THE DESIGN OF WEARABLE TECHNOLOGY: ADDRESSING THE HUMAN-DEVICE INTERFACE THROUGH FUNCTIONAL APPAREL DESIGN

A Thesis

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by

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ABSTRACT

Wearable technology, as a new application environment for electronic and computing devices of all kinds, presents many new challenges to designers. The fields of human-computer interaction and functional wearability must each address new problems in the design of wearable technology. Wearable technology also introduces new social concerns, as it can mediate the ways in which an individual is perceived by others, interacts with others, and manages his/her own physical space.

Because the field of wearable technology is very new, the design of wearable technology is still relatively unexplored. The dominant design culture in current wearable technology research, that of electrical engineering and computer science, is unused to addressing variables related to the human body, mind, and social interaction. Good design choices for wearable technology depend on understanding and acknowledging the wide array of interdisciplinary variables that affect user interaction with a wearable device. The functional apparel design culture brings an interdisciplinary approach to wearable technology design, and its structured design process offers designers a means of organizing and addressing issues, and identifying new variables to be considered in future work. This thesis seeks to use the functional apparel design process to approach the new variables involved in the interface between the body-mounted device and the human user in three areas: an input device (a bio-monitoring bra), an output device (a shoulder pad vibrotactile display), and the aesthetic and psychological issues of visual representation of technology (a set of massage shirts). These projects address physical, cognitive, and social user needs in wearable technology.

The development of the shoulder pad vibrotactile display sought to create an intuitive, visually subtle, physically comfortable tactile display device within a

standard garment insert, using the volume of the shoulder pad as an integration space. The evaluation process found the use of a pre-existing garment space such as the shoulder pad to be successful for the integration of electronics, and the device to be perceptible at a low level of resolution.

The bio-monitoring bra study evaluated several variables involved in the use of garment-integrated contact (not adhesive) electrodes for bio-monitoring, an input modality that creates a low cognitive load for the user. Garment-integrated electrodes were designed to replace the medical standard adhesive electrodes, to increase the physical and social comfort of the user. Contact electrodes were tested in both an EMG (muscle activity) configuration and in an ECG (heartbeat) configuration. The ECG configuration recorded a useable signal during periods of low activity level, but the EMG configuration was not able to capture useful muscle activity data.

A set of massage shirts was developed to investigate the varying social needs of users regarding the visual display of garment functionality. Two focus groups were conducted, and an application was chosen (shoulder and back massage) that was attractive and useful to subjects with a wide variety of personality types and aesthetic tastes. Three prototypes were constructed, with the same vibrating shoulder and back massage, but with the embedded technology concealed or displayed to varying degrees. These prototypes were evaluated, to determine the relationship between subject self-perceived personality and desire to conceal or display technology. Results showed the application to be attractive to most users, and aesthetic needs to be quite varied, even within an individual.

The functional apparel design process, as well as the knowledge and intuition about the body interface gained from the study of functional apparel design can help to broaden the scope of interdisciplinary variables considered in the design of wearable technology, and thereby produce a more successful design.

BIOGRAPHICAL SKETCH

Lucy Dunne was born in Albany, NY on October 27, 1980, the daughter of James Dunne and Lucy McCaffrey Dunne. After graduating from Bethlehem Central High School, Delmar, NY in 1998, she entered Cornell University in Ithaca, NY. During her undergraduate studies, she focused on functional clothing design, and specifically began to research wearable technology during her Junior year. She spent the spring of 2001 studying Art History in Paris, with the Wells College Paris program. That summer she interned at Starlab in Brussels, Belgium, as part of the *i-wear* intelligent clothing consortium, researching application areas and theories of intelligent clothing, with a focus on personal expression in intelligent clothing. As an Honors student at Cornell, she completed a thesis entitled “Smart Systems: Wearable Integration of Intelligent Technology”, which involved the design, construction, and testing of a smart winter jacket for athletic users. Lucy graduated with Honors from Cornell University in May of 2002, with a Bachelor’s of Science degree in Textiles and Apparel, concentration in Apparel Design.

In August, 2002, Lucy entered the Graduate School at Cornell University, remaining in the Department of Textiles and Apparel. As a graduate student she served as a teaching assistant for basic sewing and patternmaking courses, as well as a research assistant for several faculty research projects. Her thesis work was presented at several conferences in the US and Europe, and published in the proceedings of these conferences. The work was completed in August of 2004. Lucy will continue her studies in wearable technology as a PhD candidate in the Department of Computer Science at the University College Dublin, Ireland.

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INTRODUCTION

In the last decade, personal computing technologies have become pervasive in western society. Electronic devices have become increasingly mobile, portable, and accessible, both in their physical form and in their application scenarios (new or expanded uses for these devices.) This has created the potential for constant or pervasive computing access for the user, mostly through portable (carry-able) technologies: pocket-sized phones, palm-top computers, clip-on radios and music players. Now academic researchers as well as commercial developers of technology have begun to explore the design of wearable devices, technologies which are integrated directly into a garment (smart clothing), or body-worn accessories which are intended for constant or situation-appropriate accessibility and use.

Appropriately, as use of computer technology has become so much an integrated part of everyday life, more research has been done on the effects of using such technology, including analysis of human interactions with computers. Human-computer interaction (HCI) as a field of study has become well-established. Traditionally, however, HCI analysis has focused on a static environment. The newer fields of ubiquitous and wearable computing have recently introduced into this analysis new variables relating to movement and to social interaction. Wearable computing adds more physical/cognitive/psychological variables, as the human-computer interface moves closer to the skin, interacts more with external attentional demands, and becomes more intimately related to an individual's sense of self.

Because wearable technology is still a new field, there are many important issues relating to the design of such technology which have yet to be addressed.

Considerations such as social acceptability, physical comfort, ease of interaction, and user expectations of wearable devices are often shelved or marginalized in academic research, mostly because the main focus of this work to date has been on functionality, and because the "soft" requirements are frequently outside of the researcher's expertise. The fields of research which gave rise to the initial development of wearable technology (those of electrical engineering and computer science) have no precedent of intimate interaction with the human body/mind/psyche in a continuous-operation, body-mounted paradigm, since these variables have not existed in prior research (mobile or desktop devices). In the commercial arena, ignoring these considerations is often the cause of failure for a new product. Because of the high-tech nature of wearable devices, the designer or researcher often seeks to exploit their high-tech science-fiction aesthetic and cultural impact (in the design itself, or retro-actively when presenting the research to laypeople). This attracts a small niche market, but the larger part of the population is not willing to adopt this aesthetic for the marginally increased utility of a wearable device.

Wearable technology must be considered both as a device and as a garment, but it is difficult to reconcile the requirements of these disparate product groups. Devices and garments hold very different cultural roles in terms of duration and frequency of use, range of usage situations, product life cycle, price point, care, cleaning, and many other factors. For example, consider the reconciliation of the roles of a portable music player and the roles of a jacket. The music player is used in many diverse situations and environments. It is perhaps used every day, and in several different environments during the course of a day. The jacket, on the other hand, may also be worn every day (although probably not year-round), but is rarely worn throughout the course of a day, and is only used in a specific set of environmental conditions. The jacket itself is occasionally cleaned, the music player is not. The issues involved in this specific example can be seen as one of reconciling functionalities. The function of the music player (personal audio entertainment) is needed in a given set of situations, which overlaps but is not the same as the set of situations in which the function performed by a jacket is needed (maintaining warmth, protection from environmental elements, personal expression.) In the commercial arena, product life cycle also comes into play. A jacket today can be worn for as little as one season, and is expected to be priced accordingly. A music player, by contrast, is expected to last several years, at least. Thus, incorporating the music player into the jacket requires either an increase in the lifespan of the jacket, a decrease in the lifespan of the music player, or a modular interface of the two—accompanied by an associated price change.

There are, of course, many design spaces in which user requirements are not as stringent as the above example. Medical devices, as well as industrial and military applications, require much less accommodation of both physical, mental, and social user comfort. These applications allow the temporary suspension of generic cultural norms if the device fills an immediate need. Conversely, the mass-market design space poses the most difficult design problems, and requires the consideration of an almost infinite set of intangible variables.

Several of these intangible variables related to personal identity, social interaction, and physical comfort are also issues that are addressed in functional clothing design. Although the nature of human variability renders a perfectly complete (simultaneous resolution of all design issues) analysis nearly impossible, several design methodologies have been developed by functional clothing designers to help insure a thorough, detailed analysis of the problem situation and possible solutions. These methodologies help the designer to quantify an intuitive design process and eliminate false or inaccurate assumptions.

While the functional apparel designer does not possess the expertise or experience to be as fully aware as a computer scientist or engineer of the intricate variables involved in the design and fabrication of the hardware and software of a device, similarly the computer scientist or electrical engineer does not posses the expertise or experience to be as fully aware as a functional apparel designer of the intricate variables involved in the design and fabrication of a device which meets the user's physical and psychological needs. Clearly, both are needed. However, neither group or design culture currently encompasses the new variables that are created by the integration of technology and apparel design. It appears that the functional design process itself, which relies on the designer's awareness and open-minded thinking to identify new areas for consideration in design, is perhaps the most useful tool for bridging this gap.

Accordingly, this thesis applies functional apparel design methodologies to investigate the interface between the human user and the garment-integrated wearable device in three major areas: input to the device, output of the device, and the visual expression of the technology embedded into a garment. Issues investigated include: garment-appropriate application and distribution of wearable technology, wearable garment-integration of technology, and socially accommodating wearable technology design.

CHAPTER 1: BACKGROUND

1.1 Wearable Technology

Wearable technology is a term used to describe many different forms of body-mounted technology, including wearable computers, smart clothing, and functional clothing. The overlap of these areas is depicted in Figure 1.1. This section will define and describe wearable technology, wearable computers, and smart clothing. Section 1.2 will describe and define functional clothing.

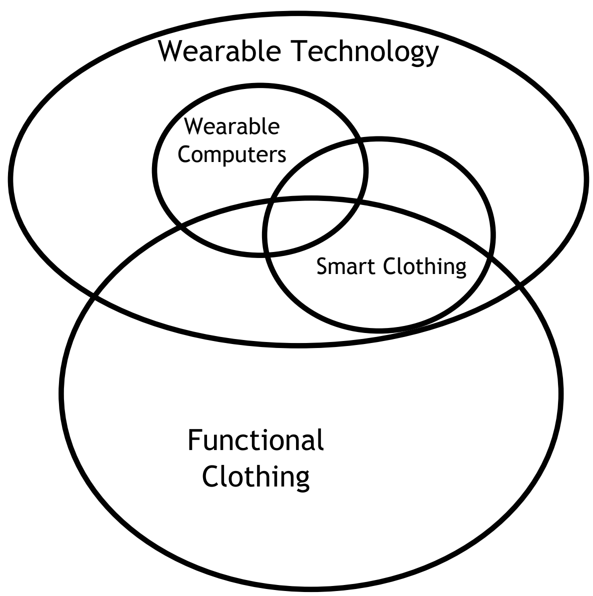


Figure 1.1: Forms of Body-Mounted Technology

The first form of wearable technology was probably the wrist watch, said to have been invented as early as the late 1500s (Childers, 1999). The watch was a technology designed to provide a specific service, to which users found it convenient to have access at all times. Similarly, the portable radio, which evolved into the walkman, was also perpetuated because of the user's desire to have access to that specific service at all times. The desire for continuous access has pervaded most of the development of wearable devices.

The development of computers has also exhibited a progression toward mobility and portability, from gigantic mainframe computers to desktops to laptops, to PDA's, and now to wristwatch computers. Development of wearable *computers* (specifically, as opposed to the general development of wearable technology) has been driven almost entirely by the desire for this kind of constant-access service. The term 'wearable computer' has been defined as a "fully functional, self-powered, self-contained computer that is worn on the body.... [and] provides access to information, and interaction with information, anywhere and at anytime" (Barfield & Caudell 2001). The distinction between wearable technology and wearable computers is blurry. Wearable computers are part of the larger classification of wearable technology, which also includes devices which may or may not "compute"; they may perform other functions and consist only of an electrical current and a switch.

Wearable computers are generally designed to possess many of the same capabilities of desktop or other computers—focusing on communication, data processing, and accessibility of information. Commercially available wearables are designed to incorporate most of the same processing functions of a laptop or handheld computer, with modifications primarily in the input and output devices. However, although their functionality is the same, wearables do not have the same market as laptops or PDA's. Primary markets for wearables are military applications, industrial applications (primarily for situations in which the worker must remain mobile or retain the use of both hands while accessing information or gathering data) and developer applications (kits designed for developers of wearable computing software or hardware). (Charmed, 2003; Via, 2003; Xybernaut, 2003)

While many industrial wearable computers are "wearable" simply by being mounted on the body (usually in a belt or backpack form), other wearable devices are designed to be hidden on the body or in the clothing. The first known wearable computer was in fact developed as an aid to cheat at roulette. This device calculated odds based on the physical trajectory of the ball, and used a communicator housed in the shoe to transmit information to a remote partner who heard the output as a series of tones. (Thorp, 1961). Although visually subtle integration of technology is clearly a necessity in many applications (such as in covert communication or surveillance), it has seldom been addressed by designers of wearable devices. This is due in part to the relationship between physical size of components and functionality. Even as components continually decrease in size, the standard "needs" for a computer increase. For instance, most of the power and functionality from a 1990 computer could be integrated into an easily-concealed device, but that kind of capability would not be considered enough, by today's standards. Thus the "necessary" size continues to be too large to subtly integrate.

