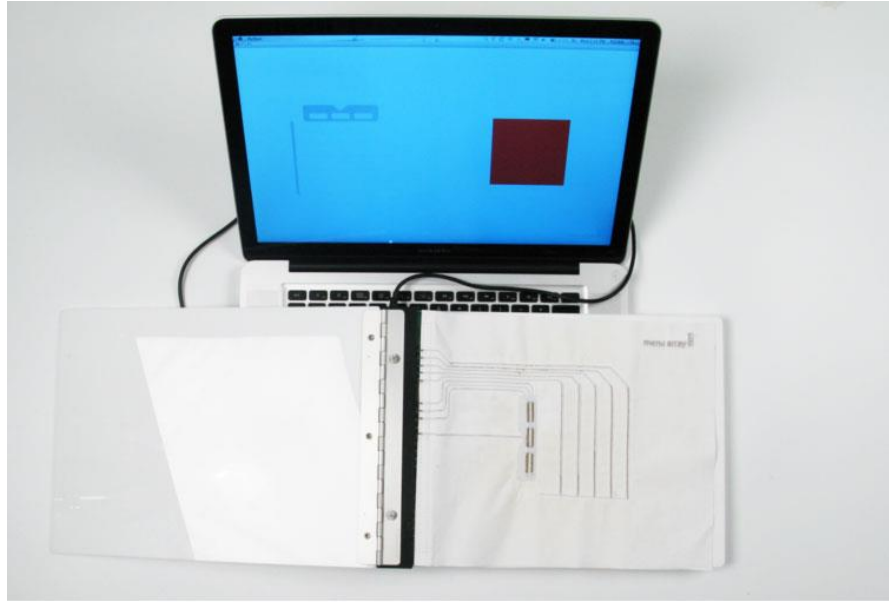
Figure 21 – Electronic Textile Interface Swatch Book.

In this vein I directed the creation of the Electronic Textile Interface Swatch Book (ESwatchBook) to help teams work together around an artifact that provided a talking point and shared meaning [32, 75, 112]. The ESwatchBook was also a prototype mechanism for developing textile-based active touch interfaces for exploration and observation. The set of swatches initially created were variations on embroidered touch surfaces. Some of these surfaces used single raised 'selectors' mimicking the interface used in the "Is It Gropable" study. Other designs incorporated ridges and valleys made with non-conductive polyester thread used to guide the fingers to conductive touch points (Figure 22).
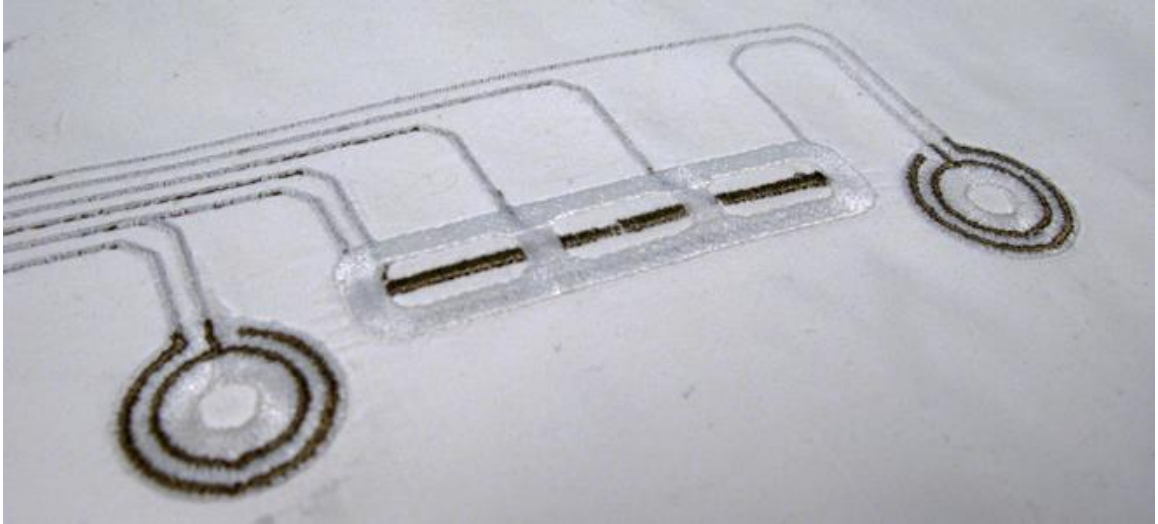
Figure 22- Notice the center touch area on this 'rocker switch interface' has valleys for the fingers to fall into place.

The ESwatchBook development was also useful for testing types of interactions. Starting by imitating interactions used by other interfaces and graphical user interfaces, the research also looked at how to expand beyond these types of touch interactions. A good example of this exploration was with the familiar jog-wheel interfaces. The embroidered jog-wheel incorporated both an inner and outer jog which could vary the speed or resolution of scrolling items, while tapping and swiping could be useful for start stop and single skip functions.
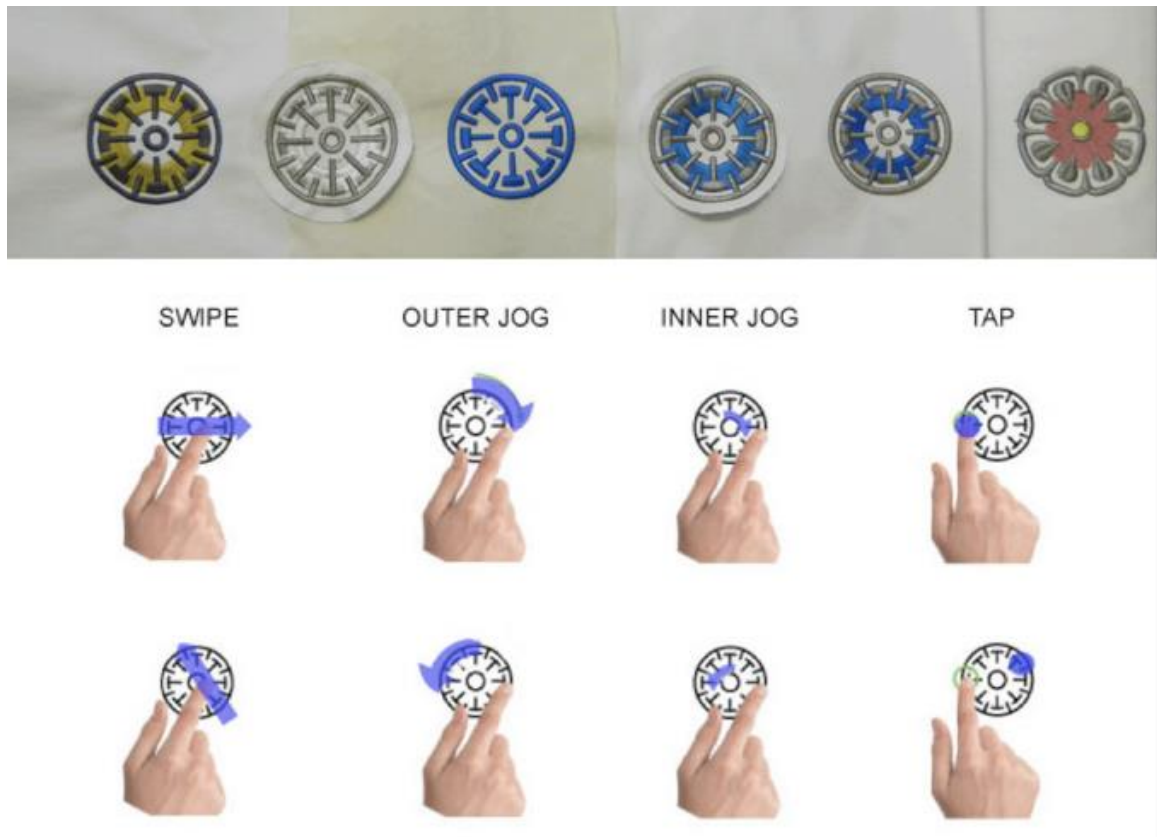
Figure 23 - Iterations of embroidered jog-wheel interfaces for the ESwatchBook and interaction styles explored for using the textile interface.

4.3.2   Using Active Touch Wearable Electronic
Textile-Based Interfaces, Collaboration Case Studies

While I was simultaneously using the ESwatchBook as a rapid prototype mechanism to explore types of textile interface interaction, I was also facilitating using it and other e-textile input interfaces to display this technology to designers and artists in a non-threatening form factor. These explorations and case studies were an important step for me to understand how the communities of practice that might design PDIs in

the future would respond to textile input interfaces. Part of this effort was undertaken with a series of workshops at design and arts universities and conferences [75, 112]. The participants in the workshops consisted of both faculty and student designers leading to rich discussion about how the ESwatchBook could be used and improved, and also about the use of textile-based on-body interfaces within the arts.

While three of the four completed workshops dealt solely with academia, the Smart Fabrics Conference workshop had many participants from industry. Some industry participants even inquired about having a workshop at their respective companies. This is exciting because it hopefully shows that when electronic textile input interfaces are presented in a familiar way to industry and this information is backed up with knowledgeable workshop facilitators, industry professionals may as one participant stated, "see the possibility to get ideas about new applications".

One of the facilitators of the workshops explained: "It was important for me to convey to the fashion designers (people who had never explored this technology before) what was possible so they were not limited by lack of knowledge. In the beginning, I think it helped to stretch the limits of our ideas, and then scale it back down for feasible execution. The ESwatchbook gave them some indication of the types of technology they could work into the garment, but once they had their concept down they relied on group knowledge to implement their design."

Recently, I have used the ESwatchBook and other items as boundary objects for wearable technology transdisciplinary teams [14, 114]. In this way, the ESwatchBook acts a design tool, and also illuminates interest from fashion designers, artists, and other skill based disciplines in working with textile-based on-body active touch interfaces.

Figure 24 – Rho wearing the "Hood" developed through an transdisciplinary team using the ESwatchBook.

One such project focused on the creation of a wearable musical instrument. Over the course of one week, an Italian musician named Rhò, an architect, a computer scientist, a fashion designer, an engineer, and a digital media expert came together to create one wearable musical instrument: "the Hood". There were communication and ideation challenges to overcome in a team with such diverse skill sets. Wearable technology is a unique working space, allowing for, and often requiring, diverse

participants who may have fundamental differences in their formal training. A fashion designer has a different thought process, product goals, and even vocabulary than a computer scientist. A musician has a very creative process and his or her time scale for creation might diverge from all other design fields. On top of disciplinary differences, there are also cultural (American and Italian) variances in process, which this multicultural team also highlights. These conflicts must be reconciled for true collaboration to take hold. It cannot be expected that everyone on the team learn the skills of the other team members, especially over such a short time frame. I used the ESwatchBook framed as disciplinary boundary object allowing for discussion and shared understanding, leading to a productive creative team process. *"This is an analytic concept of those scientific objects which inhabit several intersecting social worlds and satisfy the informational requirements of each of them. Boundary objects are objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites"* [91].

The Hood was also an opportunity to test our active touch sensing techniques in a real world, high stakes scenario. Benford et. al discuss "why work on performance led research in the wild". *"The public deployment of artworks offers a test-bed for putting emerging technologies into the hands of users in a "realistic" situation, meaning a situation in which the technology needs to be made to work and is treated in some sense a professional product - this is the "in the wild" aspect of the approach."* [6]

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The hardware designed and field tested in collaboration with Rhò uses some of the same sensing techniques outlined in Chapter 3 and used in my final study prototype in described Chapter 6. The hardware consists of a microcontroller to drive the system, and a Bluetooth module to communicate with a laptop. On the front of the garment, 'smart LEDs' were included for visual feedback, sewn-in wiring was used to make touch points for discrete input, while a proximity sensor was included for continuous input. The entire system runs from a rechargeable lithium-ion battery, charged via USB. Thin un-insulated wire is used to create interlacing touch points much like the pattern for selection points chosen in Komor et al.'s "is it gropable" study [48] only at a much larger scale. The wire was chosen over conductive thread used in the ESwatchBook because the 'Hood' needs to be made more robust for performance. The wire was hand stitched onto yarn and fabric and then sewn down with a domestic sewing machine. Enameled magnet wire was chosen for leads to the touch points due to its size and malleability as compared to other insulated wiring, thus interfering less with the drape of the garment. The leads were soldered to a connector so that the micro controller and battery could be removed easily from the garment. Because the collaborative team decided to incorporate LED display of interaction this means this performance prototype cannot be washed or submerged in water. The Hood is to be worn on the outermost layer only during performance so wash-ability was not a priority.

On looking back over the process Rhó states: "My time on the project was exciting and inspiring, but also hard. It stressed me in a way, when I got here I did not know how to deal with the guys (engineers / computer scientist), I thought they were really

talented people, so I had to prepare myself to learn. When I met them, I had to deal with a new language, new stories, with a new environment, which is not a usual one for a musician. It's not only about using one software or another, but it's how to translate a process, something artistic, to people who come from technology, and how to transform a technology process in to music." This is as I would expect, but there was continued interest from Rhò in collaboration and the creation of wearable music controllers after this initial encounter. This continued interest reinforces the sentiments expressed by designers and artists from earlier workshops in the legitimacy of these types of electronic textile input interfaces as an option for on-body interaction.

I learned quite a bit from the actual performance with the garment. There was a moment when the garment lost Bluetooth connection and had to be reset before the show. Because of this disconnection in future performance (and user studies) I switched to using Wi Fi connection. There was also an issue with calibrating the capacitance of the Hood, and eventually I found that if the calibration was performed while the wearer was touching (the metal) laptop it effected the grounding of the system. I remembered both of these "lessons learned" when I created the prototype for the PDI study outlined in Chapter 6.

Another recent project that I tested aspects of e-textile interaction "in the wild" was called Le Monstré [116]. Le Monstré is a responsive performance garment, changing the sound and projection of the performance space through audience interaction. As

the audience is invited to investigate the garment through touch and pull, capacitive and resistive strain sensors relay the interaction as WiFi MIDI signals. The garment was designed as an investigation into the technology and arts collaborative design process. The performance garment is constructed of many different textures. Some of these textures include conductive materials, which act as capacitive sensors recognizing touch. Other portions of the garment contain ribbons that are attached to stretch sensors. Each of the sensing textures are designed to be explored through touch. Within the larger context of the performance's theme of connectedness through media, Le Monstré explores physical connectedness, and how that affects media.

Figure 25 - Interacting on stage with Le Monstré garment. Photograph by Saftey Third Productions.

4.4   Impact of Active Touch Wearable Electronic

Textile-Based Interfaces.

The research in this chapter answers my second research question. ***Can active touch aid in making on-body textile interfaces more accurate and quicker to interact with than interfaces without such affordances***. The "Is It Gropable" study gives insight directly into these metrics with respect to textile-based on-body active touch interfaces. In this chapter I have described the design of active touch textile based interfaces and techniques for creating [32, 48, 115, 118] I have also shown how active touch interfaces can be useful in real world performative settings, including how sample interfaces themselves can be used in a collaborative transdisciplinary design process. [4, 10, 14, 20, 21, 27, 79, 112, 114, 119, 120].

Using *prototype textile interface artifacts such as the Electronic Textile Interface Swatch Book, The Hood (e-textile garment music controller), and Le Monstré (an interactive participatory performance garment) (*contribution)* I have described ways that textile-based on-body interfaces using active touch are of interest to designers, artists, dancers, and musicians. These prototypes have also been shown to work "in the wild" with case studies and descriptions of use published in academic conferences [114, 116]. My assumption is that these types of collaborations will become even more rich with research and development surrounding Proprioceptive Display Interfaces.

Chapter 5

Passive Touch / Active Touch Preliminary Study

Building on my work in textile-based on-body active touch interfaces I am interested in the effect of combining active touch and passive touch. To test the human factors surrounding the combination of active touch and passive touch for use with PDI location of on body interfaces, I ran a preliminary study. This study begins to answer my third research question. ***Can combining active and passive touch techniques aid in making on-body textile interfaces easier to locate and use, more accurate, and quicker than interfaces without such affordances?*** The preliminary study investigates a person's accuracy of finding a point on the body (the forearm) without visual attention with and without the addition of passive touch (and to a small extent active touch).