Still other wearable devices have been developed to obtain data from the body itself in a portable, convenient manner. In hospital environments, sensors can be adhered to the skin and the patient tethered to a data-collection unit. As the computational technology required to collect sensor data decreases in size, that data-collection unit can be physically mounted on the body, removing the tether and subsequently the necessity of having the patient confined to the hospital. Collecting physiological data for medical diagnosis has been described as a snapshot or sample of the actual physical state. The continuous monitoring afforded by a wearable device transforms the snapshot into a moving picture, reflecting the entire actuality of the physical state (Vivometics, 2003).

In the latter half of the 90s, software applications began to establish distinct functionality that differentiated the uses of a wearable computer versus a desktop or laptop computer. These applications centered around the "always-on" requirement of a wearable, and began to incorporate active responses, such as the wearable remembrance agent, which automatically retrieves relevant archived files as the user inputs new text or notes into the computer (Rhodes & Starner, 1996). Context-awareness in information retrieval, storage, and processing is one of the primary advantages to computing in the mobile environment.

1.2 Functional Clothing

Traditionally, the concept of functional clothing design addresses the ability of clothing to assist the body's natural mechanisms to regulate temperature, manage moisture transport, protect from environmental hazards, and resist impact and abrasion. These goals have primarily been achieved using passive technologies: technologies such as performance fabrics, whose properties remain constant in many environmental conditions and over time. Although the term "functional clothing" has traditionally been used to describe garments or accessories which protect the body from physical threats, every body-worn object or garment performs a function, be it physical, psychological, or social.

It is a common misconception that humans began wearing clothing for functional or protective reasons. In fact, there is evidence to suggest that the body naturally adapted to primitive climates, and the first garments were draped around the pelvic region to protect the genitals from magic (Renbourn and Rees, 1972). This demonstrates the psychological functionality of a garment.

The first forms of protective clothing most likely existed to serve one of two crucial functions: protection from environmental conditions, and protection from weapons of war. Protective garments were constructed from materials available to the society creating them, and also highly influenced by social factors such as aesthetic customs, and psychological or spiritual traditions.

New forms of protective clothing generally were created to counteract a new physical threat, such as a chemical hazard or new weapons, or to improve an existing protective garment using new technology, such as fire-proof textiles.

Functional clothing differs from other forms of clothing (apparel, fashion) because its primary focus is on the function performed by the garment. The functional approach does not, however, inherently disregard aesthetics or expression, as these can also be considered user needs or functions of clothing. Figure 1.2 shows a general breakdown of the areas of functionality that can be performed by clothing.

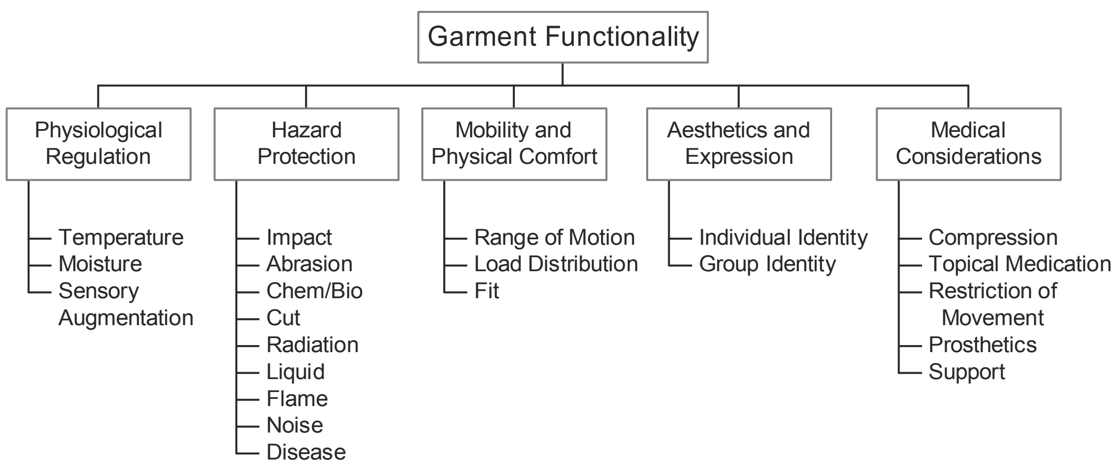


Figure 1.2: Areas of Clothing Functionality

1.2.1 Wearability in Wearable Technology

Wearable technology is the intersection of the fields of ubiquitous computing and functional clothing design. However, the functional design process has yet to be reliably incorporated into the design of wearable technology. The ways in which humans interact with computing devices are often more understood by the designers of wearable technology than the ways in which humans interact with clothing. Both are highly dynamic and culturally influenced, and the consideration of both is essential to successful design.

Technology can be used to create a new level of functional clothing with increased capability and more dynamic responsiveness. However, it also introduces new variables into the design process. Traditionally, functional clothing design has required little analysis of the cognitive interaction of the user with the garment, generally limited to donning and doffing procedures. Adding computational functionality requires that the user be able to operate the device within the given context—requiring that cognitive needs be added to the design consideration. The structure of the design process allows for the integration of such concepts, but since wearable technology is a relatively new field of investigation, design criteria and relevant variables are still not very well defined, especially in the mobile environment.

Aside from cognitive considerations, wearable technology also introduces new physical and psychological variables. Specifically, electronic components can affect functional design in the physical areas of thermal management, moisture management, mobility, durability, flexibility, and sizing and fit, as well as the psychological areas of cognitive load and attention. In the following sections, several traditional functional clothing design areas of consideration will be examined with respect to the additional variables and requirements of wearable technology.

1.2.1.1 Thermal Management

The human body tightly regulates its temperature just below 100F while operating through ambient temperatures of 68F to 138F (Guyton, 1977). To manage the heat produced by the body, functional garment systems of all kinds incorporate thermal adjustability through layering, venting, and accessories such as cool water or air pumps. Integration of wearable electronics introduces new challenges for thermal management, by adding the heat produced by certain electronic components to that produced by the body. Though the additional heat can be a benefit in some environmental conditions, it more frequently contributes unneeded heat. The smaller the area over which electronic components are distributed, the smaller the area over which heat is initially distributed. Recent advances in miniaturization have not been paralleled by similar advances in component power consumption. As a result for a consistent level of functionality smaller components generally are hotter.

Without thermal management, the body often absorbs the excess energy from the component. Excess heat can be removed from the body by means of conduction, convection, radiation, or evaporation. Conductive transfer from components is often facilitated through heat sinks. Convective transfer can be facilitated by incorporating vents or spacer fabrics into the garment, to permit air circulation between the components and the body, which can also facilitate evaporative transfer through perspiration. Radiation is a less efficient (passive) means of transfer.

1.2.1.2 Moisture Management

Most printed circuit boards (flexible or otherwise) are made of completely impermeable plastics and resins. While these materials are standard to manufacturing processes and provide the circuitry with necessary support and stability, any impermeable barrier too close to the body can be uncomfortable. Impermeable barriers can hold in heat and moisture, thereby reducing comfort and wearability. Moisture management can be facilitated through use of breathable or wicking fabrics, or by permitting airflow (through aforementioned spacers or vents) to permit evaporative cooling. Additionally, to preserve their functionality, wearable electronics need to be protected from perspiration as well as environmental moisture, such as precipitation or spilled liquids, as well as perhaps the extreme moisture present during laundering.

1.2.1.3 Mobility

The natural physical movements of daily life are habits which have developed given a perception of body area, or proxemics (Gemperle, Kasabach, Stivoric, Bauer, and Martin, 1998; Hall, 1969). Wearable technology design, especially in situations where resources do not permit custom-design of computing components, often results in bulky devices mounted onto the body. Adding bulk or volume to the body must be accomplished in ways that do not interfere with natural movements. Design must also take into account situation-specific movements required for the accomplishment of a task. In more extreme situations, where weight is a factor as well as volume, weights should not interfere with stationary or dynamic balance. Locating weights close to the body's center of gravity can help reduce the perception of weight (Watkins, 1995).

1.2.1.4 Flexibility

Standard solid printed circuit boards (PCBs) are often difficult to integrate into clothing or body-mounted forms because of their inability to conform (statically or dynamically) to the contours of the body. Flexible PCBs are available with optimal bend radii of 1-2 millimeters. The problem from a wearable perspective is that the flexibility of a finished board is dependent on the layout of the components it is populated with. The boards are only flexible outside of the regions populated with components. Aggressive flexion or torsion in a component populated region will weaken electrical connections and could cause components to be ripped free from the circuit board.

In order to use flexible PCBs in garment integrated wearable electronics the component layout needs to be designed such that components are clustered in bend and torsion stabilized areas, and connected together by unpopulated (and thus still flexible) PCB. Alternately, the design may be segmented with components distributed over many traditional inflexible PCBs joined together with ribbon-like flexible interconnections.

1.2.1.5 Durability

The highly dynamic needs of the wearable environment can be a challenge to the development of wearable electronics. Avoiding body flex zones (body areas of greatest change with movement) and incorporating flexible stabilizers into the structure of the electronics can help to merge durability and flexibility.

1.2.1.6 Sizing and Fit

If technological devices are designed to be integrated into a garment or mounted on the body in such a way that the specific location on a given body part is important to the wearability, comfort, or functionality of the device, individual sizing and fit can become a significant issue. The anthropometric variation in the human body across the population is significant, and hard to generalize. The less fit-specific an insert is the more wearable it can be for a broad range of body types.

1.2.1.7 Garment Care

Methods of garment care currently fall into three categories: washed garments, which are submerged in or wiped down with water, with or without a detergent, either in a washing machine or by hand-washing; dry-cleaned garments, which are cleaned professionally or in the home, using a chemical solvent and no water; and not-cleaned garments, which for reasons of fragility or convenience are not cleaned. Submersion in water or solvent can be detrimental to electronic technology, if it is not first completely encapsulated in an impermeable material. The environment of a washing machine or dryer also poses severe risks to technology, due to the rigorous physical environment in which the electronics and conductors experience extreme amounts of flexion, and also due to the possibility of experiencing high temperatures. Some electronic components can withstand the environment of the washing machine/dryer and are unaffected by submersion in water (provided there is no active power source connected), but many more can not.

Currently the solutions offered for these problems in commercial wearable technology are removable technology and encapsulated technology. Removable technology integrates a modular or stand-alone unit of technology, which can be removed fairly easily from the garment prior to cleaning. Encapsulated technology is completely encased in a protective material, which prevents water or solvent from reaching the electronic components, and offers some degree of flex prevention.

1.2.2 The Functional Apparel Design Process

Because clothing remains close to the body at all times, the functional apparel designer has necessarily been very aware of the physiology of the body, and the needs of the user. Although its focus has been traditionally on protecting the physical body, its structure easily permits the analysis of social and psychological needs as well. The functional design process is a user-centered process which examines a wide range of variables, including physical and anatomical considerations, mobility and movement, situational hazards, and ease of use. Initially, functional apparel was designed by engineers and materials scientists, who learned principles of apparel and design through experience. In the early 1970's, the process was approached formally by apparel designers, leading to an expansion in the awareness of the complex variables involved in the design process (Ashdown, 2003).

The steps of the functional design process are outlined in Figure 1.3. It is important to note, however, that the outcome of the final step in this process is not necessarily the best solution. The process is intended to be iterative, with the results of each step being reflected back on the previous steps to help illuminate assumptions and offer alternative solutions.