5.1 Methods and Participants

Methods

The preliminary study consisted of a short survey and physical touch test. The short survey questioned the participants use of technology and wearable technology. The questionnaire also asked generic demographic questions such as age and gender identification.

The physical human factors test began by asking the participant to wear a white jersey knit long sleeve tee shirt. After the shirt was donned a binder clip was used to make sure that all the participants sleeves fit similarly (snug) around the forearm. The sleeve was gathered around the arm and held by the binder so that the sleeve touched the top (back of hand side) of the forearm. The participants arm could turn inside the sleeve without turning the sleeve. For example, with the arm outstretched if the participant moved his hand from palm down to palm up the arm moved beneath the fabric.

Before the touch trials began, the participants were asked to close their eyes and touch their nose with both hands, like in a sobriety test. All participants were able to complete this task which is some indication that their proprioceptive and kinesthetic abilities were within a normal range. The researcher then used a permanent marker to make a quarter inch touch target dot at about 3/4 distance from the wrist to the elbow. Care was taken not to press the skin beneath the sleeve while making the touch target dot, in order to prevent inadvertent learning.

Touch Target Trials

The participants were asked to try to touch the target dot on their forearm with the index finger of the opposite hand, while their eyes were closed. They were asked to use only their index finger with one touch.

Before each trial the participant was allowed to look at their whole body in a mirror including the target dot on their forearm (they were not allowed to touch the dot at this time however). The participants were then asked to close their eyes and to perform the following with their eyes closed: raise hand above head, turn around in a circle, put their arms down by side, raise arms palm up out to sides, move arms to front, turn palms down, place arms by side. At this point, the researcher notified the participants that they would place the participants' finger in non-toxic children's washable finger paint (blue). While the participants kept their eyes closed, they were asked to touch the where they believed the target dot to be located on their forearm. The participants were then allowed to open their eyes and look in the mirror again. This process was repeated 4 more times for a total of five touch target trials.

After five trials, the researcher created a small incision in the fabric at the location of the dot and inserted a fabric cord nub cufflink (Figure 26). This produced a nub both below the fabric (against the skin) and a nub above the surface of the fabric. The participant was then asked to perform five more touch target trials with orange finger paint.

Figure 26 – Fabric nub cufflinks

A photo was taken after each of the 10 touch target trials to making it easier to distinguish the order of the touches after the participant has finished. When the touch target trials were done, the binder was removed from the sleeve and the participant was asked to remove the shirt while being careful not to disturb the finger paint touch marks.

Before the participants left, they were asked to record anything they noticed about their experience on the back of the questionnaire they took before the touch target trials.

I then measured the distance of the touches from the target dot to determine if there was a difference between the touches with and without the sensation of the nub against the skin.

Participants

Participants were recruited through word of mouth and were not paid to be a part of this study. There were six participants in my preliminary study (three identified as female and three identified as male). Five of the participants were right handed and one was left handed. The age of the participants ranged from 26 to 42 years old. All of the participants owned a smart phone and had the phone with them, from the questionnaire I can assume that the participants were all familiar with wearable technology even if they did not own or wear any on a regular basis.

5.2 Results

The results of the study show that the average distance of a touch from the target dot without the nub against the skin of the arm is 1.63" as compared to .55" with the additional passive touch sensational reference of the nub against the skin. The average farthest distance from the target dot also is reduced from 2.55" to 1.25" as seen in Table 1.

Table 1 - Distance in inches from touch to target dot in Touch Target Trials.

Trials	P1M	P2M	P3F	P4M	P5F	P6F	Average
T1 no nub	1.25	2	1	3	1.5	1.75	
T2 no nub	2.5	2	2.75	0	0	2	
T3 no nub	1	1.25	2.75	0.5	2	0.75	
T4 no nub	0.75	1	1.5	0.5	0	0.75	
T5 no nub	1	1.25	3	1.5	0.5	1	
Average Distance	**1.3**	**1.5**	**2.2**	**1.1**	**0.8**	**1.25**	**1.35**
Largest Distance	2.5	1.25	2.75	3	1.5	1.75	2.13

Trials	P1M	P2M	P3F	P4M	P5F	P6F	Average
T1 with nub	1.25	0.75	0	1.5	0	1	
T2 with nub	0.75	0	0	1.5	1.5	0	
T3 with nub	0	0	0	0	0	0	
T4 with nub	0.25	1.25	0.25	0	0	0.5	
T5 with nub	0	2	0.25	0	0.5	0.5	
Average Distance	**0.45**	**0.8**	**0.1**	**0.6**	**0.4**	**0.4**	**0.46**
Largest Distance	1.25	2	0.25	1.5	1.5	0.5	1.17

The distance was measured from the center of the touch blob where the fingertip

might have been aiming (seen in Figure 27).
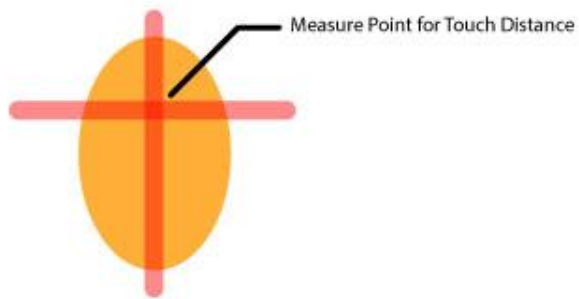
Figure 27 – Measuring point from finger paint blobs
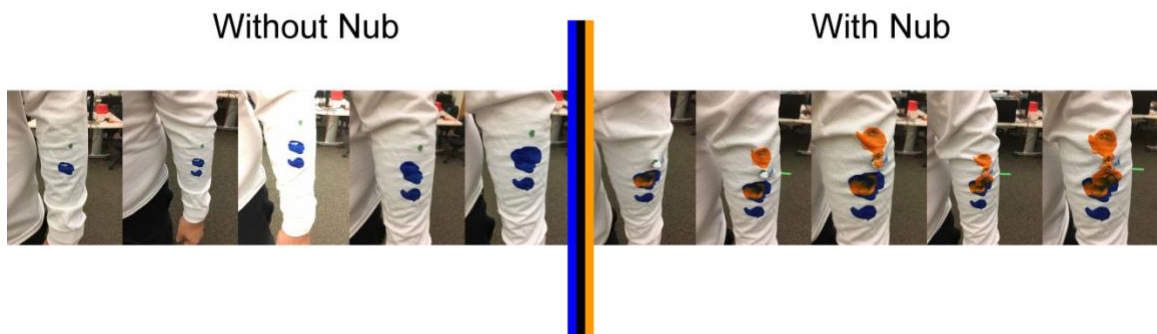
Figure 28 - Example of touch target trials from participant 1.

Figure 29 – Close up after final touch target trial of participant 1.

5.3 Discussion

In the study described in Chapter 6 I investigate the effect of vibration as a means to stimulate passive touch sensation it will be better to produce trials randomly with and without sensation. However, because here I was only testing with an addition of a fabric nub I decided it was more valid to test everyone first without the nub and then with the nub. It would be cumbersome to remove the nub after its addition, and it is closer to the final system I envision to test quickly after the addition of the nub. As the nub is applied the body will sense it the greatest, and as the body becomes used to the sensation through *masking* [13, 15–17] it will sense the presence of the nub less and less. Because all participants received the nub condition second there could have been some motor learning effects in the results.

I chose to create a standard tightness in the sleeve against the skin where the sleeve could still move across the skin. I made this choice because this is how people comfortably wear clothes. If the test garment were very tight (which might aid in passive touch testing) it would not act as a realistic application of how a garment might be worn in everyday life.

Through observation of the trials with the nub, many participants adjusted their touches instantaneously if they detected the nub on the edge of their finger. This *active touch* correction was spontaneous and unprompted. This reinforces earlier finding of the "is it gropable" study [48].

One issue that arose during the study was that the finger paint wet through the shirt. This produced a wet feeling against the skin. As the study progressed I had to ask the participants to ignore the wet feeling. Explaining to them that they were trying to hit the dot not the wet feeling. After each trial before the addition of the nub, some participants tried to reference against the wetness on their skin (which is still an attempt to use passive touch to aid in locating the touch target). One participant stated "without the nub I had to guess based on memory where the dot was, and with the nub I could slightly feel on my arm where the dot was, so vectoring was easier". Another participant stated that "the visual reference of the dot prior to the test was almost no help in locating the dot on the arm. The nub was initially more accurate but became more difficult to locate after some tries". This last testimonial is consistent with the concept of *masking* over time. This study mainly looks at change in distance from touch target of initial land-on touch with the addition of passive touch. The outcomes of this study suggest that this will improve accuracy, access time of an interface, but I created a more sensitive test system (described in Chapter 6) to understand these metrics.

This simple preliminary study seems to show there is evidence that passive touch can aid in non-visual interactions with an on-body interface. The participants even used their sense of active touch to self-correct when they felt the nub on the edge of their finger.

Chapter 6

Textile-Based On-body

Proprioceptively Displayed Interface

Interaction Usability Study

Following the study described in Chapter 5, I developed a more robust study to investigate the effect of combining active touch and passive touch, including the addition of vibrotactile stimulation. This much larger study is an effort to complete the answer to my third and final research question: ***Can combining active and passive touch techniques aid in making on-body textile interfaces easier to locate and use, more accurate, and quicker than interfaces without such affordances?***

6.1   Metrics for Textile-Based On-body Interaction

Usability Study

Throughout this usability study, I compared different on-body textile interfaces with an audio display while in a mobile (walking) condition. The metrics I employ to quantify the differences between the interfaces are time to touch, accuracy, and workload.

Accuracy

My goal was to find which interfaces are the most accurate using the audio cues to prompt for different types of selections. If I were to have five selections 1, 2, 3, 4 & 5 as an example, I would prompt for each equally and randomly to look for how often the study participants correctly answered. Accuracy included the *Accuracy of overall Task Completion,* which will include instances of insertions (false positive), deletions (false negative), substitutions, and true positives.

Time to Touch

To measure access time, I used the wearable device (a study prototype to collect wearable interaction information) to record the time it takes from each audio prompt to the first recognizable touch activation interaction with the interface; however, this does not necessarily mean the first correct interaction.

Workload

To place a value on the workload required to operate the different interfaces, I administered a NASA TLX survey [67] to each participant.

6.2 Active Touch / Passive Touch Combination Usability Study Design

6.2.1 Body Location: (Forearm)

From the results of the extensive literature review (just as in the Chapter 5 study) I have chosen to focus my usability study on the forearm. Research conducted by Francine Gemperle [29] and Paul Holleis [42] on designing for wear-ability helped narrow down body locations for testing. Even though my study focuses on interactions and selections rather than displays and notification, my selection of the forearm is also informed by Chris Harrison's research on wearable display location [39]. Other research in the social acceptability of wearable interactions also supports the decision to place the primary physical interface on the forearm [21, 79]. While the interface using passive and active touch will be located on the forearm, the microcontroller and networking components are located around the neck.

6.2.2 Textile-Based On-Body Physical Interface Style and Ability Comparison

To examine whether adding passive touch to an active touch interface aids in operating on-body textile based interfaces, I created four test conditions.

Condition 1 participants operated an interface with surface stitched touch points, thus an almost flat fabric interface (Figure 30). This type of stitching is a flat stitch much like a sewing machine would produce. The design of the touch points is round with an inner conductive trace (connected to ground) and an outer conductive trace acting as a lead for individual capacitive sensors. Participants could touch any part of the touch point to make an activation as long as they touched both the inner and outer conductive traces.

Condition 2 participants interacted with a raised embroidered interface (Figure 30), thus increasing the active touch of the interface. I sewed the embroidery over thin craft foam. The foam remained under the embroidery (between the fabric and the thread) making the sewn elements stand up higher from the surface of the fabric. This method of construction is a common a technique used by embroiderers. Condition 2 closely resembles the type of embroidery used in the "is it gropable" study [48].

Condition 3 participants worked an interface with the same embroidery that also incorporated metal snaps ("nubs") under the fabric to give passive touch sensation against the forearm (Figure 31).

Condition 4 used the same interface as condition 3 but with the addition of vibrotactile stimulation.

The pattern of the interface was the same for each of the conditions and contained five touch points (Figure 32). The touch points were spaced 1.5" apart as measured from the center of the touch point. This distance between touch points was derived from the literature review for the passive touch body map (Chapter 2). The sleeve was symmetrical and could be placed on either arm making the system usable for right-handed and left-handed participants. I also designed the sleeve to fit a large variety of forearm circumferences so that a close to uniform tightness against the arm could be maintained across different participants by using hook and loop (Velcro) strips and elastic (Lycra) mesh fabric. (Figure 32). The fabric for the outer layer of the sleeve was a medium weight woven polyester twill, chosen for its non-absorptive properties as well as its color. The choice in color was important so that the embroidery and conductive thread would not stand out visually in contrast to the fabric. I wanted the tactile nature of the interface to be the focus of the study, rather than the visual nature of the interface. This is not to say that a visually contrasting interface wouldn't help in usability, but that is not what I was researching.

The weight and drape of the sleeve is similar wearing a shirt and outerwear garment, such as a long sleeve knit tee with a sports coat. It was important that the feeling of the sleeve compare to wearing traditional clothing so that participants did not feel uncomfortable, either physically or socially while using the prototype. I also hope that this study become applicable to the garment industry where drape and weight are important.
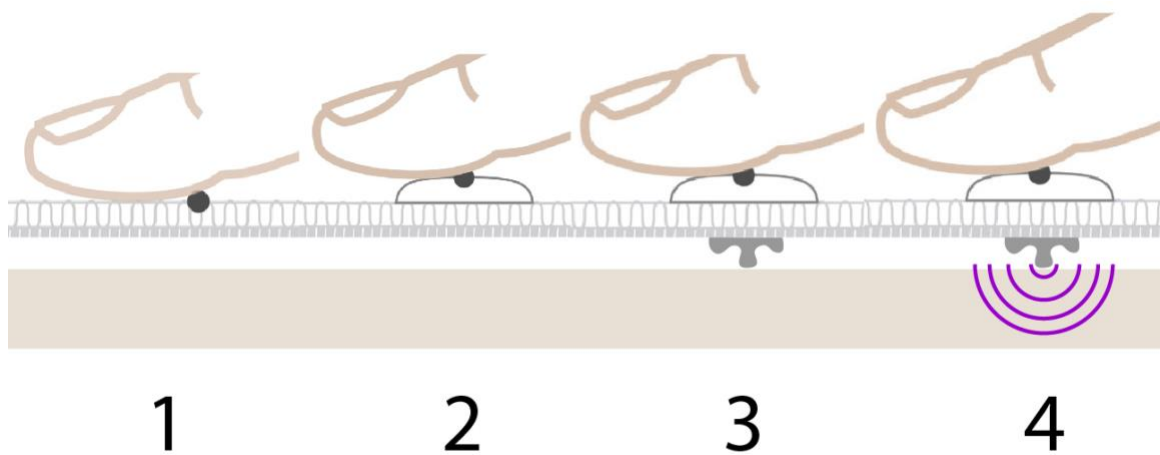
Figure 30 -These are the four interface interaction conditions. Condition 1 is made with just sewing machine stitched conductive thread on the surface of the fabric. Condition 2 adds a raised surface for active touch feel. Condition 3 adds a metal nub projected against the skin of the forearm. Condition 4 creates vibration before a touch is prompted.

Figure 31 - Face of fabric and back of fabric with regards to condition.

The inner and outer conductive thread traces are used to sense the presence of a finger touch through hybrid capacitive resistive sensing. The user just needs to touch both traces, but any portion of the traces will do.

Figure 32: Interface layout and sleeve fit.

In condition 4 each touchpoint is vibrated in a specific sequence before an audio prompt is given. Triggering the vibration before the audio prompt more closely parallels what might happen with a system in a real world scenario. A user of such a commercial system would probably feel a vibration notification before a decision is made about how to interact with the system. The goal is to indicate with vibration the location of all touch points prior to a selection being made. So every touch point vibrates before each audio prompt. I conducted a small vibration preference study with 14 people (separate from the 104 study participants) to allow individuals to feel different vibration patterns and comment on which ones might help them locate touch points. One pattern vibrated the touch point in sequential order 1, 2, 3, 4, 5 separated by a time delay of 130 milliseconds. Individuals commented that this pattern "felt like a vibrating phone being dragged across their arm". This is consistent with research about vibro-tactile adaption and the perception of vibration patterns space closely in location and time (as described in Chapter 2). A second pattern vibrated in an order of 1, 3, 5 and then 2, 4 with a delay of 130 milliseconds. I also tried single tap and double tap vibrations for each sequence. Because of the larger distance and non-sequential order, participants in the vibration preference study said that this second pattern felt more like individual points of vibration. It also seemed to help to have a combination of single tap and double tap. The final vibration pattern used in the study was: 1, 3, 5 single tap , and 2, 4 double tap vibrations with a 130 millisecond delay.

6.2.3 Touch Target Trials

After consent procedures, the study session began with each participant donning the wearable system. I gave the participants a short training session to make sure they knew how to interact with the wearable system, and also to make sure the system was working properly. Training included a single audio prompt from the system and corresponding touch for each of the touch points. During the testing session, the system prompted the participant with an audio prompt via headphones. The cues denoted which touch point the participant should touch: "one", "two", "three", "four", or "five", in English using the voice and pronunciation from translate.google.com. After the system recognizes a touch, it emits a feedback beep to notify a selection has been made. During training I told the participants which touch points corresponded with each number, and instructed participants to touch with the pad of the finger rather than the very tip. The pad of the finger allows more contact with the touchpoints making it easier for a selection. Participants were asked to directly aim for the touch point they were trying to activate rather than feel or grope [48] along the surface for the touch point. If they were unable to hit the touch point by aiming, they were instructed to then feel for the nearest touch point. They were asked to make sure they received a confirmation selection beep for each audio prompt. The system gives the same confirmation beep response for every selection and does not alert the participant if the selection is correct or incorrect. Correctness of selection was purposefully withheld to mitigate learning effects during the target touch trials. The instructions and training session took approximately four minutes to complete.

Before the test sessions of the study started (after the training session and while wearing the interactive system) I led the participants through a walking track set up in a laboratory environment. The participants then walked around the track five times to learn the path through the walking track. This process took about 5 minutes and varied per participant's pace. As the study began, participants were asked to make selections as quickly and accurately as possible. Each participant was told to "please make selections as if you are in an important meeting and your phone begins to ring and you need to silence it." The participants were also asked to walk naturally with their hands by their sides until prompted to touch.

There were two interaction rounds to the study for each participant. In round 1, the participant was allowed to glance at the interface and activate using visual attention. In round 2, the participant wore blinders, and could not see their interactions (Figure 33). In each condition half of the participants started without blinders (round 1) and the other have started with blinders (half of the participants started with round 2).

For the study, there were 26 unique touch target scripts (to be used in each condition), one for each participant in the four interface conditions, prompting each of the touch points ten times for a total of 50 prompts. Each script had a random order of prompts. The time between prompts was also randomized between 10 and 20 seconds so that participants would not be able to anticipate a prompt. Each script lasted 13 minutes. Individual participants completed the same touch target script twice, once with visual attention, and once without visual attention. Each condition used the same 26 scripts.

The time of the audio prompts and all touches on a touch point were recorded by the system.

Figure 33: Blinders used for non-visual interaction round in all conditions

6.2.4 System Technical Description

With help I designed the study system from off-the-shelf components pre-mounted on printed circuit boards, a hardware expert combined the components to work to my specifications and tolerances needed for the study. These boards are mounted on a larger carrier board with point-to-point soldered connections. I created a custom pouch (Figure 34) to hold the system around the participant's neck for ease in donning and doffing the system.

Figure 34: Technical system in neck pouch.
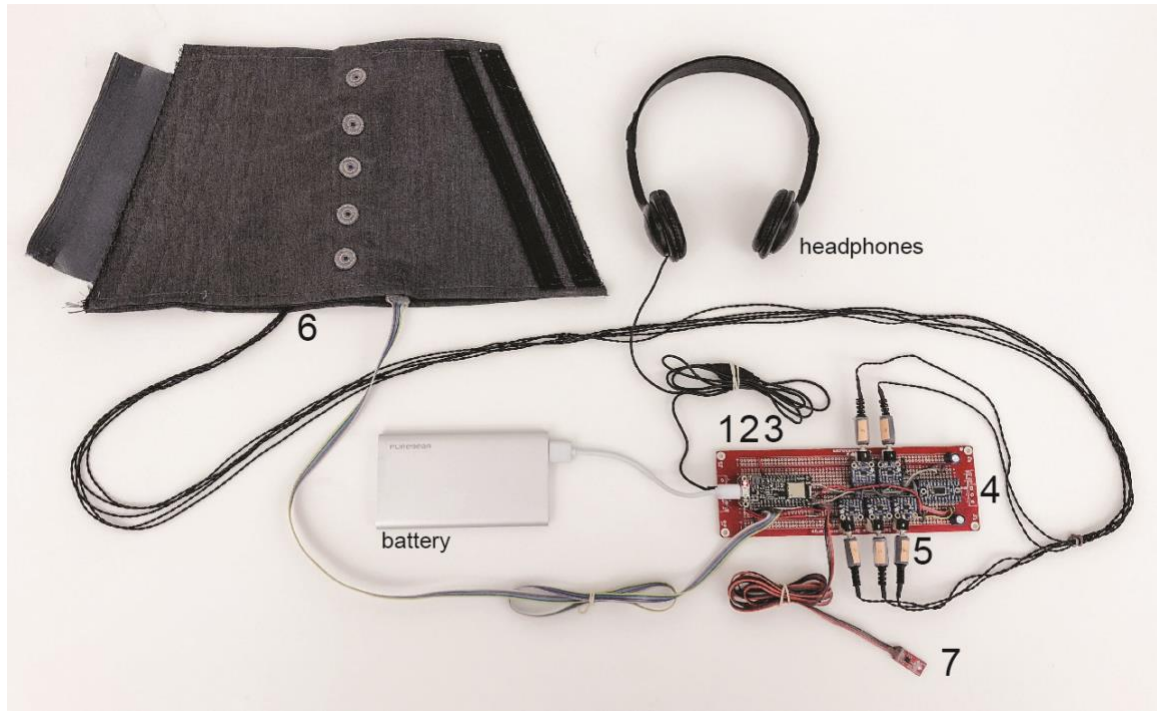
Figure 35: Technical components of wearable system.

	Functionality	Component
1	Main Processor	Cypress STM32F205 core
2	802.11 WIFI communications	Cypress WICED module
3	MP3 Playback	VLSI Solutions VS1053B
4	I2C Multiplexer (1 to 8)	Phillips TCA9548A
5	LRA Driver	Texas Instruments DRV2605L
6	LRA Actuator	Engineering Acoustics Tactor
7	Accelerometer	ST Micro LSM9DS1

The capture software is a multi-threaded architecture utilizing queues for inter-thread communication. The data is captured utilizing timed interrupts for reliable data

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acquisition. The system recorded touch selections through capacitive sensing techniques on conductive thread traces very similar to those used in the Komor et al. study [48]. The accelerometer incorporated a 32 sample FIFO for local buffering. The accelerometer was worn on the touching finger of the participant. These are critical to capture data without dropping samples while simultaneously serving the WiFi subsystem and SD card reading and writing. This architecture supports a capture rate of 100sps from both the touch points and the accelerometer. The system control is operated through a terminal window on a laptop and WiFi connection. I could change the script, and add condition flags and participant identification numbers to the data files. A WiFi connection is necessary for the start and stop of the study scripts, but once a study script is started if the WiFi is disconnected from the device it will continue to prompt and record data to the SD card until the end of the script. Raw data of the touch interactions was collected from the SD card at the end of each day.

The system recognizes a relative capacitive value (from the system) above a threshold of 10 for five contiguous samples as a touch selection for the purposes of delivering a feedback beep to the participant. The system must have a capacitive value below the threshold for five contiguous samples before it will recognize another touch (so that it will not make multiple selections when a participant lingers on a touchpoint). This touch identification method was used only for the purposes of system interaction by participants, raw data of all system capacitance changes were used to analyze results.

Figure 36 details a touch that started at about 111.5 seconds in response to an audio

prompt which began at 110 seconds. Notice that there is some noise from the other touch

point sensors but it is clear that only a single touch point is being activated. Figure 36

denotes a touch selection on a prompt without vibration.
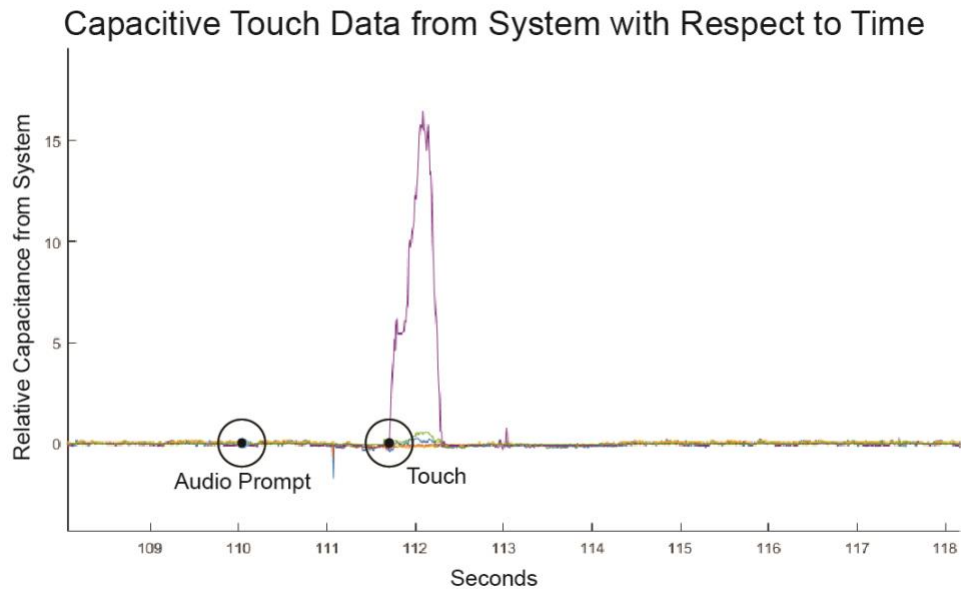
Figure 36: Example of a single touch target trial showing the raw capacitive data change over time,

without vibration. The dot indicates the start time of the audio prompt. The five different color lines

denote the five different touch point sensors.

Figure 37: Accelerometer magnitude data from the touching finger for the same touch target trial as figure 36.

Figure 38: Accelerometer 3 axis data from the touching finger for the same touch target trial as figure 36.
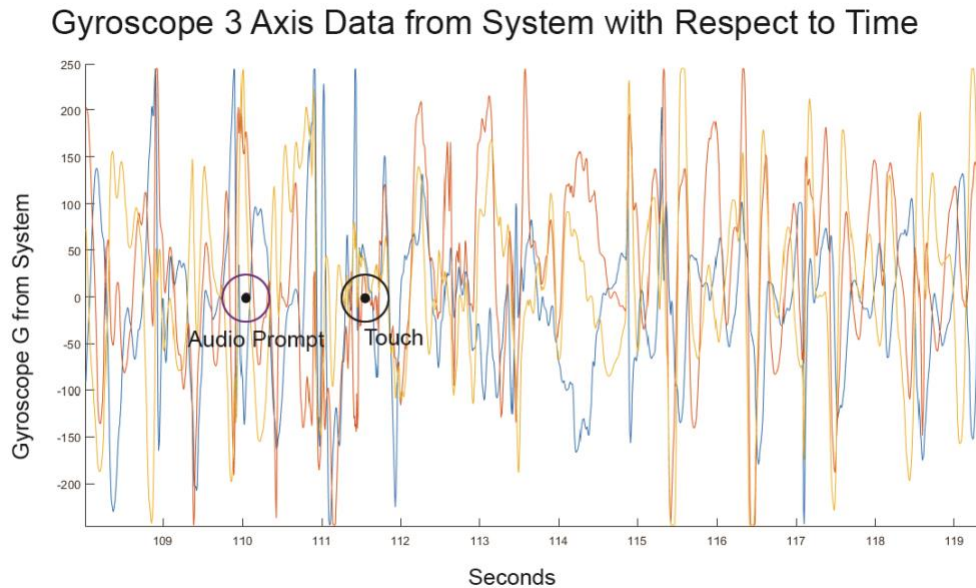
Figure 39: Gyroscope 3 axis data from the touching finger for the same touch target trial as figure 36.

Figures 36 through 39 show additional data that was acquired by the accelerometer / gyroscope attached to the participant's touching finger. Figure 37 clearly shows the magnitude of the impact of the participant's touch. Figure 38 shows the change in force by directional axis during the motion to a touch and returning to the rest state of a participant's arms by their side. The gyroscope and accelerometer data are not as clear because this study was a mobile study and there was a great deal of noise created by participants swinging their arms. Due to this noise and the fact that the touch data was so clear I have decided that the accelerometer data was not needed to determine the outcome for my thesis.

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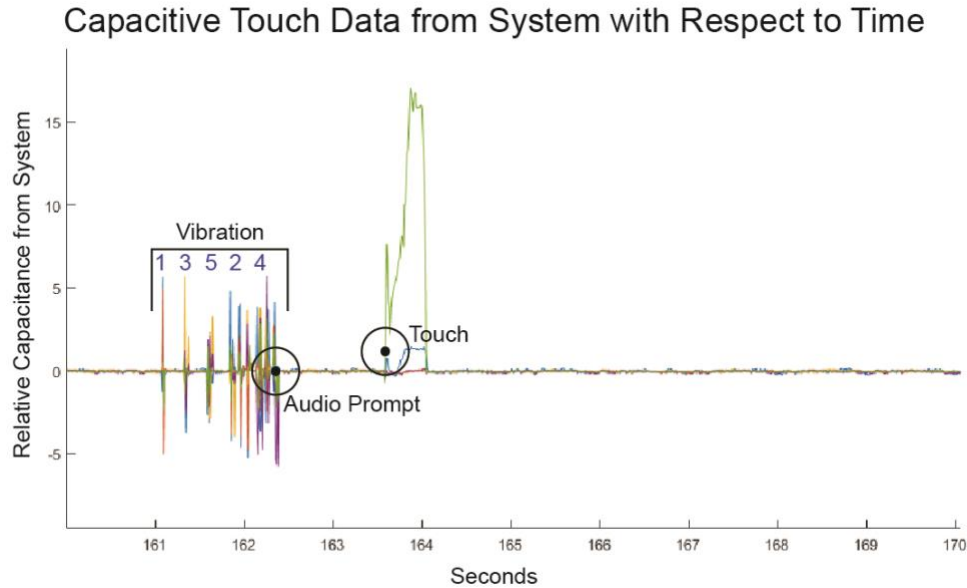
Figure 40: Example of a single touch target trial showing the raw capacitive data change over time, with vibration. The five different color lines denote the five different touch point sensors. The numbers (1,3,5,2,4) represent the order and timing of vibration motors associated with those touchpoints on the arm, graph shows that the vibration has an effect on the capacitive sensors in the system.

Interestingly Figure 40 shows the vibration's effect during a target touch trial on the capacitance of the system. For the purposes of understanding when a participant made a touch this effect does not interfere with our data, but in other scenarios where the vibration might be stronger and happen during a touch this is an important effect to note.