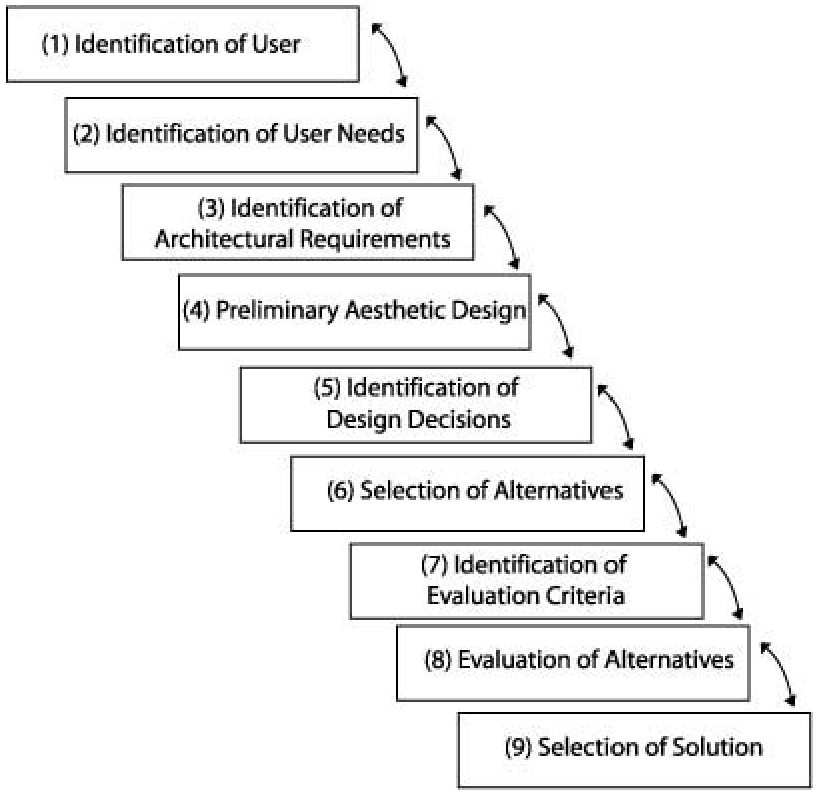


Figure 1.3: The Functional Apparel Design Process

The design process begins with a thorough analysis of the anticipated user, and the identification of the physical, emotional, and situational needs of that user. Next the peripheral variables (architectural requirements) are examined: external people or objects that the garment will need to interface with. Will the user need to sit in a chair? Drive a car? Wear a backpack? These are peripheral variables that will influence the physical form of the garment. Once these design criteria have been established, the initial aesthetic design is created within the framework of the user's needs. Design decisions are evaluated and re-evaluated, and alternative solutions are generated for each decision. Alternatives are then evaluated on a weighted scale, to arrive at the best solution or combination of solutions for each decision. These are then incorporated into the first prototype, which is subsequently evaluated in laboratory or field trials. The results of the prototype evaluation are used to influence the modifications made in the next prototype, and the design process begins again. This insures that an incorrect assumption or poor component choice is corrected before the design is finalized. When resources permit, multiple designs are often compared to each other, in order to examine the strengths and weaknesses of each.

The differences between functional clothing design and current wearable technology design lie primarily in two areas: variables addressed, and iterative design. The focus of functional clothing design is on the interaction between the body covering and the body itself, as well as the physics or mechanics of the function performed by the protective garment. The focus of electronics design is on the task(s) performed by the device: the design of the hardware and software necessary for the desired device functions. Functional clothing designers have previously had no need to address variables of electronic functionality, efficiency, or durability, and likewise device designers have previously had no need to address the interface between the device and the human body. Researchers in wearable technology have defined the scope of their projects to be focused on areas with which they are familiar and have some degree of expertise: usually device functionality and wearable technology applications. The focus therefore being on the achievement of a specific functional goal (rather than a fully developed "end product"), the evaluation process is designed to evaluate only the success or failure of this particular aspect of the device design. For this reason, the variables that are so common in functional clothing design (variables of the human interface) do not emerge as reasons for design failure.

More significant, however is the lack of an iterative process in the current design of wearable technology. Even as a new field, it is populated primarily by isolated, short-term projects that are rarely built upon. Therefore, although human-interface variables may emerge as obstacles in testing, they are rarely applied to future work, and thus design flaws are perpetuated.

The reasons for the disparity in focus areas of technology design and functional apparel design are debatable. They may arise from a difference in design culture, or worldview held by designers within a particular group: a general point of view regarding the direction to be taken in designing a new innovation. They may also arise from a lack of resources (time, money, knowledge) in other disciplines. However, it is important to note that each group has strengths in design as well as weaknesses, and that the strengths of both groups are necessary for successful design.

A thorough design process is necessitated by the numerous and diverse variables that must be taken into account when designing for a human body, mind, and psyche. Successful design relies on all variables being addressed.

1.3 Western Clothing Forms: A Technological Perspective

Currently, the emphasis of wearable technology research is primarily on innovation and abrupt progress. As technology experts, most researchers in the field have little expertise on the "soft" variables of human physical, cognitive, and social needs. However, as this section will illustrate, abrupt, revolutionary design innovation does not always meet the needs of all users. Often it is a more gradual introduction of an innovation that allows the user to comfortably assimilate a new idea.

A revolutionary design process rarely takes into account what has gone before, except perhaps in order not to repeat it. This is characteristic of a modernistic philosophy, innovation without reflection. An evolutionary process requires that the designer first be well informed of the history and state of the area of investigation, in order to take into account existing norms when gradually introducing an innovation. This awareness and referencing is more characteristic of a post-modernistic philosophy, although in wearable technology the process always retains a modernistic drive toward innovation, progress, and augmentation of human abilities, as well as a modernistic scientific method of analysis.

The lack of informed, evolutionary design in wearable technology is particularly evident as it applies to the physical form of the technology. In this thesis, the focus is on garment-integrated wearable technology, or “smart clothing”. Garment integration specifically requires that the designer work within the cultural framework of clothing and body adornment. Understanding the history of how members of a given society or culture create, use, modify, and dispose of their clothing can help to provide some perspective for the design of wearable technology. Similarly, an examination of how previous technological advances have influenced the cultural perceptions of clothing can illuminate the potential changes that may occur as a result of the introduction of wearable technology and smart clothing.

In any age, at all times, in every culture, there is a general consensus of appropriate clothing forms and clothing usage. This consensus results in a popular concept of clothing, meaning a combination of what clothing should look like, how it is worn, how it is used, how it is cleaned, and how (and how often) it is acquired and disposed of. Throughout the centuries, as the shape, structure, function and availability of clothing has changed, the popular concept of clothing has also changed. These changes have sprung from constantly changing aesthetic preferences, social influences, and from technological innovations. Understanding the ways in which new technologies have made changes in the clothing concept possible, and the ways in which these changes have occurred in society can help to inform the designer, whose decisions will influence the impact that wearable technology can have on the clothing concept. This section will outline a brief history of the evolution of the western clothing concept, and the interaction between changes in the clothing concept and technological advances.

1.3.1 Colonial America

One example of this change occurred when the colonization of North America in the eighteenth century removed the colonial population from the technology of Europe and Asia. In other parts of the world, fabrics of a fine quality with elaborate and colorful surface embellishments, made with advanced weaving and dyeing technologies were either locally manufactured or imported from other countries. However in the American colonies, these textiles were very expensive and difficult to procure. Therefore the earliest settlers wore garments made from homespun fabric, fabric that was woven on hand looms using homespun yarns.

The tailored shapes of the clothing worn by the colonists reflected the prevailing concept of western countries, in contrast to most eastern societies which had very different customs of clothing construction. These cultures often employed draped garments or garments constructed out of very simple shapes (squares, rectangles), relying more on intricate surface design and advanced weaving techniques to add interest to the garment, rather than complex shapes and tailoring.

1.3.2 The Emergence of Ready-to-Wear Clothing

Another example of the relationship between technology and popular clothing concepts occurred in the nineteenth century, in the shift from individually tailored garments to ready-to-wear. In the eighteenth century, individual garments were made to measure by skilled artisan tailors. Tailors measured various dimensions of each client by marking their lengths on a strip of parchment paper. These markings were then transferred to chalked outlines on fabric. A tailor's primary skill was in his artful cutting of the fabric, to produce the desired fashionable shape. Access to the knowledge of how to craft well fitting tailored shapes was controlled with a strict guild and apprentice system (Kidwell, 1974).

The clothing concept in western countries during this period was similar to that of the preceding centuries, dating back to about the 11th century (Payne, Winakor, and Farrell-Beck, 1992). Clothing forms and silhouettes were complex: men wore some form of tailored, form-fitting trousers or pants, shirts, and jackets. Women wore skirts and bodices or one-piece dresses, and an array of underclothing that varied by class and age. Many women wore corsets almost continually. In all classes, clothing was fairly difficult to obtain and consequently was worn for a substantial period of time (relative to today's standards) and often passed down within a family, or to servants or dependants.

1.3.2.1 The Industrial Revolution

The industrial revolution caused changes in almost every sector of industry, and created the first significant change in this clothing concept, bringing the beginnings of ready-to-wear clothing. New advances in textile production made fine textiles available to the American market. Americans no longer had to import their textiles under heavy taxation (Payne et al., 1992).

By 1802, the tailor had adopted the use of a tape measure for the first time. Instead of relying on his experience and personal skill in cutting, the art of creating patterns for complex, fitted garments could be altered into a "scientific", reproducible process based on body proportions (Kidwell, 1974). During the 1812 war, the first large-scale ready-made clothing manufacturing operation began, a coordinated hand-sewing effort launched by the US Army to outfit soldiers in uniforms. Soon commercial companies joined the ready-made clothing trend, and by 1818 the Brooks Brothers firm was selling men's suits off-the-rack. Initially, ready-made clothing was available only to men and children, although selected loose-fitting garments such as capes, cloaks and petticoats were available for women. The manufactured clothing industry started to take shape in the early 1800s. Despite a depression, in 1837 New York City wholesalers sold $2.5 million in ready-made clothing. By 1850, there were 4278 clothing manufacturers in the United States (Payne et al., 1992). Cultural changes brought on by the technological revolution would also impact the popular concept of clothing. Technology sped up the pace of life, and consequently sped up the process of acquiring and wearing clothing. Textiles were more readily available, and garments were less expensive and easier to produce. The nineteenth century began the mass acceptance of of-the-rack clothing.

The shape and function of clothing had not changed much from the eighteenth to nineteenth centuries. Men were still seen in suits similar to those worn today, and women wore various forms of skirts and blouses or dresses, with an assortment of ever-changing undergarments. Corsets were still worn continuously. The significant changes were seen in the shortening of the lifespan of individual garments. By the end of the nineteenth century, clothing was fairly easy to obtain, and worn for a shorter period of time than in the preceding century.

1.3.2.2 The 20th Century

In the early twentieth century, the most significant change was seen in the technology for garment manufacture. The nineteenth century had introduced the concept of ready-made clothing, and had established such garments as acceptable, at least for men. This paved the way for the development of a market for mass-manufactured clothing. By the end of the nineteenth century, women's casual clothing was also available as ready-to-wear. Technological advancement in machines for garment manufacture further reduced the time and cost of making clothing. Soon the old cornerstone of the tailor's art, cutting, was also delegated to machines. Garments could now be cut up to 40 layers at a time. Pressing machines and gas irons similarly sped the production process (Kidwell, 1974).

With the rise of manufactured clothing, the garments produced soon came to include the full range of women's clothing. The ease of availability and lower cost of mass-produced clothing overrode the desire for custom made, individual clothing in most of the population. However, the desire for more options provided a market that supported an increasing variety of products. As the century wore on, ready-made clothing became more varied, easier to produce, and cheaper for the consumer. Parallel to this, major changes in fashion and aesthetic tastes for women's clothing contributed to the ease of manufacture. Not only did technology make the process of manufacturing clothing faster and easier, but social movements toward less elaborate and restrictive clothing for women made fashionable garments easier to manufacture. Clothing became much more simple and easy to construct; moving from the elaborate corsets, voluminous skirts, and heavily constructed three-piece suits of the early 1900s, clothing followed a steady simplification trend over the course of the twentieth century. New styles (such as knitted garments and bias-cut garments) demanded the development of technology to facilitate their manufacture, at the same time as new technological innovations influenced the progression of style change.

1.3.3 The Computer Age

The late twentieth and early twenty-first century saw another wave of technological advance. The popularization of computer technology in the late twentieth century soon spilled over into most manufacturing sectors. In the same way that the industrial revolution saw machines performing tasks in a fraction of the time they took by hand, the end of the twentieth century saw computers taking over the operation of these machines (Hoffman and Rush, 1988). More than mere automation, computers offered the apparel industry new ways to efficiently design and manufacture clothing, shortening the development cycle of new styles. New software systems based on CAD (Computer Aided Design) programs made patterning, grading of patterns into different sizes, and marker-making (the process of laying pattern pieces to use fabric efficiently) easier to create, revise, and communicate (Taylor, 1990). Computer Aided Manufacturing (CAM) automated some construction processes as well as offering new technological solutions to speed the manufacturing process, such as laser cutting systems, pressing machines, and computerized embroidery machines (Gray, 1998).

The popular clothing concept in the twentieth century changed in many ways. Culturally, over the course of the twentieth century clothing became more gender-neutral than it had ever been. For the first time, the clothing concept approached equality between the sexes (Horn, 1975). Technological advances in manufacturing made clothing easier to produce, as did the simplification of clothing styles, and these two factors combined to contribute to an increasingly popular view of clothing as "disposable", easy to obtain and worn for a very short period of time, less than six months for some garments. The traditional concept of fashions marketed by "season" quickly declined, as consumers purchased clothing more frequently. Instead of new lines introduced three or four times per year, new styles began to be available almost continuously.