6.2.5 Facilities

I conducted the study in a walking condition. Participants were instructed to walk at a normal pace around a track constructed in our laboratory (see figure 45). The track is approximately 25.2 meters long and is denoted with pairs of flags hanging from the

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ceiling with their tips 0.75 meters apart. Each flag is hung so the tip is approximately 1.6 meters above the floor. The lab chose to use hang flags from the ceiling to ensure that participants are engaged in a head-up task. If the participants follow a path laid out on the ground, a head-down condition would have ensued, which I considered to be inappropriate given the nature of the study (as walking around, head down, is not typical behavior). In an effort to accurately calculate the speed and distance traveled by the participants, a set of motion sensors is mounted in the ceiling of a testing room between each pair of flags (see figure 41). The sensors are connected to a computer in the laboratory via Bluetooth. Every time a participant walks between a pair of flags, the sensor records the instance and sends that information to the computer. In this way, I can calculate the instantaneous and average speed of and total distance traveled by each participant as they walk from flag to flag along the track.
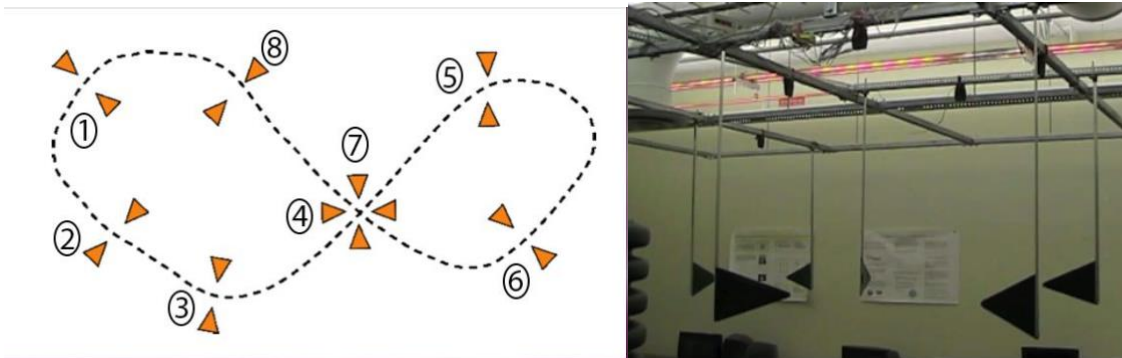
Figure 41: (A) The path participants will walk, starting at flag 1 and proceeding either clockwise or counterclockwise. (B) The flag and sensor configuration that comprises our walking track.

Table 2: Participants

Condition	Average Age	Male	Female
1	24.03	14	12
2	25.62	15	11
3	26.31	14	12
4	24.42	13	13

There were 104 individual participants in this between-subjects study, 26 in each condition. The age of the participants ranged from 18 to 61 with an average age of 25.32 years. The participants self-identified as 48 female and 56 male. Four of the participants were left-handed (one in each condition) and the other 100 were right-handed. Within condition 1 the average age was 24.03 and there were 12 females. Within condition 2 the average age was 25.62 and there were 11 females. Within condition 3 the average age was 26.31 and there were 12 females. Within condition 4 the average age was 24.42 and there were 13 females.

6.3   Active Touch / Passive Touch Combination Usability Study

Results and Discussion

6.3.1 Results

I measured accuracy as the number of correct touches (touching the touch point that was prompted) out of total touches collected. A small number of touch samples were discarded due to system error at the time of touch. This error showed up as sample overruns, or the system collected no data for a number of seconds (even when there is not a touch there should be data collected). Time to touch indicates the time from the beginning of the audio prompt to a touch on the interface. The average accuracy for the first round an individual participated in (including visual and non-visual interaction) was 88.99% and the average accuracy for the second rounds was 90.84%. This result suggests that there was very little, if any, learning between the first and second round of the study. As expected the accuracy is much better for visual interactions at 99.1% as opposed to a non-visual accuracy of 81.01%. The average time to touch from the audio prompt in the visual condition is 1.34 seconds and in the non-visual condition is 1.65 seconds. It can be expected that it would take longer to find the touch point in the non-visual condition.
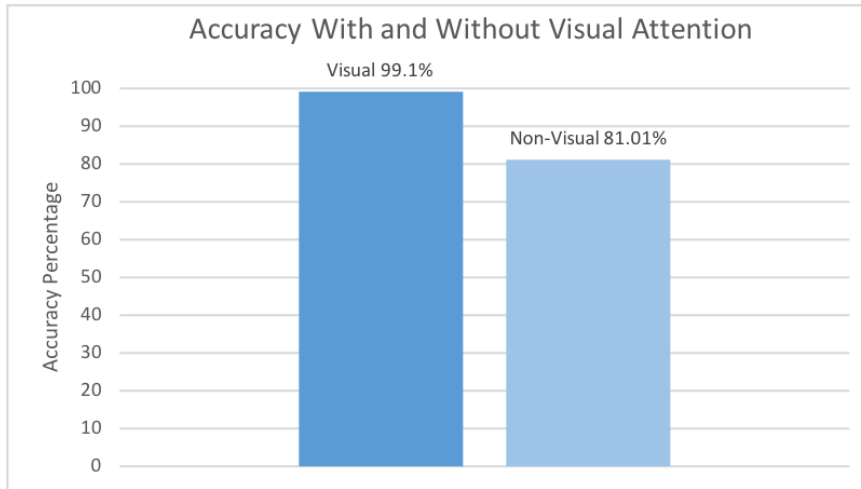
Figure 42: The accuracy across conditions with and without visual attention.

I determined the time to touch and touch point with the following algorithm:

1. Starting at the beginning of the audio playback time until 5 seconds after, look for the largest peak in all button channels that exceeds a relative capacitive value threshold of 4. This threshold is smaller than the threshold of 10 used for audio feedback during the touch trials, but after viewing the data this was the lowest threshold that accurately determined a touch from the data, thus letting me capture touches that were performed but might not have received a feedback beep. As an example, if someone touched the system lightly once and the relative capacitive value reached 6, but then touched it harder and it reached 15, I would want to count the initial touch for accuracy and time-to-touch.

2. The maximum value found across all touch point channels indicates the selected touch point.

3. In the selected touch point channel, step backwards until the time is found where the channel crosses the threshold.
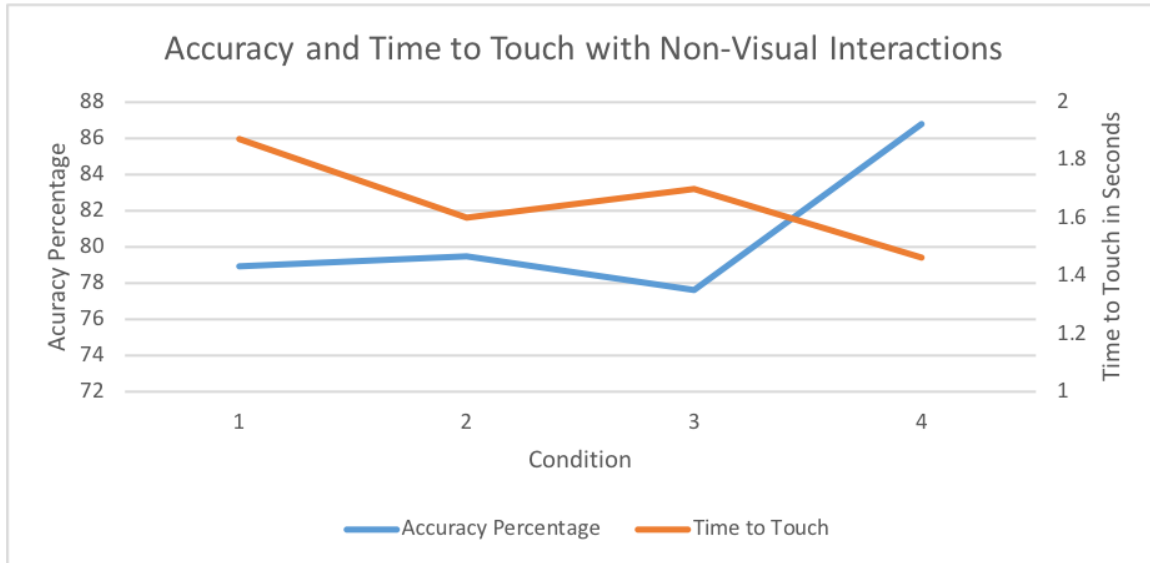
Figure 43: This graph shows that the difference in the four conditions observed in this study both in accuracy and time to touch.

The results this study as illustrated in Figure 43 show that the addition of the passive touch static nubs in condition 3 did not have the anticipated effect. The accuracy and time to touch for each of the first three conditions are very close and within a standard deviation of each other. The average accuracy of non-visual interactions in condition 1 is 78.92%, condition 2 is 79.39%, and condition 3 is 77.58%. The average time to touch of non-visual interactions in condition 1 is 1.87 seconds with a standard deviation of .68 seconds, condition 2 is 1.60 seconds with a standard deviation of .47 seconds, and condition 3 is 1.70 seconds with a standard deviation of .59 seconds. It is important to note that these times are the start from the beginning of the audio prompt and end at the touch interaction. What is promising is that the accuracy of condition 4 (with vibration) jumps to 86.76% and the time to touch shortens to 1.46 seconds with a standard deviation of .42 seconds. Some participants might have moved their hand towards the interface at

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the start of the prompt, while others may have waited until the full word had been pronounced before moving to make an interaction. The reported times to touch would indicate that the addition of the passive touch static nubs did not help participants locate the interface touch points any quicker or with better accuracy. However the addition of vibration before the audio prompt seems to have helped the participants move to the touch point faster and with greater accuracy.

Table 3: Accuracy of Participants with Non-visual Interaction with Respect to Condition.

Condition	Mean	Variance	Standard Deviation
1	0.78929	0.01223	0.11059
2	0.79385	0.016612	0.12889
3	0.77577	0.030627	0.175
4	0.8676	0.006426	0.08016

The means and standard deviation of the accuracy of participants using the system with non-visual interaction can be found in Table 3. I used a 4 way ANOVA to measure the significance of the change in of overall accuracy including both visual and non-visual interactions between conditions (4 conditions, with 26 participant in each condition ,with 100 samples per participant) and found significance with a p-value .04. The p-value for the change in accuracy between conditions of just the non-visual interactions across conditions is .052 (4 conditions, with 26 participant in each condition ,with 50 samples per participant).
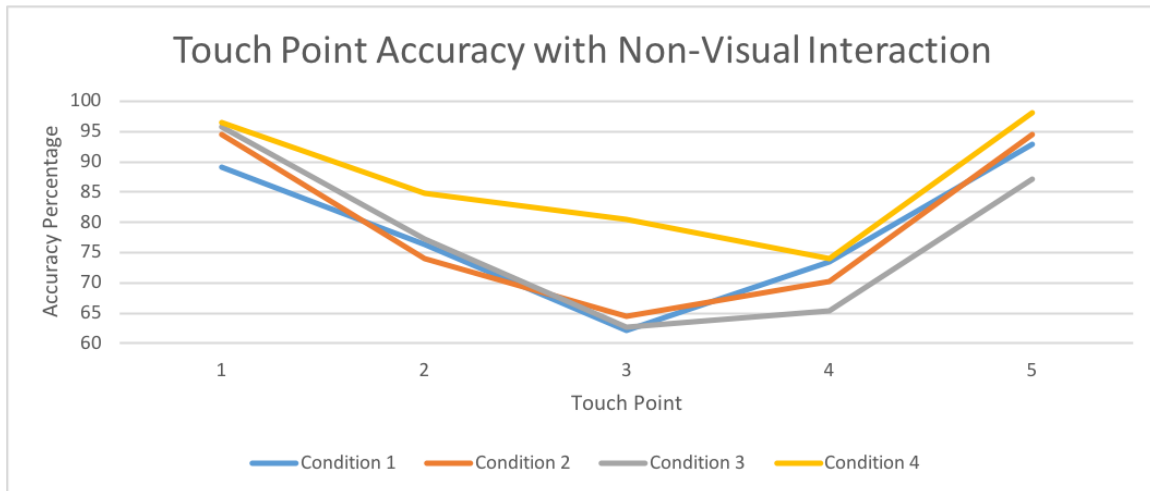
Figure 44: This graph shows the non-visual accuracy of each touch point by condition.

One predictable, but also interesting finding shows the change in accuracy based on the position of the individual touch points in the interface (Figure 44). The touch points on the edge of the interface (1 and 5) have much better accuracy than those in the middle of the interface. The middle touch point (3) has the worst average accuracy across all conditions at 63.11% (in conditions 1,2 and 3). However although condition 4 has better accuracy on all touchpoints, it has over a 17 percentage point advantage in accuracy on the middle touch point at 80.47%.

After the touch interaction portion of the study, I asked the participants to fill out a NASA Task Load Index worksheet for the non-visual interactions. The NASA TLX is a worksheet with six Likert scale (1-20) questions. Low is 1 on the scale and 20 is high on the scale for all questions except for performance where 1 is perfect and 20 is failure. Our participants were asked to rate their confidence in their performance as they did not have access to their actual touch data results.

Nasa Task Load Index Results for Non-Visual Interactions
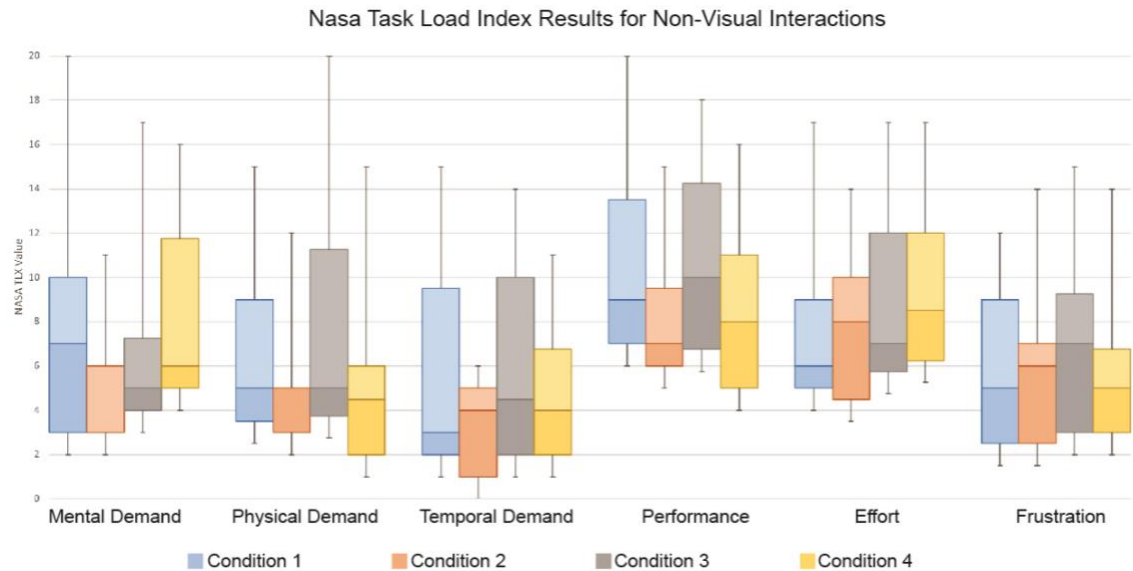
Figure 45: NASA Task Load Index survey data by condition for non-visual interactions.

6.3.2 Discussion

Part of my hypothesis was that the addition of the passive touch static nubs (without vibration) would aid in the accuracy and time to touch of interacting with the touch points. I found this part of the hypothesis to be false. I based this hypothesis on the results of the earlier preliminary study using a fabric nub against the skin (Chapter 5). That study shows that the addition of the nub aids in locating the touch point, and that people are able to touch closer to the target with the addition of the nub. There are some major differences in how this study was designed which might explain the different outcome.

First, I found that individuals have widely varying kinaesthetic and proprioceptive abilities, or at least they have different ranges of ability to touch a specific on-body location without visual attention. Some people were exceptional when it came to

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accurately interacting with our system, and some people were not very good at all. The accuracy of non-visual interactions in our study ranged from around 31% to 96% within the first three conditions. This variation of ability did not have any correlation to age, as shown in Figure 46, or gender. Even though the average accuracy for the first three conditions condition are very close to each other, the vastly different ability of individuals in the conditions combined with the fact that this is a between subjects study cause our p-values to be very high when only looking at the first three conditions.
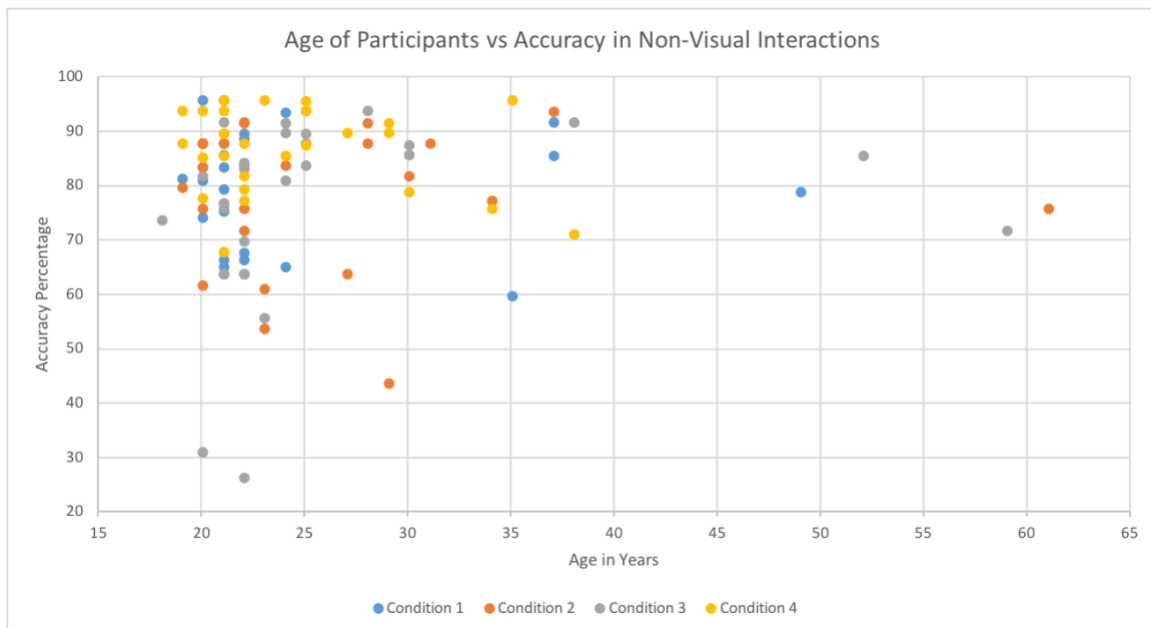
Figure 46: This scatter plot indicates the accuracy of non-visual interaction had little correlation to age.
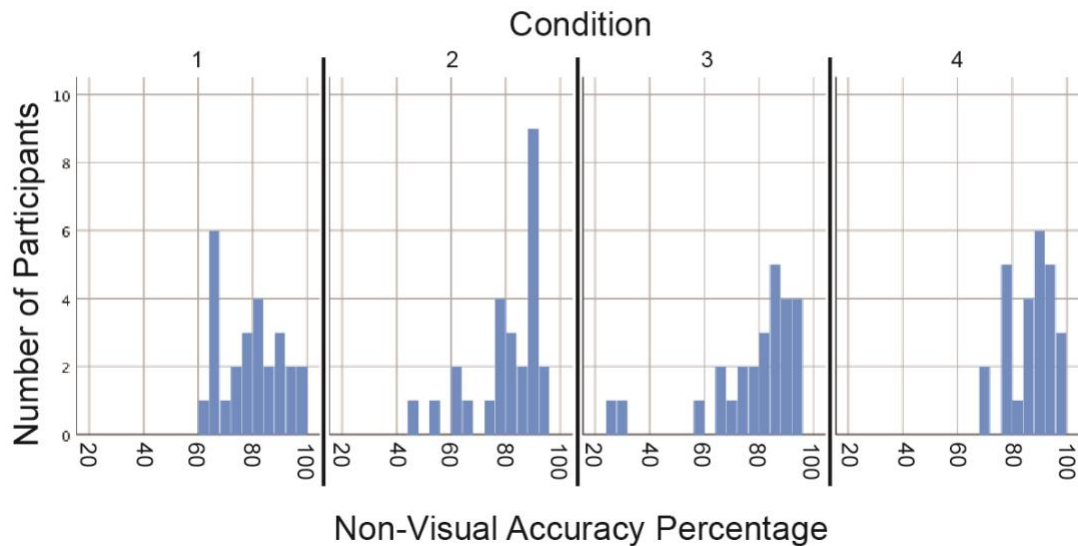
Figure 47: This histogram shows the variance in participants ability to accurately select the correct touch point when prompted.

It is also interesting to note that during the study, the system was more responsive (capacitive sensing) to some people, and less responsive to others. Those who had problems activating the sensors were asked to wipe their hands with a wet towel and this helped the system recognize their touches. This capacitive sensitivity issue might be easily resolved with system self-calibration, but is an important point to raise if this type of sensing were to be used in a commercial product.

Outside of individual's varying abilities, another major difference which I believe caused a different outcome to the earlier preliminary study (Chapter 5) is the amount of time the participants were wearing and interacting with the interface. In that study, the participants were asked to touch the target almost immediately after the addition of the passive touch

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nub. In this study, the participants were wearing the interface with the nubs for almost 9 minutes before the study began collecting data. The fact that the presentation of the nub stimuli is constant means that the participant's body is probably masking, or habituating to, its effect. "Masking is a phenomenon by which the performance at identifying a target stimulus is decreased by the prior or subsequent presentation of a masker stimulus" [13, 15–17]. The masking effect might have also been heightened because of the nubs in this study were metal. Because the metal nubs conduct temperature better (than fabric) they would quickly acclimate to the participants body temperature making them harder to notice. The texture of the metal snaps was also smooth, and thus might have made habituating to the presence of the metal snaps easier than a rougher surface. Because of this masking there is no benefit added by the passive touch metal static nub. In fact, as the sleeve was removed after the study, many of the participants had very distinctive impression marks made by the metal snaps, and most were surprized by the marks even making comments about the fact that they did not feel the metal snaps (nubs).

In regards to the effect of adding active touch embroidery to the accuracy and time to touch, again I see very little if any improvement in the second and third condition from the results of this study. This result is partly expected because the participants were asked to aim for the touch point rather than feel for the touch point. If they did not hit the touch point they were then asked to feel in the local area until they made a selection. This might account for the slight decrease in time to touch for conditions 2 and 3, as they had embroidery that was easier to feel. If this study were set up as Komor et al.'s study had been [48], where participants were asked to feel the interface, the addition of active touch

embroidery could have had a greater impact on accuracy. Because of this, I still believe that the active touch embroidery (or raised touch points) is helpful in the design of an industry/commercial wearable device to increase the accuracy of use.

To develop a prototype and method of study to record the effects of the addition of vibro-tactile stimulation I also found it necessary to use Engineering Acoustics Tactors which are much larger than normal LRA vibration motors. I first created the system with smaller LRA motors (which might be found in smart phones today), but these motors did not create the amount of vibration needed for the study, and test participants said they hardly felt the vibration. The larger Engineering Acoustics Tactors worked well but the tradeoff is that they were heavier and larger (about 1.5") across. The vibrating section of the tactor is focused and was attached to the metal snap nub. The weight and size of the tactor motors would have also made the gropability of the vibrating sleeve system very different from the other sleeves, this is another reason why the participants were asked to aim (instead of grope) for this study. In the future vibrating motors or other forms of localized stimulation might advance which would enable a better test prototype.

Table 4: The non-visual interaction mean accuracy and mean time to touch across conditions.

Condition	Mean Accuracy	Standard Deviation of Accuracy	Mean Time to Touch in Seconds	Standard Deviation of Time to Touch
1	78.91%	11.06%	1.8718	0.68191
2	79.44%	12.89%	1.5993	0.4673
3	77.61%	17.50%	1.7	0.5879
4	86.76%	8.02%	1.4625	0.41886

The accuracy of participants is over 9% better with the addition of vibro-tactile stimulation in condition 4. The accuracy of the edge touch points (1&5) is up to 33% better (condition 3) than the accuracy of the middle touch points (2,3,&4) (Figure 51). This is a predictable outcome, but it manifests so dramatically in the results that I can make some suggestions about interface design for on-body interactions. The center of the interface is also where I see the biggest improvement from the first three conditions to condition 4. It seems the addition of vibro-tactile stimulation displaying the location of the interface before an interaction improved the accuracy of the middle touch point by almost 17% the comparison of the accuracy of just the middle button also has a significance p-value of .019. When designing a textile-based on-body interface, aside from including vibro-tactile stimulation, it would also be prudent to locate frequently used, and important selections at the edges of the interface rather than in the middle of the interface.

Table 5: Distance by Touch Point of Incorrect Selections

	1 Away	2 Away	3 Away	4 Away	Total Wrong
Cond 1	247	16	5	13	281
Cond 2	261	13	0	9	283
Cond 3	280	13	0	1	294
Cond 4	171	2	0	0	173

There is another way to look at the accuracy of using the system as it changes from condition to condition, and that is how wrong was a wrong answer. When calculating accuracy I only observed whether the answer was correct or incorrect, but by showing the distance by touch point I find that not only were there less wrong touch selections in condition four, but when the touch selection was wrong it was closer to the right touch point. Table 8 shows the number of wrong touch selections by how many touch points the selection was away from the prompted touch point. In condition 1 there were 281 wrong selections, of those 247 were only one touch point away from the correct selection (if touch point 1 was prompted then the participant touched touchpoint 2), 16 were 2 touch points away (if touch point 1 was prompted then the participant touched touchpoint 3), 5 were 3 touch points away, and 13 were 4 touch points away. In contrast condition 4 had no incorrect touches more than 2 away from the correct touch point. This trend suggests that as active touch and passive touch stimuli were added to the system the distance by touch point from the correct touch point became smaller. This finding is important because even if the participants were selecting wrong answers, they were closer to the right answer. If a potential system were designed to allow for time to investigate with active touch, the use of passive touch vibro-tactile stimuli aiding in closer to correct

initial land-on of the interaction will improve the time to touch and accuracy of such a system.

When looking at the results from the NASA Task Load Index worksheet, the median scores were very close across conditions. Mental, Physical, and Temporal demand range from 3-7 which is on the low side of the scale. Effort to use the system ranges from 6-8 across the conditions and frustration ranges from 5-7. These results indicate that participants perceive the system to not demand too much in its operation. The results for performance range from 7-10 across conditions. This result would suggest that the participants had mixed feelings about the confidence of the accuracy of their performance in their non-visual interactions (leaning towards confident) (Figure 45).

There are some suggestions that I can now make about methods used to research a person's proprioceptive ability to interact with an on-body interface, and the effects of adding additional tactile sensation (in active or passive touch). I wrongly assumed that individuals would have similar proprioceptive abilities. Perhaps a within-participant study would help to mitigate the effects of variance on the scientific significance of findings.

6.3.3 Limitations of Study

This study was heavily informed by past research including research into active touch afforded interfaces [48] as described in Chapter 4. If a potential system were designed to allow for time to investigate with active touch it seems clear the use of passive touch vibro-tactile stimuli would aid in closer to correct initial land-on of the interaction, improving the time to touch and accuracy of such a system. However, designing a study to test for all of these variables at the same time is difficult, and thus I focused my efforts on investigated the addition of passive touch affordance through metal nubs and vibro-tactile stimulation. Even though I was not able to examine all of these variables within the scope of this one study I was able to glean new insights into areas I could improve if I were to run this study again.

In this final study I decided it would be hard to fully measure the effects of active touch while also measuring the effects of passive touch. Because I already conducted a study on active touch gropability, I focused more heavily on the effect of adding passive touch to an input system. I did this by asking participants to aim for the correct touch. Point instead of "feeling" or groping for the touchpoint. As in the preliminary study described in Chapter 5, the addition of raised embroidery would still have some effect in aiding interaction if the participant missed a touchpoint when aiming, thus being able to find the nearest touch point. This interaction however is different from being able to feel along the surface of the fabric for the correct touch point. The textile itself also only senses

touch at the touch point, so when the participant moves across the surface of the fabric only the touches that land on a touch point are collected with time stamps in the data.

There are some also limitations that come with conducting a between participant study. It is hard to validate the results of the NASA Task Workload Index survey as the comparison in conditions are from answers between participants. NASA TLX surveys are really meant to be used in within subject comparison, where a single participant is asked the difference in workload between conditions. Even though it is hard to validate the outcomes of the surveys in this case, they are still helpful to provide some insight.

Also if I were to run this study again I would collect more physical data about the participants. For example forearm length and circumference would have been interesting to know per participant to see if there was any correlation in arm size to accuracy of interaction. One participant was 6'9" and the sleeve only took up half the distance from his wrist to his elbow. This participant's non-visual interaction accuracy was 72%. Was it the scale difference in regards to the participant's body that led to this lower accuracy?

Aside from physical body data, if I were to run the study again I would also collect more qualitative data as well, such as work life and leisure activities. During conversations with participants I could see were performing with better accuracy in real time through the WIFI connection I anecdotally noticed that some of these participants played musical instruments (guitars). For example participant ID30 played a number of stringed instruments and keyboard, he is 31 years old and had a non-visual accuracy of 88%. It

would be interesting to perhaps see if involvement in occupations or hobbies that utilize non-visual proprioceptive skills lead to transferring those skills to on-body interfaces like the one I was using for our research

Another limitation of the study comes in the form of learning. It seems that participants who had the visual interaction round first did somewhat better on their non-visual interaction round (Table 6).

Table 6: Accuracy of Interactions of Non-Visual Interaction Rounds

Condition	Non-Visual 1st Round	Non-Visual 2nd Round
1	78.01%	79.71%
2	77.46%	81.03%
3	74.88%	80.02%
4	85.42%	87.78%