1.3.4 Customization and Adaptability

The beginning of the twenty-first century witnesses the beginning of another conceptual change in the popular approach to clothing. The new speed of manufacture brought on by CAD/CAM technology creates potential for more agility in the industry response to consumer demands. "Just-in-time" response allows retailers to obtain only what they have demand for, when they need it, further accelerating the cycle of manufacture to sale (Glock and Kunz, 2000). And a new trend toward mass-customization of clothing makes it possible for each garment manufactured to have the specific fit and appearance requested by the individual consumer (Abend, 1996). The new technology of manufacture (such as single-ply cutting and digital printing) and team-based factory production methods offers the potential to meet these demands (Anderson, Brannon, Ulrich, Marchall, and Staples, 1998). Additionally, computer-aided patterning software used in conjunction with new body-scanning technology offers the potential for garments to be automatically custom-fit to each consumer, bypassing the extensive and time-consuming fitting process (Abend, 1996).

This technology is still new, but beginning to show visible effects on the popular clothing concept. Commercial endeavors have been launched at the mass market scale by Levi's, Land's End, and Brooks Brothers, and small internet companies are also using these technologies. Some predict that in the next few decades we will see clothing become more individualized while maintaining its short life cycle.

Table 1.1 summarizes the changes in various influencing aspects of the clothing concept over the last 3 centuries.

Table 1.1: Changes in the Clothing Concept

	Colonial America	**Industrial Revolution**	**Ready-To-Wear (1900s)**	**21st century (customized)**	**Wearable Technology**
Garment cost	High	Moderate	Low	Moderate	High
Garment lifespan	High	Moderate	Low	Low	High
Size of style selection	Infinite	Low	Low	Infinite	Low
Difficulty of Manufacture	High	Moderate	Low	Moderate	High

1.3.5 The Emergence of Wearable Technology

Today's prototype configurations of wearable technology do not take into account the existing parameters demanded by today's clothing concept. Consumers today relate to clothing that is modular, layered, and disposable. Integration of an entire system into a single garment makes it necessary for the user to wear that specific garment any time they need to use its electronic capability. It also creates a garment with so much built-in electronics that it becomes far from disposable, and must be worn as long as the device is useful, or risk rendering the electronic device unusable. Removable devices are useful in many applications where the device is carried in many different situations, but often that solution is not visually discreet or can create a difficult user interface.

Many designers of wearable technology approach the problem with the aim of "revolutionizing" apparel or computers. This, however, has not yet proved a viable means of introducing wearable technology products to the mass-market. Acceptance of an innovation relies on many complex variables. Rodgers and Shoemaker (Sproles, 1979) describe the process in terms of these variables: relative advantage (the degree to which the innovation is more satisfactory than previous alternatives), compatibility (the degree to which the innovation is consistent with existing norms and values held by adopters), complexity (the difficulty a consumer has in understanding and learning to use an innovation, including integrating it with other owned artifacts), trialability (the extent to which the innovation may be tested on a limited scale before the decision to adopt or reject is made), and observability (the degree to which the innovation is visible and communicable to others). In terms of wearable technology, relative advantage provided by the embedded function is the primary source of consumer attraction, as an augmented garment or wearable device exists to impart added or improved functionality. For the innovation to be accepted, the user must first subscribe to the attractiveness of the relative advantage of the device (which can be counteracted by the complexity of its use), and then must be satisfied personally with the balance between compatibility and observability (a very individual preference).

The current pace of fashion and technological trends has led wearable technology designers to disregard the importance of compatibility in consumer acceptance of innovation, and to adopt the "revolution" approach instead of "evolution". This approach has been successful in some forms of mobile or desktop technologies, mostly because the functionality of the device has provided enough benefit to the user to outweigh any effects its appearance or social significance might have. However, body adornment carries a great deal of identity, even more so than carried mobile devices do. The mounting of a device directly onto the body, in a constant-wear paradigm, necessarily includes the visual appearance of the device in the individual's displayed identity. Because of this, technological innovation in the form of body-worn devices must adhere to the methods and pace of social assimilation of other body-worn articles, such as apparel and accessories. In other words, as Davis points out, in the evolutionary approach of apparel design, successful innovation is introduced gradually, and happens over a long period of time (Davis, 1992). A large-scale change, like the transition from passive to active clothing forms, takes a much longer period of acclimatization than smaller forms of change similar to those seen in fashion trends. Identifying the essential elements of the current clothing concept and preserving enough of these elements can help to ease transition for the consumer.

Because of the complexity of the variables involved in innovation that is directly tied to individual identity, successful innovation also requires a deeper examination of the user's identity, including physical, cognitive, and social variables.

1.4 Configuring the User in Wearable Technology Design

As previously discussed, the awareness of the designer is crucial to the success of the design process. However, beyond remaining aware of the entire scope of possible influencing variables, the designer must also remain aware of his/her influence on the identity of the target user: physically, cognitively, and socially. As with the wearability variables discussed in section xx, the identity of the user is even more complex in the design of wearable technology than in the design of functional clothing or computing devices. This section will discuss the influence of the designer on the identity of the user.

Computing and electronic technologies exist to expand the capabilities of the user. However, especially in the early development of new technologies, the design of the technology necessarily inhibits the ultimate scope of possibilities for the user's expanded capability. Woolgar describes the process of designing based on assumptions about the character and abilities of the user as "configuring" the user, which he defines as "defining the identity of putative users, and setting constraints upon their likely future actions" (Woolgar, 1991). This inhibition is more clearly evident in certain technologies, and can be recognized in areas where previously developed technology has exhibited similar difficulties.

Computer technologies have existed for long enough that their social shortcomings have been well-documented. The impacts of computing technologies on users and user groups, on social networks, and even on the cognitive processes of the user have been extensively investigated. The development process can be described as one of circular influence, where the design of the technology impacts the behavior of the user (the technology configures the user), which then impacts the design of the technology (the user configures the technology). It is also described as a networked process, in which both user and designer are part of extensive social networks which actively shape the development and of the technology. (Suchman, 1999, Woolgar, 1991)

The impact of a technology on its user can extend past the user's actual physical involvement with the technology—into their social interactions, self-identity, and occupational capabilities, among other things—but many more obvious effects stem only from the direct interaction. Wearable technologies, on the other hand, are designed for constant-wear and continuous use. This means that any interaction effects between the user and the device can impact every area of the user's physical, cognitive, and emotional/social state. The field of wearable technology is a relatively new field, and most prototypes are only in their infancy. But because wearable technologies are often closely related to other forms of computing technologies, their constructive effects can, to some degree, be compared to those of desktop, laptop, and mobile computers. Certainly much of the cognitive configuration of a user in computing technologies can be directly applied to wearable technologies, as can the communicative configuration effects. But the scope of impact in wearable technology is that much broader, because of the extended wear period and increased situational involvement. Additionally, physical effects of wearable technology are vastly different from physical effects of other forms of computing technology, due mostly to the intimate physical interface between the body and a body-mounted device, which may possess weight, volume, sharp edges, and even generate excess heat.

The physical configuration of a user has been previously examined in other forms of technology by examining factors which affect performance or which actively prohibit the inclusion of groups of users based on physical abilities or physical characteristics (Weber, 1999). Body-mounted technologies are relatively rare and have not been studied, but the physical effects of mounting weights, volumes, and impermeable objects on the body for other purposes have also been well-investigated. (Diffrient, Tilley, and Bardagjy, 1991; Watkins, 1995)

The current development environment for wearable devices bears much similarity to the environment surrounding the early developers of personal computers—key actors, involved in a relatively homogenous social network, designing for a user who bore strong resemblance to the designers themselves, and later for a remote constructed user whose actual abilities and needs were relatively unknown. (Bardini and Horvath, 1995). The development thus far of wearable technologies has proved limited in scope, and successful only in specific niche markets. Examining the existing prototypes and the trends in development illuminates assumptions on the part of designers which limit the range of potential users, and homogenize the user into a pre-defined size, shape, social status, habit, and situation.

These are the types of assumptions which the design process described in section 1.2.2 can address. Once these assumptions are identified and appropriate design criteria are established, solutions can be developed that will compliment the user's desires and needs.

1.4.1 Physical Configuration of the User

Most of the development of wearable technology is done by those who specialize in computer hardware or software. Very few projects are undertaken by researchers with expertise in functional apparel design, human factors engineering, human physiology, or anthropometry (the study of human body measurements). As a result, many "wearable" devices are designed in such a way as to be realistically un-wearable, or wearable only by a small segment of the population.

The physical configuration of a technology can severely limit the definition of the individuals who may use it. Weber, in a study of military cockpit design, points to the physical limitations on the potential stature of the user as dictated by the design of an aircraft cockpit. Potential users who do not “fit” the technology as designed are simply prohibited from using it. Similar fit restrictions are placed on protective garments used in the cockpit. (Weber, 1999).

Wearable technology can be similarly restrictive. The more specific in physical dimensions a body-mounted technology is, the more restrictions it places on the range of potential users. Prohibitive factors most often have to do with limits of the body, limits of reach and field of vision. Two good examples are the Twiddler single-hand chording keyboard and the Eyetop head-mounted display. (Eyetop, 2003; Twiddler, 2003). The Twiddler keyboard is a very common keyboard/pointer interface used with wearable computers. It uses combinations of pressed buttons (chords) to write text. However, the Twiddler comes in one generic package, with uniform button spacing. Many users, particularly females or individuals with small hands, find certain chords very difficult, or even painful, to reach. Thus the keyboard presumes a user of minimum hand span. The Eyetop display is a glasses-mounted display that contains a 0.5” LCD screen, located in the upper corner of one eye. This design is similar to many head-mounted displays, but differs in its inflexible architecture—the display can not be adjusted to a different focal length or placement angle. The user has no ability to adjust the physical placement of the screen, and therefore must contort the focus or angle of their vision to conform to the existing placement. In a review by TechTV, many users found this display physically debilitating, inducing nausea and dizziness. (Wong, 2003). Fixed placement of a head-mounted screen therefore presumes a user of pre-determined head size, eye placement, and field of vision.

Although prohibitive physical factors provide a clear, definite example of physical configuration of wearable computer users, the majority of physical influencing factors (physically preventive factors) do not absolutely prohibit the use of a device by certain users (example: the user can in no way reach the controls). Instead they decrease the physical comfort of certain users until they are ultimately discouraged from using the device (example: the user has trouble reaching the controls, and thus does not want to use the device). The interaction of a device with the body is complex, and affected by the distribution of weights (both in a static situation and as they affect mobility and movement), pressure on the skin, and the fit (or lack of fit) of the device on the user's body. The fit factor can be the most important factor (depending on the design of the device; some designs demand less precision of fit), because it can have a substantial effect on both pressure and weight distribution, as well as introducing other variables.

The location of a weight on the body has a significant effect on the perception of that weight by the user. Weights located close to or on the center of gravity (usually somewhere on the body trunk) are the least perceptible, and as the distance from the center of gravity increases, the perception of weight generally increases (Watkins, 1995). This pertains to the location of weights on limbs (the forearm is a popular place in wearable computers) as well as the attachment of weights to the torso (weights allowed to swing free will seem heavier than weights closely tethered to the body). Part of the reason that weights located close to the center of gravity are easier to carry is due to the fact that loads in these areas are most often carried using the stronger muscles of the legs. Muscular strength varies across user groups (men vs. women, adults vs. children vs. older adults, etc.), thus a weight easily carried by one group may be very fatiguing for another group. Weights balanced around the center of gravity are easier to carry than unbalanced loads. An imbalanced load must be compensated in posture, to prevent falling over. This compensation can lead to muscle fatigue, pinched nerves, and repetitive strain injuries. Figure 1.4 illustrates a wearable computer worn by a food processing plant quality assurance inspector (Georgia Tech, 2003).

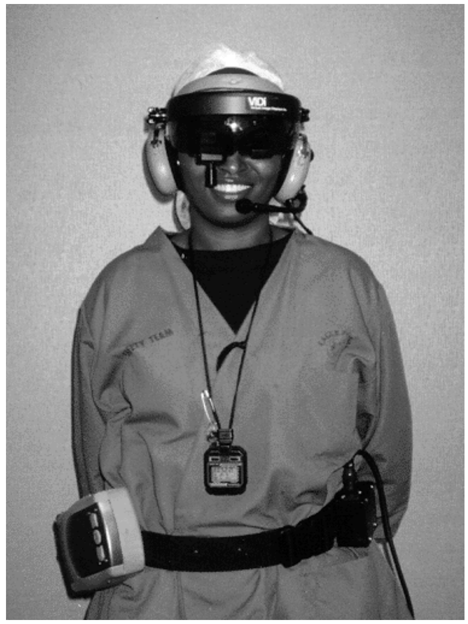


Figure 1.4: Industrial Wearable Computer (Georgia Tech, 2003)

The load here is unbalanced about the body's center axis. In addition, a large volume has been introduced to one side of the body. It is clear that this will impose changes on the user's movements. How will it dictate the kind of gait that is developed to compensate for the weight? How will the user have to move to avoid bumping into or getting caught on objects in the environment? The headgear also imposes user issues. The system will regulate exactly what the user can see and hear, therefore configuring his senses. This system will configure movement patterns in the user as he adapts to the physical presence of the computer.