I tried to minimize the effect of participants learning to use the system by not giving feedback about the correctness of the selections made. This seems to have worked. Figures 48 and 49 show that across conditions there seems to have been little to no learning during the non-visual interaction rounds. Another way of describing this is that participants did not get better while using the system without visual attention.
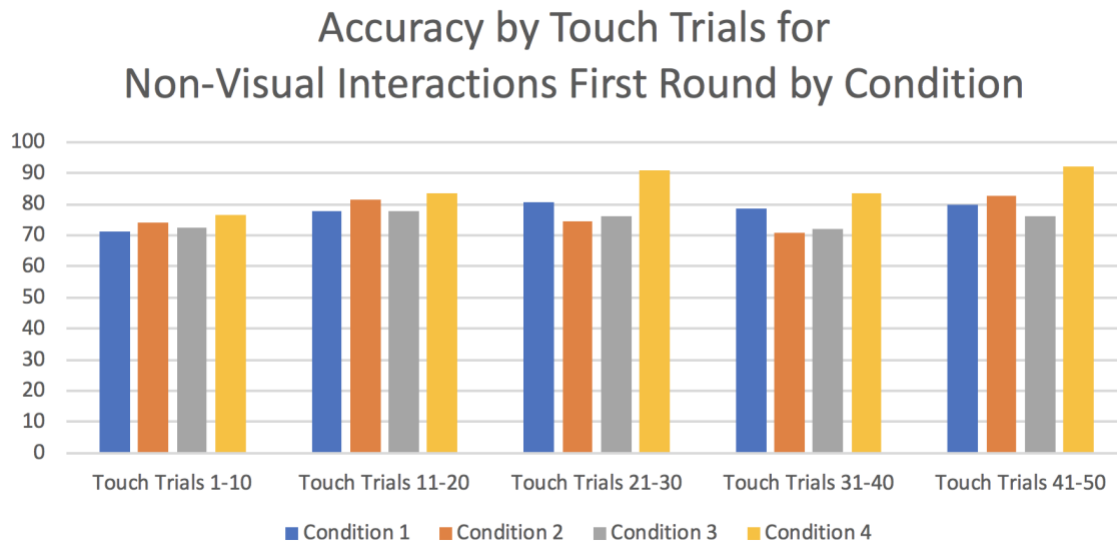
Figure 48: This graph shows the accuracy of non-visual first round interactions. Colors denote conditions. Each bin is a group of 10 touch interactions starting with the earliest interactions moving to the last interactions.
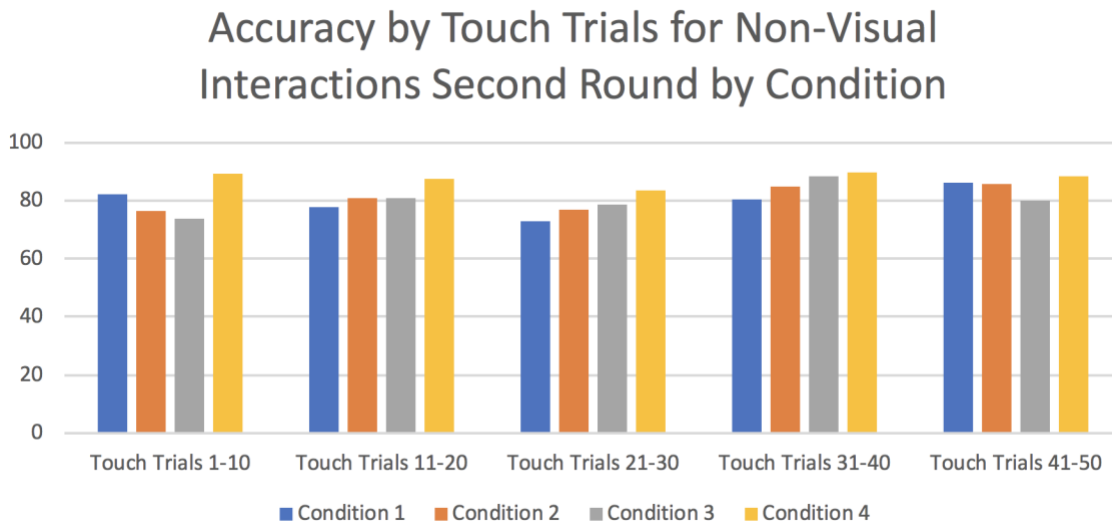
Figure 49: This graph shows the accuracy of non-visual second round interactions. Colors denote conditions. Each bin is a group of 10 touch interactions starting with the earliest interactions moving to the last interactions.
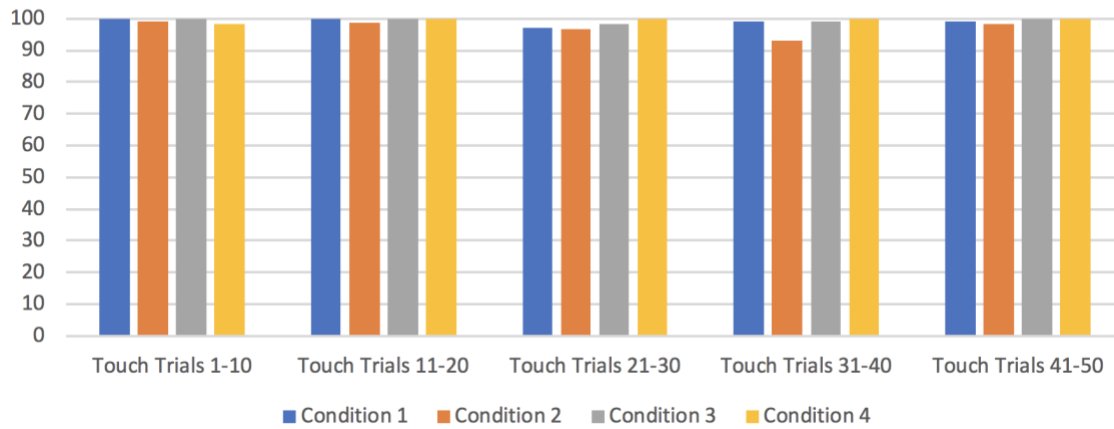
Figure 50: This graph shows the accuracy of visual first round interactions. Colors denote conditions. Each bin is a group of 10 touch interactions starting with the earliest interactions moving to the last interactions.
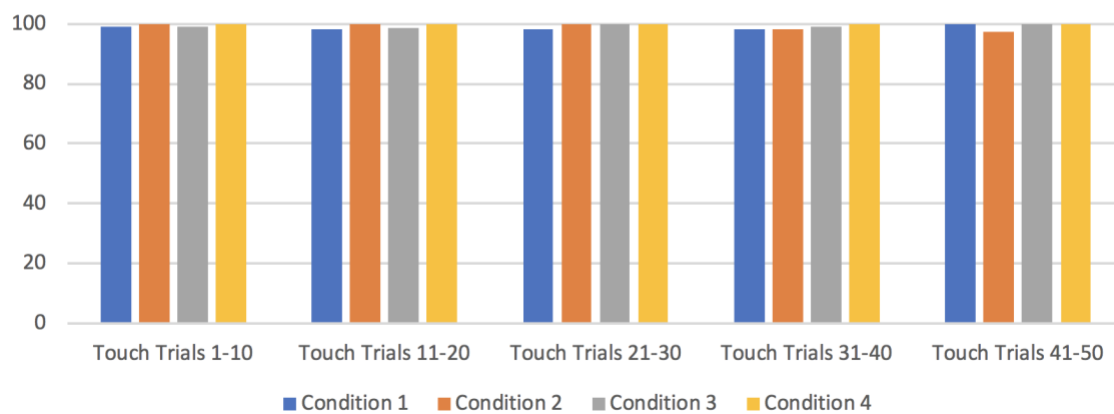
Figure 51: This graph shows the accuracy of visual second round interactions. Colors denote conditions. Each bin is a group of 10 touch interactions starting with the earliest interactions moving to the last interactions.

It is hard to tell if participants got better during the visual condition, because interactions in the visual condition are consistently near perfect (Figures 48 and 51). Because second round non-visual interactions are better than first round interactions I can assume that participants did learn while interacting with the system visually. Even though the system does not give a correct response feedback during the visual condition the participants can visually confirm they have selected the correct response. For the first round visual participants the visual confirmation coupled with the motor repetition of interacting correctly with the touchpoints over 50 interactions likely helped them learn to use the system better before their non-visual round.

6.3.4   Lessons Learned

I learned some valuable lessons for future research while conducting the experiment described in this chapter.

- PDIs using vibro-tactile stimulation do increase the accuracy of using an on-body electronic textile interface system, and when the vibration is presented right before it also makes the time to touch quicker as well.

- Individuals' sense of kinaesthetic proprioception is drastically different from one person to the next. For the purpose of designing studies researching proprioception, it would be better to study fewer conditions as a within-subject study. For the purpose of designing PDI wearable interfaces, designers cannot rely on every individual to have a great sense of proprioception.

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- Because of the increased accuracy of touch points at the edge condition of wearable on-body interfaces, designers might want to place the most used and most important interaction points at the edges. Conversely, "dangerous" interactions with more severe consequences for accidental activations should be mapped to middle touch points.

- Metal static nubs are not effective for aiding in passive touch location of wearable interfaces, because the body habituates to the sensation of the nub against the skin and masks its effect. The fabric nubs in the preliminary were more successful, perhaps a study should be completed about the texture of the static nub and its effects.

- Users believe that fabric based interfaces have low mental, physical, and temporal demand. They also seem to believe that they don't take too much effort, and are not that frustrating to use. However, they are only somewhat confident in the accuracy of their non-visual interactions.

6.4   Impact of Active Touch / Passive Touch Combination Usability Study

The research study in this chapter answers my third research question. ***Can combining active and passive touch techniques aid in making on-body textile interfaces easier to locate and use, more accurate, and quicker than interfaces without such affordances?***

This was *an assessment (through usability studies) as to whether proprioceptive display of on-body interface PDI location through vibro-tactile stimulation aids in finding and using interfaces on the body, allowing designers to create designs with quicker and more accurate interactions. (*contribution).* I found that only adding static passive touch metal snap nubs was not as effective as adding a vibro-tactile display before interaction. Proprioceptive display of on-body interface location through vibro-tactile stimulation does aid in finding and using interfaces on the body. The addition of active touch and passive touch with vibration creates an almost 8% improvement in accuracy as it also reduces time to touch by an average of almost .4 seconds (22% faster) over a flat fabric interface.

Chapter 7

Design Guidelines for Textile-Based On-Body Interfaces

What follows is a distillation of the information provided in this dissertation into a concise set of *guidelines and considerations for producing textile based interfaces for on-body wearable technology interactions (*contribution)* for designers to use as a reference in their design process for on-body interfaces.

- **Proprioceptively Displayed Interfaces (PDIs) that present passive touch vibro-tactile stimulation at the location of touch interaction points aid in accuracy of using the on-body interface and the time to touch (access time).** This guideline is derived from the active touch / passive touch combination study presented in Chapter 6.

- **Vibration used in Proprioceptively Displayed Interfaces to locate touch points should be temporally spaced between touch point vibration.** In the study presented in Chapter 6 the vibration was spaced by 300 milliseconds. Vibrating motors should not temporally overlap in vibration. Participants in a vibro-tactile preference study had a more difficult time distinguishing between touch points if more than one motor was vibrating at the same time. This finding is also reinforced in academic literature reviewed to make the Passive Touch Body Map in Chapter 2.

- **Including different vibration patterns for different touch points aids in distinguishing between touch points**. Participants in a vibro-tactile preference study said they felt like they could distinguish between touch point locations better when all the vibration patterns were not identical.

- **Passive touch metal 'nubs' or static (non-vibrating) projections against the skin do not seem to produce a lasting sensation against the skin.** The human body habituates to the presence of these 'nubs' and masks the sensation. The masking or habituation of the sensation of the nub is expected as revealed from academic literature reviewed to make the Passive Touch Body Map in Chapter 2. The study in Chapter 6 also showed that after some time the presence of the nub against the skin did not help improve the accuracy of using the system.

- **The edge selections of on-body interfaces (in this case touch point 1 and 5) have better non-visual accuracy of use than selection points in the middle of an interface. Perhaps place more frequently used selections and those selections with a tendency to be used with non-visual attention for a system in these locations.** This guideline is derived from analyzing the data collected from the final study in Chapter 6. Touch points on the edges of the interface were more accurately selected when prompted, touch points in the center or middle of the interface had the worst accuracy in non-visual conditions.

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- **Raised embroidery or other raised surfaces on an on-body electronic textile interface can aid in active touch investigation.** Active touch can produce a higher accuracy in using an interface when a user is given time to feel across the surface of the interface. In such cases a dwell time of 400 milliseconds is recommended for a touch point selection. This research on active touch (gropable) embroidered additions to on-body textile-based interfaces can be found in Chapter 4. [48]

- **Multi-touch interfaces, or those on-body interfaces that include an anchor (using the thumb to hold on a touch point for activation) have better accuracy of use.** This research on active touch (gropable) embroidered additions to on-body textile-based interfaces can be found in Chapter 4. Part of the "Is it gropable" study was to compare multi-touch interfaces with single touch interfaces. [48]

- **On-body location of electronic textile interfaces can be a complicated choice involving many factors specific to the intended use of the interface.** I created an extensive resource simplified and synthesized for designers called Wearable Technology Body Maps and it is available to help in choosing on-body location when working through a design process. [111, 113]. A selection of the Wearable Technology Body Maps specific to Proprioceptively Displayed Interfaces can be found in Chapter 2.

Chapter 8

Conclusion and Future Work

8.1 Conclusion

In conclusion I believe I have shown my thesis **that through the combination of active and passive touch in the form of Proprioceptively Displayed Interfaces PDIs, wearable textile-based on-body input interfaces will be faster in access time, more accurate, and easier to use** to be true. I have done so by answering three main research questions.

I have demonstrated *effective techniques to create and design on-body textile-based interfaces that are robust, reliable, and accurate* by using these *tested techniques and processes for creating embroidered interfaces for on-body touch based interactions (*contribution)*

I have also shown that *active touch embroidery aids in making on-body interfaces more accurate and quicker to interact with than interfaces without such affordances*. I have done this through user studies and by using *prototype textile interface artifacts such as the Electronic Textile Interface Swatch Book, The Hood (e-textile garment music controller), and Le Monstré (an interactive participatory performance garment) (*contribution)* I have shown that textile-based on-body interfaces using active touch are

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also of interest to designers, artists, dancers, and musicians. These prototypes have also been shown to work "in the wild" with case studies and descriptions of use published in academic conferences [114, 116]

I have also confirmed that **combining active and passive touch techniques aid in making on-body textile interfaces easier to locate and use, more accurate, and quicker than interfaces without such affordances.** I did this by conducting *an assessment (through usability studies) as to whether proprioceptive display of on-body interface location through vibro-tactile stimulation aids in finding and using interfaces on the body, allowing designers to create designs with quicker and more accurate interactions. (*contribution).*

Finally I created a concise set of *guidelines and considerations for producing textile based interfaces for on-body wearable technology interactions (*contribution)*.

8.2   Future Work

8.2.1 Possible Applications

There are many potential uses for PDIs outside of the initial motivating applications of mainstream commercial products and accessible interfaces for people with visual impairments as outlined in Chapter 1. I thought it might be useful to highlight some areas where I would be very interested in seeing the research from this dissertation being applied.

Emergency Responders

Emergency responders such as fire fighters are a group that would benefit from PDIs, as the interface could be controlled without seeing the interface. If a fire fighter within a building needs to relay information to a counterpart outside the building without voice contact, in noisy and low visibility situations, an on-body interface could be a life-saving tool. [102] The addition of vibration within the PDI could aid the firefighter in accurately making selections even while wearing gloves.

G-Force and Zero Gravity

Yet another application of PDIs could be in-flight suits for both pilots and astronauts. It could prove easier for an astronaut or pilot to slide their hand up against their own body, instead of reaching out against the force of launch to reach a specific button on a vehicle-mounted interface. The textile-based interfaces I have researched might also have a greater resistance to the vibration created in launches. The on-body interfaces will surely be lighter than their hard-cased environment mounted counterparts, which is also a great cost benefit when sending these interfaces into space. In a microgravity scenario, pushing against oneself would be much easier than pushing against another object as it is an internal force.

Figure 52 - Astronauts have to deal with opposite extremes of force against the body, from lift off to microgravity. Proprioceptively Displayed Interfaces may be easier to interact with in such situations rather than a vehicle mounted interface. (photos used from NASA.gov are not copyrighted)

Gravity also helps us interact with objects: without gravity to help rest hands against a keyboard, the muscles in the arms and hands must work harder to stay in the correct position to type [65]. Without gravity to hold our feet against the ground, microgravity also creates a circumstance where a person's orientation with their environment is always in question. Having a PDI solves many microgravity problems. It would always be within reach and easily found through the body proprioception and the affordances offered through the PDI.

8.2.1 Future Research

There are a number of directions I am interested in exploring stemming from the work in this dissertation.

Analyzing accelerometer data that was collected for this study, but not needed to prove the thesis, is a clear next step in investigating how people use PDIs and on-body interfaces. Could how a person moves to interact with the system affect time and accuracy? With additional funding and a collaboration with a machine learning expert there could be interesting insights to still come from data already collected.

There are also other interesting topics to be investigated through user studies with regards to PDIs such as:

- What types of vibration patterns work best for signifying touch point location through passive touch?

- What effect does body shape (body mass index, length of arm, muscle tone) have on vibro-tactile stimulation when used to locate touch points?

- What effect does training and practicing with musical instruments or other devices that are used with non-visual interaction have on an individual's ability to interact non-visually with a PDI.

Aside from the human factors user studies that could be an extension of this work, I feel that there could be some more qualitative studies about people's experiences using PDIs. As one of my motivating applications was to create PDIs in a way to make them useful

for people with visual impairments, I think that I should let people with visual impairments use a PDI and give feedback. Another study could incorporate both people with visual impairments and sighted individuals to understand if the public might view the use of PDIs as an assistive device, or just a piece of wearable technology.

Also I believe the body maps and design guidelines could be reconfigured as a web application. Such a web application could serve as an entryway for designers to create appropriately placed wearable technology, while also utilizing research in their design process. I imagine an interface that would build a heat map of on-body location as designers made choices specific to the use of their device. This web application could also be built to study the types of disciplines interested in designing wearable technology, and how this type of tool might help transdisciplinary collaboration.

APPENDIX A: RESEARCH CHART

Research Questions	Lab Tests / Designs	Active Touch	Swatch Book	Design Work	Passive Touch Preliminary Study	Active Touch / Passive Touch Final Study
R1 - What are the techniques to create and design on-body textile-based interfaces that are robust, reliable and accurate? Chapter 3.	Embroidery vs print tests. Thread and Machine tests including new tension arms etc.. Wash tests	Designing prototypes for study initiates textile work, making a conductive thread interface an interactive system.	Helped create new sensing technique best for on-body interactions..	Designed new textures, and used new materials for added robustness needed in performance		
Methods	In lab material tests for viability. Design iterations.	In lab material tests for viability. Design iterationsl	In lab material tests for viability. Design iterations.	In lab material tests for viability. Design iterations.		
Assessments	Working prototypes	Working study equipment	Working prototype	Working prototypes		Working prototypes
Contributions	Durability results of construction methods / Multi-layer embroidered connections, printing methods for etching piezo electric material for use in textiles, embroidery and embellishment combination for sensing movement / validation of knitted techniques.					
Papers	"Can I Wash It" Zeagler et al. 2013 // "Textile Interfaces" Zeagler 2012 et al. // "Etextile Knee Sleeve" Byrne et al. 2013 / / "Sensor for Tilt Angle" Lee et al. 2016 Patent					
R2 - Can active touch aid in making on-body textile interfaces more accurate and quicker to interact with than interfaces without such affordances? Chapter 4		Study specific to answer if the gropability of textiles aids in non visual interaction (active touch)	Designs and workshops showing the use of embroidered textiles by designers	Using the swatch book and textile techniques gained working with designers to validate usefulness // Also social acceptability study to see how to design interactions for public. Investigating on-body location of interfaces.		
Methods		User study	In lab test and qualitative observation / feedback	Qualitative from design case studies. Literature review and synthesis	User study	User study
Assessments		Data from user study	Proof of concept usability testing / feedback from participants.		Observations from preliminary study.	Data from user study.
Contributions		Human factors study that shows improved accuracy with multi touch embroidered interfaces, and the ability to use an Active Touch embroidered interface using specific current leakage sensing technique.	Variation of embroidered interfaces using active touch and designed for interactions mimicking known GUI interfaces. Feedback from designers about interfaces, building an understanding of how to present this work to the design community.	Use case scenarios using design tools (ESwatchBook) developed to aid in creating textile on-body interfaces, and framing interdisciplinary wearable tech work within HCI concept of boundary objects / Design process development for wearable technology / New tools for designers to help in aiding on-body location decisions developed from synthesis of literature, including passive and active touch / Social acceptability of on-body interactions at different body locations.		
Papers		"Is it Gropable" Komor et al. 2009	"Textile Interface Swatch Book" Gilliland et al. 2010 // "Electronic Textile Interface Workshop" Zeagler et al. 2013	"In Harmony" Zeagler et al. 2017 // "Policy Design Framework" Baker et al. 2015 // "Imagining Futures" Gandy et al. 2016 // Body Maps Zeagler 2017a // "Where to Wear It" Zeagler 2017b // "Don't' mind me touching my wrist" Profita et al. 2013 // "Social Comfort of Wearable Tech" Dunne et al. 2014 // "The Assistive Wearable: Inclusive by Design" Zeagler et al. 2018		
R3 - Can combining active and passive touch techniques aid in making on-body textile interfaces easier to locate and use, more accurate, and quicker than interfaces without such affordances? Chapter 5 & 6.					On-body simple touch target testing with and without passive touch stimulation	On-body touch target testing between four conditions with 104 participants. Testing prototype was developed using techniques learned in R1 and R2.
Methods					User study	User study
Assessments					Data from user study	Data from user study
Contributions					Results from preliminary study show that non-visual target touching of an on-body location is more accurate with the addition of passive touch (non-vibrating nub against the skin).	Results from study show that non-visual target touching of an on-body location is more accurate with the addition of active and passive touch including vibro-tactile display. Design Guidelines Chapter 7
Papers						

REFERENCES

[1]   AB-004 : UNDERSTANDING ERM VIBRATION MOTOR
        CHARACTERISTICS: *https://www.precisionmicrodrives.com/application-
        notes/ab-004-understanding-erm-vibration-motor-characteristics*. Accessed:
        2017-02-06.

[2]   AB-020 : UNDERSTANDING LINEAR RESONANT ACTUATOR
        CHARACTERISTICS: *https://www.precisionmicrodrives.com/application-
        notes/ab-020-understanding-linear-resonant-actuator-characteristics*. Accessed:
        2017-07-02.

[3]   Ashbrook, D.L., Clawson, J.R., Lyons, K., Patel, N. and Starner, T. 2008.
        Quickdraw: the impact of mobility and on-body placement on device access time.
        Proceedings of CHI 2008. (2008), 219–222.
        DOI:https://doi.org/10.1145/1357054.1357092.

[4]   Baker, P.M.A.P.M.A., Gandy, M. and Zeagler, C. 2015. Innovation and Wearable
        Computing: A Proposed Collaborative Policy Design Framework. *IEEE Internet
        Computing*. 19, Sept.-Oct. 2015 (2015), 18–25.
        DOI:https://doi.org/10.1109/MIC.2015.74.

[5]   Benedetti, F. 1988. Localization of tactile stimuli and body parts in space: two
        dissociated perceptual experiences revealed by a lack of constancy in the presence
        of position sense and motor activity. *Journal of experimental psychology. Human
        perception and performance*. 14, 1 (1988), 69–76.
        DOI:https://doi.org/10.1037/0096-1523.14.1.69.

[6]   Benford, S., Greenhalgh, C., Crabtree, A., Flintham, M., Walker, B., Marshall, J.,
        Koleva, B., Egglestone, S.R., Giannachi, G., Adams, M., Tandavanitj, N. and Farr,
        J.R. 2013. Performance-Led Research in the Wild. *ACM Transactions on
        Computer-Human Interaction*. 20, 3 (2013), 14:1-14:22.
        DOI:https://doi.org/10.1145/2491500.2491502.

[7]   Bensmaia, S.J., Leung, Y.Y., Hsiao, S.S. and Johnson, K.O. 2005. Vibratory
        Adaptation of Cutaneous Mechanoreceptive Afferents. *Journal of
        Neurophysiology*. 94, 5 (2005), 3023–3036.
        DOI:https://doi.org/10.1152/jn.00002.2005.

[8]   Brown, L.M., Brewster, S. a. and Purchase, H.C. 2006. Multidimensional Tactons
        for Non-Visual Information Presentation in Mobile Devices. *Proceedings of the
        8th conference on Human-computer interaction with mobile devices and services -
        MobileHCI '06*. 159, September (2006), 231–238.
        DOI:https://doi.org/10.1145/1152215.1152265.

[9]   Buechley, L. 2006. A Construction Kit for Electronic Textiles. *2006 10th IEEE International Symposium on Wearable Computers*. (Oct. 2006), 83–90. DOI:https://doi.org/10.1109/ISWC.2006.286348.

[10]   Byrne, C.A., Rebola, C.B.C.B. and Zeagler, C. 2013. Design research methods to understand user needs for an etextile knee sleeve. *Proceedings of the 31st ACM international conference on Design of communication - SIGDOC '13*. (2013), 17. DOI:https://doi.org/10.1145/2507065.2507085.

[11]   Capraro, A.J., Verrillo, R.T. and Zwislocki, J.J. 1979. Psychophysical evidence for a triplex system of cutaneous mechanoreception. *Sensory Processes*. 3, (1979), 340–352.

[12]   Chipchase, J., Persson, P., Piippo, P., Aarras, M. and Yamamoto, T. 2005. Mobile essentials: field study and concepting. *DUX '05 Proceedings of the 2005 conference on Designing for User eXperience*. (2005), 57.

[13]   Cholewiak, R.W. and Collins, a a 1995. Vibrotactile pattern discrimination and communality at several body sites. *Perception & psychophysics*. 57, 6 (1995), 724–737. DOI:https://doi.org/10.3758/BF03213276.

[14]   Cochran, Z., Zeagler, C. and McCall, S. 2015. Addressing Dresses: User Interface Allowing for Interdisciplinary Design and Calibration of LED Embedded Garments. *ISWC '15 Proceedings of the 2015 ACM International Symposium on Wearable Computers* (2015), 61–64.

[15]   Craig, J.C. 2002. Identification of scanned and static tactile patterns. *Perception & psychophysics*. 64, 1 (2002), 107–20. DOI:https://doi.org/10.3758/BF03194560.

[16]   Craig, J.C. 1983. Some Factors Affecting Tactile Pattern Recognition. *international journal of neuroscience*. 19, 1–4 (1983), 47–57.

[17]   Craig, J.C. 1985. Tactile pattern perception and its perturbations. *The Journal of the Acoustical Society of America*. 77, 1 (1985), 238. DOI:https://doi.org/10.1121/1.392265.

[18]   Craig, J.C. and Evans, P.M. 1987. Vibrotactile masking and the persistence of tactual features. *Perception & psychophysics*. 42, 4 (1987), 309–317. DOI:https://doi.org/10.3758/BF03203085.

[19]   Cui, Y. and Roto, V. 2008. How people use the web on mobile devices. *Proceeding of the 17th international conference on World Wide Web*. (2008), 905. DOI:https://doi.org/10.1145/1367497.1367619.

[20]   Dunne, L., Profita, H. and Zeagler, C. 2014. Social Aspects of Wearability and Interaction. *Wearable Sensors: Fundamentals, Implementation and Applications*. E. Sazonov and M. Neuman, eds. Elsevier Inc. 25–43.

[21]   Dunne, L.E.L.E., Profita, H., Zeagler, C., Clawson, J., Gilliland, S., Do, E.Y. i
        L.E.Y.-L. and Budd, J. 2014. The social comfort of wearable technology and
        gestural interaction. *Annual International Conference of the IEEE Engineering in
        Medicine and Biology Society. I* (2014), 4159–4162.

[22]   van Erp, J.B.F. 2002. Guidelines for the Use of Vibro-Tactile Displays in Human
        Computer Interaction. *Proceedings of Eurohaptics*. (2002), 18–22.
        DOI:https://doi.org/10.1016/j.ajodo.2008.04.017.

[23]   van Erp, J.B.F. and Toet, A. 2015. Social touch in human-computer interaction.
        Frontiers in Digital Humanities. 2, 2 (2015), 1–14.
        DOI:https://doi.org/10.3389/fdigh.2015.00002.

[24]   Feygin, D., Keehner, M. and Tendick, R. 2002. Haptic guidance: experimental
        evaluation of a haptic training\nmethod for a perceptual motor skill. *Proceedings
        10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator
        Systems. HAPTICS 2002*. March (2002), 40–47.
        DOI:https://doi.org/10.1109/HAPTIC.2002.998939.

[25]   Fitts, P.M.P. 1954. The Information Capacity of the Human Motor System in
        Controlling the Amplitude of Movement. *Journal of experimental psychology*. 47,
        6 (1954), 381–391. DOI:https://doi.org/10.1037/h0055392.

[26]   Gallace, A., Tan, H.Z. and Spence, C. 2007. The Body Surface as a
        Communication System: The State of the Art after 50 Years. *Presence:
        Teleoperators and Virtual Environments*. 16, 6 (2007), 655–676.
        DOI:https://doi.org/10.1162/pres.16.6.655.

[27]   Gandy, M., Baker, P.M.A.P.M.A. and Zeagler, C. 2016. Imagining futures: A
        collaborative policy/device design for wearable computing. *Futures*. 87, (2016),
        106–121. DOI:https://doi.org/10.1016/j.futures.2016.11.004.

[28]   Geldard, F.A. and Sherrick, C.E. 1972. The cutaneous "rabbit": a perceptual
        illusion. *Science*. 178, (1972), 178–179.

[29]   Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M. and Martin, R. 1998. Design
        for wearability. *Digest of Papers. Second International Symposium on Wearable
        Computers* (1998).

[30]   Gescheider, G.A., Bolanowski, S.J., Verrillo, R.T., Arpajian, D.J. and Ryan, T.F.
        1990. Vibrotactile intensity discrimination measured by three methods. *The
        Journal of the Acoustical Society of America*. 87, 1 (1990), 330–338.
        DOI:https://doi.org/10.1121/1.399300.

[31]   Gibson, J. 1962. Observations on active touch. *Psychological review*. 69, 6 (1962),
        477–491. DOI:https://doi.org/10.1037/h0046962.

[32] Gilliland, S., Komor, N., Starner, T. and Zeagler, C. 2010. The textile interface swatchbook: Creating graphical user interface-like widgets with conductive embroidery. *Proceedings - International Symposium on Wearable Computers, ISWC* (2010).

[33] Goffman, E. 1959. *The presentation of self in everyday life.*

[34] Gopalsamy, C., Park, S., Rajamanickam, R. and Jayaraman, S. 1999. The Wearable MotherboardTM : The First Generation Responsive Textile Structures Medical Applications. (1999), 152–168.

[35] Hall, E.T. 1990. *The Hidden Dimension.*

[36] Hall, S.P. and Hao, Y. 2006. Antennas and propagation for body centerric wireless communication. *Proceedings EuCAP 2006* (Nice, France, 2006).

[37] Hanson, M.A., Powell, H.C., Barth, A.T., Ringgenberg, K., Calhoun, B.H., Aylor, J.H. and Lach, J. 2009. Body Area Sensor Networks: Challenges and Opportunities. *Computer*. 42, 1 (2009), 58–65. DOI:https://doi.org/10.1109/MC.2009.5.

[38] Harrison, C., Benko, H. and Wilson, A.D. 2011. OmniTouch. *Proceedings of the 24th annual ACM symposium on User interface software and technology - UIST '11*. (2011), 441. DOI:https://doi.org/10.1145/2047196.2047255.

[39] Harrison, C., Lim, B.Y., Shick, A. and Hudson, S.E. 2009. Where to Locate Wearable Displays? Reaction Time Performance of Visual Alerts from Tip to Toe. *Proceedings of the 27th Annual SIGCHI Conference on Human Factors in Computing Systems*. (2009), 941–944. DOI:https://doi.org/10.1145/1518701.1518845.

[40] Harrison, C., Ramamurthy, S. and Hudson, S.E. 2012. On-body interaction: armed and dangerous. *Proceedings of TEI 2012*. (2012), 69–76. DOI:https://doi.org/10.1145/2148131.2148148.

[41] Hoggan, E., Brewster, S.A. and Johnston, J. 2008. Investigating the Effectiveness of Tactile Feedback for Mobile Touchscreens. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. (2008), 1573–1582. DOI:https://doi.org/10.1145/1357054.1357300.

[42] Holleis, P., Schmidt, A., Paasovaara, S., Puikkonen, A. and Häkkilä, J. 2008. Evaluating capacitive touch input on clothes. *MobileHCI '08*. (2008), 81–90. DOI:https://doi.org/10.1145/1409240.1409250.

[43] Huang, K., Starner, T., Do, E., Weinberg, G., Tech, G., Kohlsdorf, D., Ahlrichs, C. and Leibrandt, R. 2010. Mobile Music Touch : Mobile Tactile Stimulation For Passive Learning. (2010), 791–800.

[44] Jacquard by Google: *https://atap.google.com/jacquard/*.

[45] Jones, S.J. 2005. *Fashion Design*. Watson-Guptill Publications.

[46] Joseph-Armstrong, H. 2000. *Pattern Making for Fashion Design*. Prentice Hall.

[47] Kirman, J.H. 1974. Tactile Apparent Movement: the Effects of Number of Stimulators. *Journal of Experimental Psychology*. 103, 6 (1974), 1175–1180. DOI:https://doi.org/10.3758/BF03205819.

[48] Komor, N., Gilliland, S., Clawson, J., Bhardwaj, M., Garg, M., Zeagler, C. and Starner, T. 2009. Is It Gropable?–Assessing the Impact of Mobility on Textile Interfaces. *International Symposium on Wearable Computers, ISWC* (2009), 71–74.