Carrying weight can create pressure on the skin. Pain can be inflicted by carrying a weight in a sensitive area or by a sharp corner on a body-mounted object. Figure 1.5 describes the variation in torso sensitivity as mapped by the US Army:

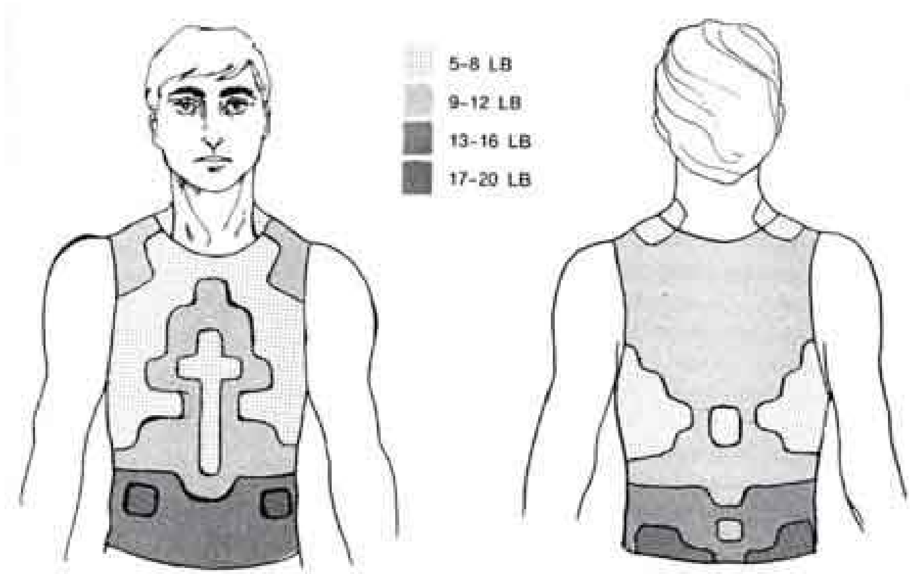


Figure 1.5: Torso Sensitivity (Watkins, 1995)

Note, however, that this is mapped to the male torso. No similar map exists for the female torso. On a woman, the breast area is extremely sensitive, but this sensitivity is often not addressed in the design of vest-based or backpack-based wearable computers. Carrying a weight over the breasts can be very uncomfortable for a woman. Figure 1.6 shows an illustration of the 2002 MIThril wearable computer. (MIT, 2002)

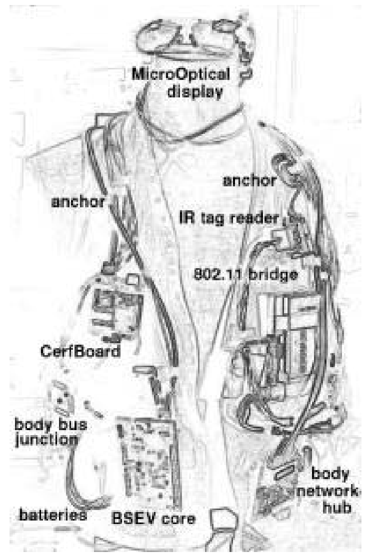


Figure 1.6: MIThril System (MIT, 2002)

Note the large, bulky, square objects located on the mid-chest. These would be directly in contact with a woman's breasts, likely creating a good deal of discomfort. Consequently, the constructed user in this scenario is male.

Similarly, location of sharp corners is very important. A sharp corner in a sensitive area can cause discomfort. As can be seen from the Figure 1.5, sensitive areas are not always easily defined. If a wearable device with sharp corners is not carefully positioned, it can inflict pressure on a sensitive area of the user's body.

The fit of a garment or device on a specific individual dictates both the amount of pressure the components exert on the body and the location of those components on the body. As previously discussed, these factors can have a significant impact on the overall comfort of the wearable device. Fit is a difficult parameter to generalize, but also one which is often generalized to facilitate mass-production. This is evident in standard ready-to-wear clothing. In order to produce clothing efficiently enough to keep costs low, garments must be made in a limited set of sizes. These sizes, however, fit only a small portion of the actual population. Sizes are arrived at by designing the garment to fit one individual perfectly (the "fit model"), and subsequently grading (changing the pattern in increments) the base pattern to produce smaller and larger sizes. Unfortunately, real bodies are not conveniently graded into neat categories. The variation in individual body measurements is almost as unique as the variation in fingerprints. In most standard garments, adjustability, ease, or stretch is incorporated into the garment to allow it to fit a broader range of actual bodies, but in many wearable devices, the placement of components is precise and must be accurately placed on any given body. An adjustable body-mounted device is usually adjustable in circumference, that is to say it incorporates some kind of stretchable or Velcro closure that can fit a range of circumferences. However, as illustrated with the torso sensitivity map, precise placement of a component on the body is three-dimensional, which cannot be achieved by adjustability in one dimension. The fit of a device on an individual can often affect device functionality, as well as comfort. For instance, a device with precisely placed sensors that must be in contact with the skin will not function if it does not fit well. Standard sizing systems routinely do not address extreme body sizes and shapes. Extremely tall, short, or wide individuals, or individuals with less common body proportions, find their needs are not addressed by the mass market. Similarly, garments sized for men will not accurately fit women. Consequently, moving technologies into the intimate physical space quickly causes a physical configuration of the user—a determination of which individuals can become users, by dictating the user's physical size and shape, as well as gait, strength, and balance.

1.4.2 Cognitive Configuration of the User

Just as a wearable device can influence the configuration of the user, the ubiquitous nature of a wearable application can likewise magnify the effects of the technology on the cognitive processes of the user. Computational devices designed to augment our mental capabilities often influence existing capabilities by encouraging the user to interact with the device in a specific way. Hoffman describes the role of a text editor software interface in constructing the gender, skills, and manner of work of the user, through the specification of the way in which the user must interact with the machine (Hoffman, 1999). However, existing computational software for desktop environments is primarily designed such that the user initiates specialized tasks, which are then delegated to the machine. Wearable devices offer the ability to interface more intimately with our existing cognitive processes. For example, much research has been done in the area of memory augmentation, just-in-time information retrieval to improve our mental recall abilities (Accenture, 2003; Rhodes, 2000; Wong and Starner, 2001). In these situations, increased influence of the device on the user's mental processes results in an elevated level of cognitive interaction between the user and the device. In the example of a memory aid, a technological augmentation can mean that the user must remember things in a specific way. A memory aid developed by Accenture, for instance, uses an interface that requires the user to use specific vocal commands (such as "nice to meet you") to trigger recording of information. Information is then stored and retrieved using similar commands. This precludes the use of other memory aids, such as remembering a conversation by a visual element (such as the strange tie the other person was wearing); instead one must remember using their name, or another audio-based contextual element. Such an assumption about the user's behavior configures other aspects of the user, such as his/her implied existing memory capacity, his/her method of recall, and the kinds of situations the user may find himself/herself in. (For instance, the phrase "nice to meet you" may not be useful in the context of a college keg party.)

Augmentation of an individual's mental capabilities in a continuous-operation, multi-contextual paradigm can also create demands which can force the user to re-prioritize his/her delegation of attention. Wearable cognitive aids are often configured in such a way that their “output” is difficult to ignore. If for instance the user views the world entirely through a filtered optical screen, a text output laid over that screen can be distracting or even totally incapacitating. Likewise, an audio output can prevent the full use of the sense of hearing as well as requiring the user to attend to the message, perhaps at an inappropriate time. Designers of devices such as Accenture’s Personal Awareness Assistant emphasize their device’s social subtlety (others are not aware of the device functioning) as a justification for continuous operation (i.e., no one else can hear it talking, so therefore it can talk as much as it wants). However in this configuration, the device establishes itself as the primary priority for attention, forcing the user to re-prioritize other attentional demands. This is evident in other applications besides the memory aid scenario. Any situation where the wearable device actively produces output (be it visual, audio, tactile, or of any other form) without a direct request from the user can force the user to shift their attention from the task at hand to attend to the device. The device thus imposes itself over any other concurrent activity. Similarly, however, a device which requires a direct request from the user to produce output requires that the user first realize the need for information from the computer, then perform the command and process the output. This is also an attentional demand, although it allows more flexibility of timing.

One way in which wearable technology seeks to avoid inappropriate demands by the device for attention is by embedding context awareness into the device. Through a multitude of sensors, the device can monitor the status of the user and of the user’s environment, and use that data to make decisions about appropriate information to display to and means of communication with the user. However, this kind of “intelligence” is far from fully aware. The device must be programmed to respond in a given way to a given set of sensory data. One outcome of this programming may be that the user can then be seen to adapt his/her own behavior according to the anticipated or desired response of the device. For instance, a device may be programmed to monitor the user's emotional status, and provide an "appropriate" response. That same user may then begin to regulate the physiological signals (heartbeat, perspiration, etc) through engaging in or avoiding specific activities, in order to elicit a desired response from the device, or to avoid an undesirable response from the device. Viseu (2003) points out that in the case of devices where data is collected and observed by a third party, the user may then deliberately avoid certain activities to influence the perception of their status by the external party. The technology can then be seen to configure the lifestyle patterns, activities, cognitive processes, and even physiological responses of the user.

1.4.3 Social Configuration of the User

Again, as with physical and cognitive processes, a ubiquitous wearable device shows increased influence over the social and emotional functioning of the user. Wearable devices are often used for communication between users and communication with information sources. The wearable configuration allows the communication of more than text, audio, and images—users can also monitor the physical location, physiological status, and even activity of other users. The MIT wearable lab constructs what they term "borgnets", networks of "cyborgs", or wearable computer users. The 2003 iteration of the MIThril wearable computer allows users to track the movements, status, and activities of other users. (DeVaul, 2003) This configuration clearly has a significant impact on social networks. There is an automatic increased level of intimacy with other users, if one can now monitor another's every move. Users will have different sensory experiences from non-users, and may have the ability to share experiences in real time with remote users. Sharing of experiences can lead to a "collective memory", a conglomeration of the experiences of discreet users, introduced into the group memory (Kortuem, Schneider, Suruda, Fickas, and Segall, 1999).

Wearable technology can also exert visual influences on social interactions. The head-mounted display, perhaps the most obvious and easily-recognizable element of a wearable computer, is a significant visual cue. The development of wearable technology has seldom focused on creating a visually discreet unit. Thus the "cyborg" group is relatively easy to visually identify. Personal adornment is a significant means of establishing personal and group identity (Kaiser, 1997). Groups are often defined by a visually consistent manner of dress. The cyborg visual identity is inherent in most wearable devices, because of their visually obvious presence. This identity is embraced by some and avoided by others. Many daily users of wearable computers enjoy displaying their membership in the cyborg social group, welcoming the departure from the "norms" of daily dress as a means of distinguishing themselves. However this statement is not one that the general population is likely to desire, and there is a general consensus that until such point as wearable technologies look, feel, and behave like "normal" garments, they will not be accepted by the mass market. (Post and Orth, 1997; Barfield, Mann, Baird, Gemperle, Kasabach, Stivoric, et al., 2001) Thus the physical configuration of wearable technologies forcibly places users into a social group, as perceived by others. This may have the effect of alienating the user from non-users, because of the visual incongruities, while simultaneously uniting the user with other users, for the same reasons.

An exploratory area of wearable technology which may have a significant impact on social interactions is that of expressive wearable technology. Expressive technologies apply contextual sensor data towards visually displaying emotional or physiological status. This raises many important questions. Direct expression of emotional reactions eliminates much of the ambiguity in social interactions. On the other hand, this forces the user to communicate the truth, which is not necessarily what the user would like to communicate. Alternatively, perhaps the user will then learn to control physiological responses, and re-introduce ambiguity back into the interaction. In this way, the device once again configures the manner in which physiological responses occur in the body.

1.4.4 Homogenizing the User

The limitations of production and design of wearable technology in these early stages of development have dictated a single constructed user, a mold to which other users conform in using the technology. Viseu describes the man-machine combination as a body(net), a bridge between the body and the environment. (Viseu, 2003) She describes how this body(net) mediates sensory perception, cognitive and social processes, but also how the body(net) clearly mediates the physical world, physical size and shape as well as posture and movement. Adoption of wearable technology has seen successes in areas where the problem of a homogenized user can be sidestepped: in situations where a homogenized user can be dictated, and in situations where there is only one user.