[49] Konyo, M. 2005. A tactile synthesis method using multiple frequency vibrations for representing virtual touch.pdf. (2005), 1121–1127.

[50] Konyo, M., Akazawa, K., Tadokoro, S. and Takamori, T. 2003. Tactile Feel Display for Virtual Active Touch. *Proceedings of the 2003 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems* (2003), 3744–3750.

[51] Konyo, M., Tadokoro, S. and Takamori, T. 2000. Artificial Tactile Fell Display Using Soft Gel Actuators. *Proc. of the 2000 IEEE International Conference on Robotics & Automation*. April (2000), 3416–3421.

[52] Koskinen, E., Kaaresoja, T. and Laitinen, P. 2008. Feel-good touch: finding the most pleasant tactile feedback for a mobile touch screen button. *Proceedings of the 10th international conference on Multimodal interfaces*. (2008), 297–304. DOI:https://doi.org/10.1145/1452392.1452453.

[53] Kruijff, E., Schmalstieg, D. and Beckhaus, S. 2006. Using neuromuscular electrical stimulation for pseudo-haptic feedback. *Proceedings of the ACM symposium on Virtual reality software and technology - VRST '06*. (2006), 316. DOI:https://doi.org/10.1145/1180495.1180558.

[54] Kyung, K.U., Lee, J.Y. and Park, J. 2008. Haptic stylus and empirical studies on braille, button, and texture display. *Journal of Biomedicine and Biotechnology*. 2008, 1 (2008). DOI:https://doi.org/10.1155/2008/369651.

[55] Lee, H.S., Shin, H.C., Starner, T.E., Gilliland, S.M. and Zeagler, C. 2016. Sensor for measuring tilt angle based on electronic textile and method thereof. US Patent 9316481. 2016.

[56] Lee, S. 2012. *Buzzwear: Supporting multitasking with wearable tactile displays on the wrist.*

[57]   Lilypad Arduino: *https://www.arduino.cc/en/Main/ArduinoBoardLilyPad*.

[58]   Loomis, J.M. and Lederman, S.J. 1986. Tactual Perception. *Handbook of Perception and Human Performance*.

[59]   Loomis, J.M. and Lederman, S.J. 1984. What utility is there in distinguishing between active and passive touch? *presentation at Psychonomic Society meeting* (1984).

[60]   MacKenzie, I.S. 2009. Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *Human–Computer Interaction*. 7, 1 (Nov. 2009), 91–139. DOI:https://doi.org/10.1207/s15327051hci0701_3.

[61]   Mancini, F., Bauleo, A., Cole, J., Lui, F., Porro, C.A., Haggard, P. and Iannetti, G.D. 2014. Whole-body mapping of spatial acuity for pain and touch. *Annals of Neurology*. 75, 6 (2014), 917–924. DOI:https://doi.org/10.1002/ana.24179.

[62]   Marculescu, D. and Marculescu, R. 2003. Electronic textiles: A platform for pervasive computing. *Proceedings of the IEEE*. 91, 12 (2003), 1995–2018.

[63]   Markow, T., Ramakrishnan, N., Huang, K., Starner, T., Schooler, C. and Tarun, A. 2010. Mobile Music Touch : Vibration Stimulus in Hand Rehabilitation. *Pervasive Computing Technologies for Healthcare (PervasiveHealth)* (Munich, 2010), 1–8.

[64]   Martin, T., Kim, K., Forsyth, J., McNair, L., Coupey, E. and Dorsa, E. 2011. An interdisciplinary undergraduate design course for wearable and pervasive computing products. *Proceedings - International Symposium on Wearable Computers, ISWC*. (2011), 61–68. DOI:https://doi.org/10.1109/ISWC.2011.13.

[65]   Matias, E., Mackenzie, I.S. and Buxton, W. 1996. A wearable computer for use in microgravity space and other non-desktop environments. *in Companion of the Chi'96 Conference on Human Factors in Computing Systems*. 69, (1996), 69–70. DOI:https://doi.org/10.1145/257089.257146.

[66]   Movassaghi, S., Abolhasan, M., Lipman, J., Smith, D. and Jamalipour, A. 2014. Wireless Body Area Networks: A Survey. *Ieee Communications Surveys and Tutorials*. 16, 3 (2014), 1658–1686. DOI:https://doi.org/10.1109/surv.2013.121313.00064.

[67]   NASA-TLX Workload: *https://humansystems.arc.nasa.gov/groups/TLX/*.

[68]   Nolan, M.F. 1982. Two-Point Discrimination Assessment in the Upper Limb in Young-Adult Men and Women. *Physical Therapy*. 62, 7 (1982), 965–969.

[69]   Norman, D. 2005. *Emotional Design: Why We Love (or Hate) Everyday Things*. Basic Books.

[70] Norman, D.A. 2013. *The Design of Everyday Things*.

[71] Oakley, I., Kim, Y., Lee, J. and Ryu, J. 2006. Determining the feasibility of forearm mounted vibrotactile displays. *Proceedings - IEEE Virtual Reality*. 2006, (2006), 74. DOI:https://doi.org/10.1109/VR.2006.49.

[72] Pasquero, J. 2006. Survey on communication through touch. *Center for Intelligent Machines-McGill University, Tech. Rep. TR-CIM*. 6, August (2006), 1–28.

[73] Patel, M. and Wang, J. 2010. APPLICATIONS, CHALLENGES, AND PROSPECTIVE IN EMERGING BODY AREA NETWORKING TECHNOLOGIES. *IEEE Wireless Communications*. 17, 1 (2010). DOI:https://doi.org/10.1109/MWC.2010.5416354.

[74] Patel, S.N., Kientz, J. a., Hayes, G.R., Bhat, S. and Abowd, G.D. 2006. Farther than you may think: An empirical investigation of the proximity of users to their mobile phones. *in Proceedings of UbiComp 2006: Ubiquitous Computing*. (2006), 123–140. DOI:https://doi.org/10.1007/11853565_8.

[75] Pobiner, S., Zeagler, C., Profita, H., Gilliland, S., LEE, H.S., Audy, S., Shin, H.C. and Starner, T. 2012. The Electronic Textile Interface Workshop: Scaffolding Communication Across Disciplines. *Designing Interactive Systems DIS* (Necastle, UK, 2012).

[76] Post, E.R. and Orth, M. 1997. Smart fabric, or "wearable clothing." *Digest of Papers. First International Symposium on Wearable Computers* (1997), 167–168.

[77] Post, E.R., Orth, M., Russo, P.R. and Gershenfeld, N. 2000. E-broidery: Design and fabrication of textile-based computing. *IBM Systems Journal*. 39, 3.4 (2000), 840–860. DOI:https://doi.org/10.1147/sj.393.0840.

[78] Post, E.R. and Waal, K. 2010. Electrostatic Power Harvesting in Textiles. *Proc. ESA Annual Meeting on Electrostatics*. (2010), 1–10.

[79] Profita, H.H., Clawson, J., Gilliland, S., Zeagler, C., Starner, T., Budd, J. and Do, E.Y.-L.E.Y.-L. 2013. Don't mind me touching my wrist: a case study of interacting with on-body technology in public. *Proceedings of the 17th annual International symposium on wearable computers - ISWC '13*. (2013), 89–96. DOI:https://doi.org/10.1145/2493988.2494331.

[80] Roebuck, J. 1968. A system of notation and measurement for space suit mobility evaluation. *Human Factors*. 10, 1 (1968), 79–94.

[81] Schiffman, H.R. 2001. The Skin Senses. *Sensation and Perception*. John Wiley & Sons, Inc. 412–449.

[82] Scribano, F., Bruns, M. and Baron, E.R. 1970. *DESIGN , DEVELOPMENT AND*

[83]   Seim, C., Chandler, J., DesPortes, K., Dhingra, S., Park, M. and Starner, T. 2014. Passive haptic learning of Braille typing. *Proceedings of the 2014 ACM International Symposium on Wearable Computers - ISWC '14*. (2014), 111–118. DOI:https://doi.org/10.1145/2634317.2634330.

[84]   Seim, C., Estes, T. and Starner, T. 2015. Towards Passive Haptic Learning of piano songs. *IEEE World Haptics Conference, WHC 2015*. (2015), 445–450. DOI:https://doi.org/10.1109/WHC.2015.7177752.

[85]   Seim, C., Hallam, J., Raghu, S., Le, T., Bishop, G. and Starner, T. 2015. *Perception in Hand-Worn Haptics : Placement , Simultaneous Stimuli , and Vibration Motor Comparisons*.

[86]   Seim, C.E., Quigley, D. and Starner, T.E. 2014. Passive haptic learning of typing skills facilitated by wearable computers. *Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems - CHI EA '14*. (2014), 2203–2208. DOI:https://doi.org/10.1145/2559206.2581329.

[87]   Shaeffer, C.B. 2001. *Couture Sewing Techniques*. The Taunton Press.

[88]   Sherrick, C.E. 1968. Studies of apparent tactual movement. *The skin senses*. (1968), 331–344.

[89]   Shieldex Threads: *http://www.shieldextrading.net/products/yarns-threads/*. Accessed: 2017-03-31.

[90]   Soukoreff, R.W. and MacKenzie, I.S. 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. *International Journal of Human Computer Studies*. 61, 6 (2004), 751–789. DOI:https://doi.org/10.1016/j.ijhcs.2004.09.001.

[91]   Star, S. and Griesemer, J. 1989. Institutional Ecology, Translations' and Boundary Objects: Amateurs and Professionals in Berkley's Museum of Vertebrate Zoology. *Social studies of science*. (1989).

[92]   Starner, T. 2001. The Challenges of Wearable Computing: Part 2. *IEEE Micro*. 21, (2001), 54–67. DOI:https://doi.org/10.1109/40.946683.

[93]   Starner, T., Rhodes, B. and Weaver, J. 1999. Everyday-use Wearable Computers. Georgia Tech Technical Report.

[94]   Starner, T.E., Snoeck, C.M., Wong, B. a. and McGuire, R.M. 2004. Use of mobile appointment scheduling devices. *Extended abstracts of the 2004 conference on Human factors and computing systems - CHI '04*. (2004), 1501. DOI:https://doi.org/10.1145/985921.986100.

[95] Stein, R., Ferrero, S., Hetfield, M., Quinn, a. and Krichever, M. 1998. Development of a commercially successful wearable data collectionsystem. *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215)*. (1998). DOI:https://doi.org/10.1109/ISWC.1998.729525.

[96] Sullivan, S. 2016. *Designing for Wearables: Effective UX for Current and Future Devices*. O'Reilly Media.

[97] Tiley, A.R. and Henry Dreyfuss Associates 2001. *The Measure Of Man And Woman: Human Factors In Design*. John Wiley & Sons.

[98] Toney, A., Dunne, L., Thomas, B.H. and Ashdown, S.P. 2003. A shoulder pad insert vibrotactile display. *Seventh IEEE International Symposium on Wearable Computers, 2003. Proceedings*. (2003), 35–44. DOI:https://doi.org/10.1109/ISWC.2003.1241391.

[99] Ullah, S., Higgins, H., Braem, B., Latre, B., Blondia, C., Moerman, I., Saleem, S., Rahman, Z. and Kwak, K.S. 2012. A comprehensive survey of wireless body area networks on PHY, MAC, and network layers solutions. *Journal of Medical Systems*. 36, 3 (2012), 1065–1094. DOI:https://doi.org/10.1007/s10916-010-9571-3.

[100] Verillo, R.T. and Gescheider, G.A. 1977. Effect of prior stimulation on vibrotactile thresholds. *Sensory Processes*. 1 (1977), 292–300.

[101] Verrillo, R.. 1985. Psychophysics of vibrotactile stimulation. *The Journal of the Acoustical Society of America*. 77, 1 (1985), 225–232. DOI:https://doi.org/10.1121/1.392263.

[102] Verrillo, R.T. and Gescheider, G. a. 1975. Enhancement and summation in the perception of two successive vibrotactile stimuli. *Perception & Psychophysics*. 18, 2 (1975), 128–136. DOI:https://doi.org/10.3758/BF03204100.

[103] Walters, K., Lee, S., Starner, T., Leibrandt, R. and Lawo, M. 2010. Touchfire: Towards a glove-mounted tactile display for rendering temperature readings for firefighters. *Proceedings - International Symposium on Wearable Computers, ISWC*. (2010). DOI:https://doi.org/10.1109/ISWC.2010.5665862.

[104] Watkins, S.M. 1995. *Clothing: The Portable Environment*. Iowa State Press.

[105] Watkins, S.M. and Dunne, L.E. 2015. *Functional Clothing Design: From Sportswear to Spacesuits*. Bloomsbury Publishing.

[106] Wearable Technology Affordances Body Maps: 2017. *http://wcc.gatech.edu/content/wearable-technology-affordances-body-maps*. Accessed: 2017-11-04.

[107] Weber EH. *De subtilitate tactus*.

[108] Weinstein S. 1968. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. *The skin senses*. Kenshalo D.R., ed. 195–222.

[109] Weiser, M. 1991. The computer for the 21st century. *Scientific american*. (1991).

[110] Wolff, C. 1996. *The Art of Manipulating Fabric*. Krause Publications.

[111] Zeagler, C. 2017. Where to Wear It : Functional , Technical , and Social Considerations in On - Body Location for Wearable Technology 20 Years of Designing for Wearability. *International Symposium on Wearable Computers* (Maui, Hawaii, 2017).

[112] Zeagler, C., Audy, S., Pobiner, S., Profita, H., Gilliland, S. and Starner, T. 2013. The electronic textile interface workshop: Facilitating interdisciplinary collaboration. *International Symposium on Technology and Society, Proceedings*. (2013), 76–85. DOI:https://doi.org/10.1109/ISTAS.2013.6613105.

[113] Zeagler, C., Gandy, M. and Baker, P.M.A. 2018. The Assitive Wearable: Inclusive by Design. *Assistive Technology Outcomes & Benefits*. 12, (2018).

[114] Zeagler, C., Gandy, M., Gilliland, S., Moore, D., Centrella, R. and Montgomery, B. 2017. In Harmony: Making a wearable musical instrument as a case study of using boundary objects in an interdisciplinary collaborative design process. *DIS 2017 - Proceedings of the 2017 ACM Conference on Designing Interactive Systems* (Edinburgh, 2017).

[115] Zeagler, C., Gilliland, S., Audy, S. and Starner, T. 2013. Can I Wash It?: The Effect of Washing Conductive Materials Used in Making Textile Based Wearable Electronic Interfaces. *Proceedings of the 17th annual international symposium on International symposium on wearable computers - ISWC '13* (Zurich, Switzerland, 2013), 143.

[116] Zeagler, C., Gilliland, S., Fisher, K., Boyle, S. and Levy, L. 2017. Le Monstré: An interactive participatory performance costume. *Proceedings - International Symposium on Wearable Computers, ISWC* (2017).

[117] Zeagler, C., Gilliland, S. and Presti, P. 2015. Throwing Buddy: Solving Sensor Challenges Through Soft-Good Construction , Design , and Fabric Selection. *Ubicomp/ISWC '15* (Osaka, Japan, 2015), 1319–1325.

[118] Zeagler, C., Gilliland, S., Profita, H. and Starner, T. 2012. Textile interfaces: Embroidered jog-wheel, beaded tilt sensor, twisted pair ribbon, and sound sequins. *Proceedings - International Symposium on Wearable Computers, ISWC* (2012), 60–63.

[119] Zeagler, C., Starner, T., Hall, T. and Wong Sala, M. 2015. *Meeting the Challenge: The Path Towards a Consumer Wearable Computer*. Georgia Institute of Technology.

[120] Zhao, Y., Salunke, S., Leavitt, A., Curtin, K., Huynh, N., Zeagler, C., Salunke, S., Huynh, N., Leavitt, A. and Zeagler, C. 2016. E-Archery: Prototype Wearable for Analyzing Archery Release. *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing Adjunct - UbiComp '16*. (2016), 908–913. DOI:https://doi.org/10.1145/2968219.2968577.