The first case is shown in the military and in industrial applications. In both situations, the users of a technology have relatively little autonomy over the decision to use the technology or over the specific configuration of the technology. As with other occupational technologies, if the design is not well done, the adaptation of the user to the machine can result in injuries and discomfort. Frequently the machine is not adapted to the user unless injuries occur or the worker’s pace or functionality is seen to be hindered. In a military situation, there is less anthropometric variation than in the population as a whole because of programmatic limitations based on physical size and physical capabilities, thus the sizing problem decreases. Military users often have weights and volumes imposed on them, and are expected to accommodate these changes to their physical form.

The second case is evidenced in the population of hackers and researchers who build wearable computers to their own specific needs. Depending on the skill of the builder and the time devoted to the project, such wearable technology can be very well-suited to the needs of the individual: physically, cognitively, and socially. Perhaps more importantly, the user/builder retains complete control over the functional and physical configuration of the machine. He/she can add, delete or modify software at will, re-assemble hardware, add or remove components, etc. Earlier the example of the MIThril 2002 vest was used. It was clear that the physical configuration of that wearable was ill-suited to a female user. However, the designer (and almost all of the users) of that prototype was male. Therefore the physical configuration was well-suited to his needs. Most of the hacker population builds wearables exclusively for its own use. In that way, hackers are able to configure the machine to fit themselves, and modify it if the result calls for too much adaptation on their part.

If successful adoption of wearable technologies is seen in arenas where the user is either singular or easily-dictated, failures are seen in large groups of autonomous users: the mass market. Mass market wearables have yet to take root, despite years of development and easily-available facilitating technologies. This is due to many diverse factors, but the configuration of the user ranks high among them. The most common objections to wearing technology are “it looks funny”, or “it’s so bulky”. These two complaints stem from an aversion on the part of the user to being forced to look or move in a specific way because of the technology. Cognitively, similar trends of non-use are seen. In a test of a wearable scheduling software, researchers at Georgia Tech discovered that even when fitted with a wearable software which automatically entered appointments into a calendar, users still used their paper calendars to record appointments. (Wong and Starner, 2001) Perhaps this is due to a reluctance to think or speak in a specific way in order to get the software to function properly, or perhaps it is due to an aversion to the imposed attentional demand of the machine functioning at-will and the human adapting.

In the early development of wearable technology, not much attention has been given to design for adaptability or for accommodation of a wide variety of diverse users. Consequently, a one-size-fits-all paradigm has been adopted, which imposes physical, cognitive, and social constraints on the user. A homogenized user is hypothesized, one who possesses specific physical traits, cognitive capabilities, and social identity, and who adapts in a specific way to the functionality of the machine. This paradigm has only been successful (as measured through actual adoption and use of wearable devices) in situations where the user can be specified (where users have little autonomy), and in situations where the device is designed for and by a single user.

The future of wearable technology relies on mass-market acceptance, or at least penetration into slightly larger markets. In order for usage to grow, devices must take into account the physical, cognitive, and social needs of the user, as well as the immense variation in these traits among users. Suchman (1999) describes the necessity of a shift in design culture, towards viewing the production and use processes not as discreet, unaccountable practices, but as integrated social networks, constantly influencing one another. She points to the limitations of personal knowledge as being relative to and inhibited by location, resulting in the necessity of developing a collective, objective knowledge base from the respective viewpoints of many members of the network. Localized knowledge results in either the designer designing for themselves, or the designer designing for a user of whom only a vague conception exists, full of assumptions which are often not grounded in reality (Agre, 1995). Localized knowledge is useful only when the designer *is* the sole user, a rare circumstance.

The extensive network of influencing variables that are involved in the design of wearable technology present new challenges to designers. Because of the complexity of such a design task, addressing the entire scope of necessary variables becomes a daunting task, which cannot be met by an intuitive design process. The functional apparel design process can be seen as an aid to the designer, a means by which to ensure that all variables have been taken into account, and a way in which to inspire innovative solutions. Because of its iterative nature, new or emerging variables can be analyzed and addressed before the product actually reaches the market, thereby helping to prevent the financial setbacks that can impede the commercial growth of a new industry. The long-standing tradition of thorough technical analysis in functional apparel design can benefit the design culture of wearable technology, but neither functional apparel designers nor technology designers are fully able to understand the complete scope of variables involved in the design of wearable technology, thus it is a meeting of these two worlds, as well as that of human-computer interaction, that is necessary.

1.4.5 Design Culture and the Aware Design Process

The differences in issues addressed by functional apparel designers and technology designers help to identify the areas of improvement for wearable technology design, but it is important to also examine the reasons for these differences. Why, for instance, existing wearable technology design has not to date effectively examined issues of the physical, cognitive, and social interface between the user and the body-worn device. This can arguably be traced back to differences in design culture or design worldview: the subconscious social influences on a designer that dictate the objectives for design, as well as the variables involved in the making of design decisions. However, one might also ask how a particular design culture or worldview comes into existence—how are the "popular" variables for consideration identified, and how do individual methodologies gain their popularity? Often, they arise from experience and experimentation. As a new field of investigation is established, it often initially makes use of the design culture of the field from which it emerged. This is certainly the case in wearable technology: the principles, theories, and methodologies that were successful in the design of desktop or portable devices have been applied to wearable devices, with less success. Variables and methodologies that originate within the expertise of a technology designer (for instance, the hardware or software design of a wearable device) are re-evaluated and more appropriate solutions are generated. However, in an interdisciplinary field such as wearable technology, many new variables lie outside of the bounds of the original parent field (notably, variables pertaining to the body and the human interface). In this case, there are two explanations for the failure to address these new variables: intentional disregard of new issues (based on a design cultural belief that they do not pertain to the new field, or an inability to address foreign variables or conduct new methodologies in a limited study, or the assignation of a low priority to less-understood variables) or unintentional disregard of new issues (lack of awareness of the existence of foreign variables/methods on the part of the designer).

While the functional design process emphasizes an awareness and open-mindedness in the designer, many unknown or misunderstood variables can be missed by the most aware designer, or inappropriate methods used, simply by lack of precedent. This is where the iterative nature of the design process becomes crucial: variables that have not been addressed will often emerge in various stages of the design process, at which point a new iteration begins. However, in wearable technology design, human interface issues remain unaddressed even following a design evaluation process. This is a result of two influencing factors: narrow definition of the design project goals, and a lack of iteration in the design process.

As previously discussed, many wearable technology design projects focus primarily on the function of the device, or on a technological advance (new hardware, software, etc). Thus the goals of these projects are narrowly defined, and rarely include any analysis of user comfort or acceptance of the device. Evaluation processes almost never include a real-world field test of the device (a combination qualitative/quantitative process which can be described as a new/foreign methodology in many areas of wearable technology design). This links back to the conscious disregard of new or foreign variables: reasons of design culture, lack of resources, or assignation of a low priority to foreign variables. Therefore, since new variables are not a part of the initial design goals, and are consequently not evaluated, they may never emerge as issues in the design process. And since projects are most often isolated and not continued in an iterative design process, test prototypes are rarely developed to the point where a real-world field test would be necessary, such as in a commercial sales scenario

. Of the few design projects that do reach a commercial market (or a real-world field test), in most cases, the user is specified in such a way that issues of social acceptability, comfort, and individual identity are avoided (see section xx: Homogenizing the User). In the few cases where new variables emerge in the evaluation process, they are rarely passed on to future projects, another consequence of non-iterative design.

1.5 Method of Approach

Because the field of wearable technology is still new and not well established, there are a great number of areas which have yet to be investigated. And because the technological perspective and the apparel design perspective have not yet been completely combined, the design of wearable technology is often prone to errors due to bad design choices.

As previously discussed, the new physical, cognitive, and social issues of wearable computing are complex and often interrelated. Because of this, rather than focusing on solving one individual problem or investigating one issue, this study uses the functional apparel design process and design culture to inform pilot investigations into several interrelated issues in the design of wearable technology. The functional apparel design culture brings novel expertise to the design of wearable technology, particularly in the area of human-device interface. Thus, the approach of a functional apparel designer will bring new awareness to the design process, but the awareness is by no means complete. The technologies evaluated in these investigations are chosen to avoid the complex design issues routinely addressed in technology design: they are simple technologies, without significant programming requirements, physical size, or engineering complexity. They have been chosen to allow the evaluation of specific human-interface design issues, without the complicating factors of complex technology design. Therefore, these investigations can be seen as having been conducted within a functional apparel design culture: aware of and addressing the complex variables present in that design consciousness, but unaware and exempt from the complex variables of technology design.

Three individual tests were conducted to investigate the interface between the human and the device in the three most significant areas of interaction: input to the device, output of the device (both of which address physical and cognitive issues of design), and the visual representation of garment-integrated technology (which addresses social issues of design). In addition to physical, cognitive and social issues, the following major design principles were also major themes in all three investigations: wearable integration of technology, garment-appropriate application and distribution of wearable technology, and socially accommodating wearable technology design. The projects undertaken were: the integration of electrical sensing technology for biological input in a bio-monitoring bra, the development and testing of a shoulder pad vibrotactile display, and the development and testing of shirts with a massage function and different levels of visual representation of wearable technology. All three sets of prototypes were designed for a female user. This itself is unusual in the field of wearable technology design, where the configured user is almost exclusively assumed to be male. The design process, however, is not exclusive to design for the female body—it can be applied in the same way to issues related to male anatomy and physiology.

The research process used in these studies follows a traditional design process, but projects are limited in scope and have a compressed timeline. Because this field of investigation is very new, and the under-explored variables are numerous, initial explorations were made into several important issues instead of concentrating on a single issue or design. The functional design process gives the designer a framework in which to operate to minimize the chance of incorrect assumptions leading to bad design decisions, but the variables to be included and the specific design decisions can often come only from experience and experimentation. Rather than working toward the goal of finding the best answer to one question, these studies aim to educate the designer and the design process with respect to the scope and nature of the new variables present in the wearable environment. Each experiment demonstrates the way the design process can guide decision making. Each experiment answers some questions but poses even more.

Thus the studies undertaken represent pilot investigations in each area, meant to illuminate the problems and concerns specific to each, with the intention of further investigation. As related to the design process, they represent different steps leading to the first iteration in each case, resulting in the first test prototype. The test results from the first prototype can then be used to influence the generation of the next prototype.

The following sections describe major areas of focus in the design of the three component investigations in this study, areas which represent deficiencies in prior design projects: distribution, integration, and applications in wearable technology design, and socially adaptive/accommodating design.

1.5.1 Distribution, Integration, and Applications in Wearable Technology Design

As previously discussed, wearable technology design rarely takes into account the disparity between the usage scenarios, life cycle, and cultural roles of technology and apparel. The functions of a garment and a device must be to some extent reconciled, in order to maintain the full usability and roles of both. Similarly, the manner in which a user interacts with a garment must to some extent be preserved in order for the augmented garment to be perceived as acceptable, useful, and attractive.

This end can be achieved to some extent by the distribution of technological components throughout a garment system, instead of localizing them in one unit. Localization can result in a significant weight/volume in one garment (altering the aesthetics and comfort of the garment) and significantly increasing its cost and lifespan. The function of the technology is also restricted to the situations in which the garment is comfortably worn. Distributed technology lowers the added cost of the garment (and consequently, decreases its expected lifespan), and makes it possible to coordinate the required functions of the technology with appropriate garments. Some functionality, such as data storage, is not appropriately integrated into any garment, since no garment is currently worn constantly. Since most garments are specialized to specific situations (such as uniforms, work clothing, exercise clothing, outdoor gear, et cetera) it then becomes possible to integrate functions which are useful in the given situation into the appropriate garment. Since these functions may be less elaborate than a full-function computer, they may require less processing power, storage, battery life, development time, et cetera, consequently reducing the cost of the technology and thus of the garment.

This design principle was used in the design phase of two projects: the shoulder pad vibrotactile display and the bio-monitoring bra. The vibrotactile shoulder pad display was designed to make use of the pre-existing volume created by a standard shoulder pad. Thus the volume of the electronics, the bulges and bulk that are often created by integrated technology, remained visually imperceptible. Subjects also found the augmented shoulder pad as comfortable or more comfortable than a standard shoulder pad. In this application the display unit of a complex technology was integrated into an appropriate garment: in this case, into the business jacket. Vibrotactility affords a very subtle form of computer output: a silent, invisible form of human-computer interaction. The business environment encompasses many situations in which the overt interaction with an automated or communication device (such as a cell phone or scheduling device) has a negative social impact on social interactions. Another situation which could make use of invisible interactions is one in which two or more individuals may desire to communicate with one another without the knowledge of others present (such as in a group negotiation scenario).

The electronics integrated into the garment were minimal and inexpensive: limited to a set of pancake-style vibrating motors. The test configuration relied on hard-wired interconnections, but the available volume in the shoulder pad would allow a wireless configuration without visual impact. The shoulder pad also allows the interchangeability of parts: an electronic shoulder pad set can be easily made removable, allowing one set to be used with multiple garments, and simplifying the care of the garment. Similarly, the concept of embedding electronics into the pre-existing volumes and stiffened areas of a garment allows devices to not only become easier to manufacture (by creating electronics as a single stand-alone unit that can then be integrated into a garment), but also less visually and physically perceptible (as they exploit stiffnesses and volumes that the user is already familiar with in the garment).

In the case of the bra, minimal electronic components were integrated into a standard sports bra, to test the ability to monitor heart activity and muscle activity. Small metal plates, acting as electrodes, were integrated into the bra. These components were small enough not to be distinctly perceptible by test subjects: in fact, several asked to be shown where the electronics were, after having donned the garment. The components used were standard buttons and studs, hardware commonly used in apparel, and of negligible added cost. It is conceivable that with an appropriate hard-wired connector, all of the bras that an individual owns could be bio-monitoring bras, with no significant change in their cost, appearance, or comfort. This prototype configuration relies on hard-wired connections. At the present stage of the technology, a wireless version would require significantly more electronics embedded in the bra. In the case of the shoulder pad display, the pre-existing volume of the shoulder pad provides enough additional space that integration of wireless communication capability would not significantly impact the physical presence or comfort of the shoulder pad display. However, there is no similar pre-existing volume in a bra. Therefore, successful integration would require a carefully designed (very small, and perhaps flexible) wireless communication unit. The movement of the torso (and therefore the bra) would also require significant durability.

1.5.2 Socially Adaptive/Accommodating Design

Maintaining cultural norms for apparel and technology can in some part be facilitated by distributed, well-integrated technology and garment-appropriate applications, but the definition of "norm" varies from individual to individual: it is in part what defines our individuality. This is especially evident in our aesthetic choices. Our outward visual representation is intimately tied to how we are perceived by others, as well as how we perceive ourselves. Sartorial cues communicate our individual identity and our group associations. The addition of visually prominent wearable technology can immediately place the wearer in a social group, to which s/he may or may not wish to belong. Once one group adopts a particular look, it can become highly unacceptable to another group due to the association. The cyborg/cyber-punk community may well embrace a "high-tech" aesthetic and identity, where more conservative social groups may summarily reject it. Outside of purely social concerns, there are many user groups (such as doctors) for whom an inappropriate aesthetic appearance can significantly impact occupational credibility, who at the same time may clearly benefit from wearable technologies.

In cases where technology is vitally necessary (such as wearable medical technologies for recording physiological changes), the aesthetic appearance of the technology is often sidelined in favor of reliable functionality, but can have significant impact on the way the wearer is perceived by others and how they perceive themselves. The technology can become a significant delineating factor which establishes the impaired individual as separate or different from the rest of society.

If we accept that individuals will have different aesthetic preferences for wearable technology, the question then becomes how to identify and facilitate these different tastes. Often such exploration is not practical, especially in cases where the technology itself is so costly that extremes of aesthetic expression are not easily explored, such as in the development of a full-function wearable computer. However, costly technologies are also often not the most optimal way to introduce wearable technology to consumers. Early adopters aside, the majority of the consumer public may not be willing to take the larger risk of buying an expensive article of wearable technology, especially when its social impact or symbology is not yet certain. Consumers can be introduced to wearable technology with less purchasing risk and their preferences explored by way of simpler, less expensive technologies.

To investigate the relationship between individual perception of personality and aesthetic preferences in wearable technology, three simple, inexpensive technological shirts were constructed. These shirts were identical in function (each performed a vibrating shoulder/back massage on demand), and varied in their aesthetic expression of that functionality, ranging from very subtle technology integration to very visually overt integration.

This investigation allowed subjects to be introduced to a simple garment augmented with an easily comprehended function, and to react to the garment's function and aesthetics without the psychological weight of an expensive or complicated computing technology.

CHAPTER 2: INPUT DEVICES: THE BIO-MONITORING BRA

The interaction of a user with the input modality of a wearable device can dictate the user's cognitive processes and physical movement and comfort as well as influence the usability of the device. The most common problem in input design is the creation of a large cognitive load for the user. Input methods traditional to desktop or mobile devices primarily involve keypad- or keyboard-based interaction. Some advances have been made in voice recognition software for vocal input, but this modality is less reliable in the wearable environment. A major advancement in the design of wearable technology has been the development of context-aware input. Context-awareness is more or less unique to the wearable environment, the only paradigm in which the device has access to enough context information (information about the user's state as well as environmental conditions) to provide useful input. The major benefit of context-aware input is that it poses no cognitive load for the user.

However, for context-aware input to be useable, it requires some degree of reliability. This is particularly problematic in the case of biological input, as many biological sensors are either physically invasive, obstructive to normal movement (such as impeding manual dexterity), or require constant contact with the skin. All of these factors create problems for wearability in an everyday environment. In the case of skin-contact sensors, constant contact is often achieved through adhesives or other fixatives. While functional, these solutions are not practical in a constant-use paradigm. Meeting the functional needs of the device and the physical needs of the user simultaneously is an interdisciplinary human interface design problem.

This study investigates the new variables in the wearable environment related to the design of an electrode-based bio-sensing system for context-aware input.

2.1 Methodology: Bio-Monitoring Bra

Bio-monitoring of many kinds is an attractive input source for many wearable computing applications. The obvious utility is in health-monitoring or remote medical services. But aside from purely medical applications, bio-monitoring provides a method for computing devices to use unconscious physiological changes in the user as input information to drive various functions. This kind of context-aware response can reduce the cognitive load of the user and make interfaces more intuitive.

Bio-monitoring is used in research and in medicine fairly extensively. However, the observation/data-collection environment in research or medicine is much more controlled than the wearable environment. Using bio-monitoring technology in a mobile, wearable context presents many new wearability, usability and functionality concerns.

In this study, two electrode-based bio-signals were examined: the electromyogram (muscle activity) and the electrocardiogram (heart activity). These signals can be indicators of physical activity, physical abnormalities, or even emotional states such as fear, apprehension, stress, or surprise.

The ultimate goal of this research is the creation of a truly comfortable, wearable means of gathering electrical potential signals. Female users were selected for this test, in order to take advantage of the upper torso skin contact afforded by the bra. The end use of the bio-monitoring function was conceived to be necessary for uses other than (although possibly including) medical monitoring. The end uses are assumed to be long-term, requiring continuous monitoring on a daily basis, while maintaining the physical comfort levels of an ordinary bra.

2.1.1 Background: Electromyography

The electromyogram (EMG) is a measure of the electrical potential created by tension or contraction of the muscles. It can be recorded as an individual muscle action potential (MAP) or as a combination of the activity of many muscles simultaneously. In the resting state, individual muscle fibers maintain a negative intracellular potential of 50-100mV. When the muscle is stimulated, the polarity of the cell membrane is briefly reversed. In the resting state, the sodium-potassium pump in the cell membrane is required to maintain an equal balance between positive potassium molecules and negative sodium molecules, to assist the negatively charged molecules in entering the cell. When the membrane is depolarized, sodium molecules pour into the cell, quickly establishing a measurable electrical potential (Goldstein, 1972).

Muscle fibers react to stimuli transmitted by the nerves which connect to each fiber. Multiple muscle fibers are controlled by one single nerve, and this grouping is referred to as a “motor unit”. The action potential response of a motor unit to a stimulus, when displayed in a graphical manner (via oscilloscope or other real-time graph), results in a sharp spike. However, when the action of multiple motor units (a whole muscle) is recorded, the response is seen graphically as a series of spikes of varying amplitude, which represent the responses of the various motor units contained in a muscle, as seen in Figure 2.1 (Basmajian, 1974).

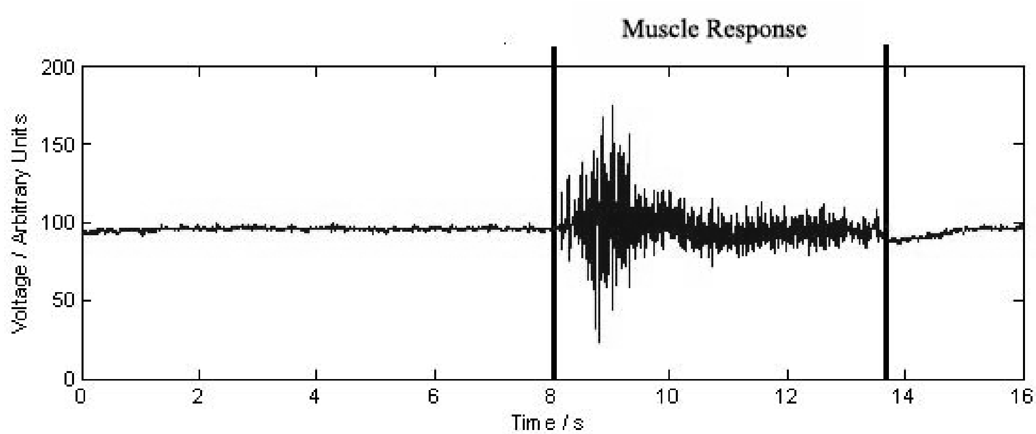


Figure 2.1: EMG Muscle Response

2.1.2 Methods of EMG Measurement

EMG potentials can be measured in two ways, each of which has its advantages and disadvantages. *Surface* EMG measurement measures the electrical potential of the muscles through the skin. Electrodes (generally two per measurement, although a third common ground electrode may also be used) are placed on the skin surface, on top of the muscle or muscle group being measured. The resulting current between electrodes is then passed through an amplifier and displayed on an oscilloscope or computer interface. This method is non-invasive and not painful, but it is also not a very precise measurement. Activity of individual muscle fibers can not be measured with this method. The current must also be passed through the skin, which can distort or dampen the signal. The method of application of the electrodes to the skin can also alter the results obtained.

Intramuscular and *subcutaneous* electrodes are two additional categories of electrodes which penetrate the skin surface to measure the muscle more directly. Subcutaneous electrodes penetrate through the dermis to the surface of the muscle fiber, and intramuscular electrodes penetrate further into the muscle fiber itself. Penetrating electrodes (generally needles or wires which are inserted into the skin) allow measurement of individual motor units. This method is more invasive, and may cause anxiety responses in subjects which can complicate resulting data.

2.1.3 Background: Electrocardiography

The heart is also a muscle, one of the most active muscles in the body. Therefore, its activity can be measured in much the same way as the activity of other muscles, through the electrocardiogram (ECG or EKG). The heart's activity is often stronger than other muscles, and can be measured from peripheral areas of the torso. Figure 2.2 shows the heartbeat waveform gathered from the trapezius muscle, which is apparent even during flexion of the muscle. The "spike" of the ECG waveform appears, although the rest of the waveform is distorted by the increased and irregular amplitude of the EMG signal (center portion).

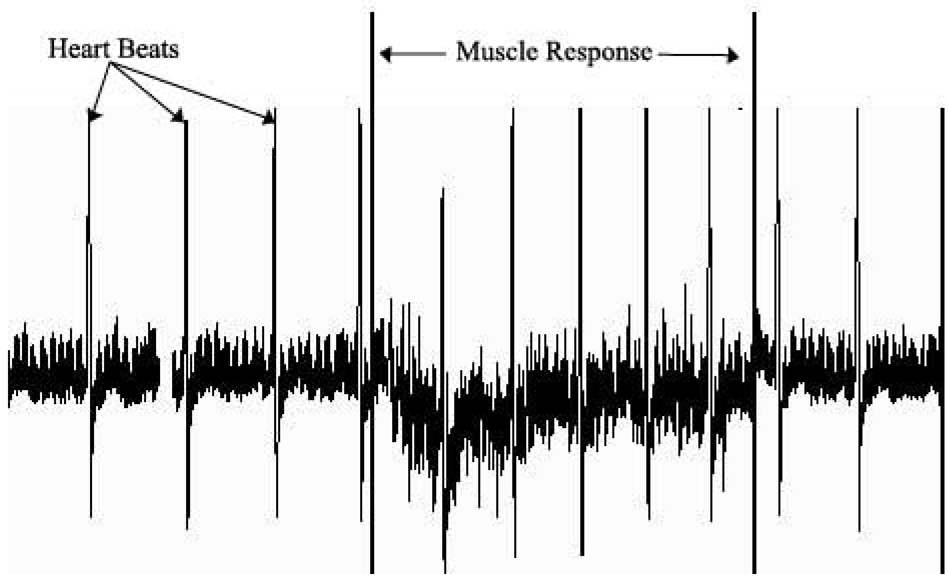


Figure 2.2: EMG of the Trapezius Muscle, Showing ECG Wave

The heart has a more complex action, however, than many other muscles. The heartbeat waveform is split into 5 segments, labeled P,Q,R,S and T, shown in Figure 2.3.

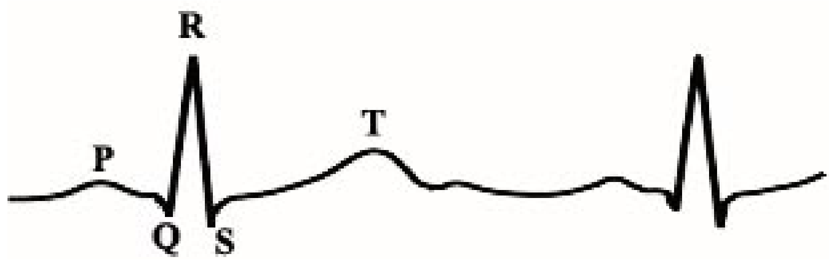


Figure 2.3: The P,Q,R,S and T segments of the ECG Waveform

In order to capture each segment of the waveform separately, 10 electrodes are used to create 12 "leads" or measurement points (the standard "12-lead" ECG recording). Lead placements are shown in Figure 2.4. 3 bipolar electrodes create "Einthoven's triangle" around the heart, recording the larger-scale electrical potentials in the torso (Figure 2.4: R, L, F). As bipolar electrodes, these measure the difference between two electrodes. Three unipolar electrodes known as the augmented leads are placed in similar positions (Figure 2.4: R, L, N). Unipolar electrodes measure the electrical potential directly under the electrode, referenced to a "null point", a point which does not exhibit electrical change during the contraction of the heart. This point is obtained for each electrode by adding the potentials of two other electrodes. The R, L, N, and F electrodes can be placed either on the hands and feet or on the shoulders and thighs. Lastly, six precordial unipolar electrodes (Figure 2.4: v1-v6) measure the electrical potential of the heart across a cross-sectional plane. These leads permit the measurement of each individual segment of the PQRST wave. The 12-lead configuration is used in situations where the individual components of the waveform need to be examined, such as in precise medical analysis of heart arrhythmias.

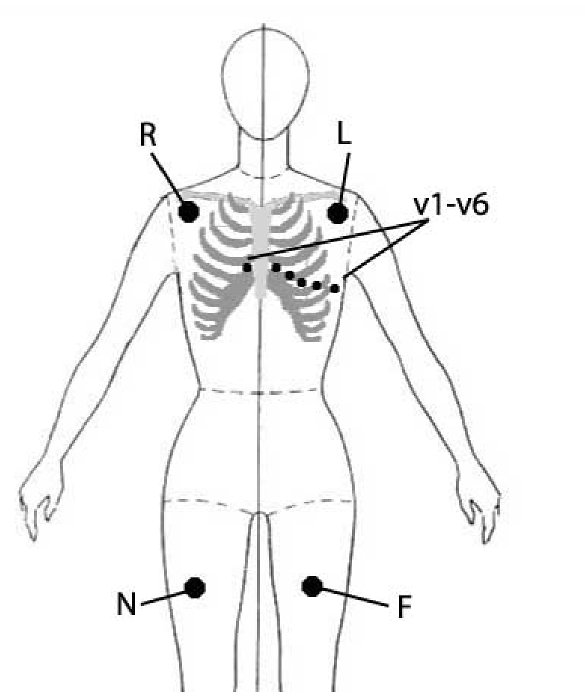


Figure 2.4: Placement of Leads for Standard 12-Electrode ECG

To obtain a full (though less precise) PQRST wave, however, all 12 leads are not always necessary. A complete wave can be captured using only the 3 electrodes that create Einthoven’s triangle (R, L, and F), as seen in Figure 2.5.

Figure 2.5: PQRST Waveform, Measured with 3-Lead ECG

2.1.4 Mobile Measurement of ECG

Although the primary environment for measuring ECG is in a controlled laboratory or clinical situation, this method does not always capture the desired ECG data. For instance, many heart arrhythmias do not occur constantly. A single monitoring session in the doctor's office may or may not catch the irregular beat. Thus, longer-term monitoring is necessary. In severe cases when continuous data is needed, the patient may be admitted to a hospital and kept in a controlled environment under surveillance. However, in the majority of cases the patient is given a "wearable" device, and instructed to wear it for a period of time while going about their normal routine. Such devices are generally referred to as Holter-type monitors. They can have anywhere between 2 and 12 leads, and may be equipped as presymptom event monitors—so that recording is activated or tagged by the patient pressing a button when symptoms are experienced. Other portable ECG monitors, known as postsymptom event monitors, are carried rather than worn. They contain 3 electrodes integrated into a handheld device, which is pressed against the skin to perform a recording following experience of symptoms. Because the electrodes are not gelled, nor is the skin prepared prior to recording, the data obtained from such a device is less precise. The device relies on the user to provide the contact, which thus is not always consistent. However, the added pressure applied by the user can help create a better contact during recording.

The alternative measurement of heart activity is through a blood volume pulse (BVP) sensor. This is an optical sensor which measures the changes in amount of light reflected by the skin. As the heart beats, more blood is pushed through the peripheral blood vessels, changing the reflectance properties of the skin. The output waveform of this type of sensor shows the R-spike of the heartbeat waveform, but not the full

PQRST detail. It is generally measured on extremities like the fingers, toes, or earlobes, where reflectance changes are the easiest to measure.

The ECG wave is typically measured using surface electrodes. However, especially in the mobile environment, the filtering of peripheral noise is a continual problem. Some types of noise, such as environmental electrical noise (caused by nearby devices, wall outlets, or power lines) are regular and can be filtered out. Other types of noise are a result of artifacts caused by the individual's movement, and are more difficult to eliminate.

The manner in which electrodes for all types of electro-dermal measurement are attached to the body can eliminate contact noise (variations in signal quality based on the amount and consistency of contact between the electrode and the skin.) Adhesives can insure that the electrode does not leave the skin surface, and strain relief on the electrode leads can minimize the effects of forces exerted on the electrode as a result of movement. Preparation of the skin prior to electrode attachment can create a more consistent and secure contact. However, the skin preparation process can be quite invasive and uncomfortable. It involves the shaving of hair in the area of the electrode, abrasion of skin using sandpaper or other abrasive to remove dead skin, and application of a conductive gel prior to adhesion of the electrode to the body.

Noise can also be experienced as a result of the activation of peripheral muscles. In the case of ECG measurement, this is minimized by placing no two electrodes on a single muscle, and using bi-polar instead of uni-polar electrodes. In EMG measurement, however, it can be more difficult to eliminate, except by very precise electrode placement.

Lastly, the most difficult form of noise to eliminate is that caused by the slippage of the skin over the muscles. Especially in the mobile environment, it is impossible to prevent the skin from moving over the muscles. This can introduce a great deal of noise that is difficult to filter out, especially during extreme motion (such as running).

2.1.5 Electrode-Based Monitoring in the Wearable Environment

The mobile environment presents many complicating factors in the measurement of electrical-potential signals such as EMG and ECG. The wearable environment, however, presents additional problems by imposing upon the data collection technology the same requirements of comfort and ease of use that exist for standard articles of clothing. Many applications of wearable technology that could utilize biological signals, such as context-aware information retrieval, provide benefits to the user that are not critically needed. Because of this, the user will not make significant changes in his/her habits or sacrifice aspects of his/her physical comfort in order to adopt this technology. Adhesive electrodes, while a reasonable inconvenience in a medical or clinical environment, would represent a significant requirement for the everyday user. Asking users to adhere electrodes to their skin every day is a request that most users would find too extreme for the associated benefit. Additionally, the long-term use of adhesive electrodes may have detrimental effects on the health of the skin, and certainly can cause discomfort in removing the adhesive on a daily basis.

For these reasons, the wearable environment requires a data acquisition system that is more comfortable and easier to use. Because an electrode is simply a conductor, investigations have been made into the fabrication of electrodes made from conductive fibers or fabrics. The Textrode, for instance, uses knitted stainless steel fibers to create a textile electrode, with the aim of improving the tactile comfort of wearing an electrode. The Textrode is not used with conductive gel, but does require adhesive to affix the contact to the skin (Van Langenhove, Hertleer, Catrysse, Puers, van Egmond, Matthys, et al., 1999). Similar textile-based electrodes have also been used to measure things like bioimpedance, or total body water content (Vuorela, Kukkonen, Rantanen, Jarvinen, and Vanhala, 2003).This application, however, measures a gradual change over a period of more than an hour. Thus problems of intermittent contact are less likely to have a significant interruptive effect on the data gathered.

2.1.6 Subjects

The user for this study was defined as a female, with a need for bio-monitoring for uses other than (but possibly including) medical monitoring. Thus an adhesive electrode was considered to be too invasive, and an alternative was sought. The female subject pool was restricted by bust size, in order that subjects would be able to fit into one set of adjustable prototype garments, without significant differences in garment pressure (fit), which would affect signal quality.

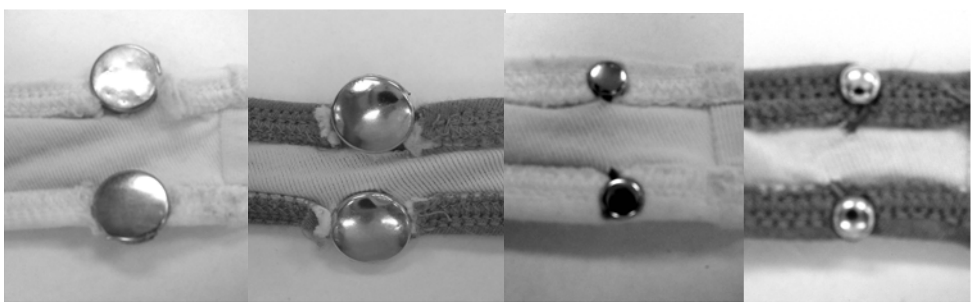
Twenty-seven female subjects with bra sizes between 32A and 36B were tested in two pilot tests: EMG data on the trapezius muscle was gathered for 15 subjects, and ECG data for 12 subjects. The EMG group was further subdivided into two test groups: 8 subjects tested the contact electrodes with conductive gel, and 7 subjects tested dry electrodes. For all subjects, there was no skin preparation prior to the test. Skin was not abraded or cleaned.

Subject participation met the requirements of the Cornell Committee on Human Subjects: subjects were informed of the requirements of their participation in the study, their anonymity was preserved, and they were permitted to discontinue participation at any time.

2.1.7 Prototype garments: EMG configuration

Based on the background research, the following requirements were established for an EMG data collection garment: 3 electrodes were necessary, two aligned parallel to the length of the muscle, approximately at its widest point, and the third located over an electrically neutral (bony) area of the body; electrodes must be held in surface contact with the skin (as sub-cutaneous measurement is too invasive for the wearable environment); and data collection equipment must be shielded from external noise.

For the EMG configuration test, subjects in both group (gel and no gel) tested 4 prototype bras and one control configuration. Each prototype bra contained 3 contact electrodes, made of metal contacts in four different combinations of diameter and shape. Prototype A contained round flat electrodes, 1.4 cm in diameter. Prototype B contained round curved electrodes, 1.4 cm in diameter. Prototype C contained round flat electrodes, 0.6 cm in diameter. Prototype D contained round curved electrodes, 0.6 cm in diameter. Figure 2.6 shows the variation in electrodes. The data collected consisted of EMG signals that varied in their amplitude, duration, and in the changes in amplitude within the signal response.



(a) (b) (c) (d)

Figure 2.6: Test Electrode Variations, EMG Configuration

The control configuration consisted of pre-gelled silver/silver chloride (Ag/AgCl) adhesive electrodes, affixed directly to the skin in the same locations as the contact electrodes in the bras. A control electrode is shown in Figure 2.7.

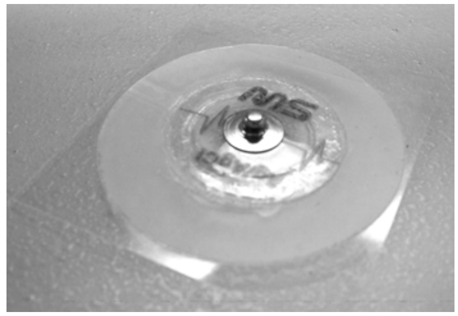


Figure 2.7: Control (Adhesive) Electrodes

The goal of the EMG test was to investigate the differences in recorded EMG signals based on the presence or absence of conductive gel, and based on the difference in diameter and surface contour of the electrode contact. Test configurations using contact electrodes were compared to control configurations using adhesive electrodes.

To measure the EMG activity in the trapezius muscle, two electrodes were placed along the length of the muscle, approximately at its widest point. These were integrated into the shoulder strap of the racer-back sports bra. A reference electrode was placed in an electrically neutral part of the torso, over the bones of the ribcage. This electrode was integrated into the lower chest band of the bra.

Fit of the garment has a direct impact on the contact and consistency of contact of the electrodes. To control for this variable, bras were modified to make them adjustable. In the shoulder pad study, a size range of prototypes was used instead of a single adjustable prototype because of the complexities involved in creating an adjustable shoulder pad. In this study, adjustability was a relatively simple and convenient process, which made it possible to insure that the fit was relatively the same across a wide range of sizes and body types. All 4 prototypes were adjustable in

3 places: each shoulder strap and the center back under-bust band. Figure 2.8 shows EMG electrode placement and adjustability points.

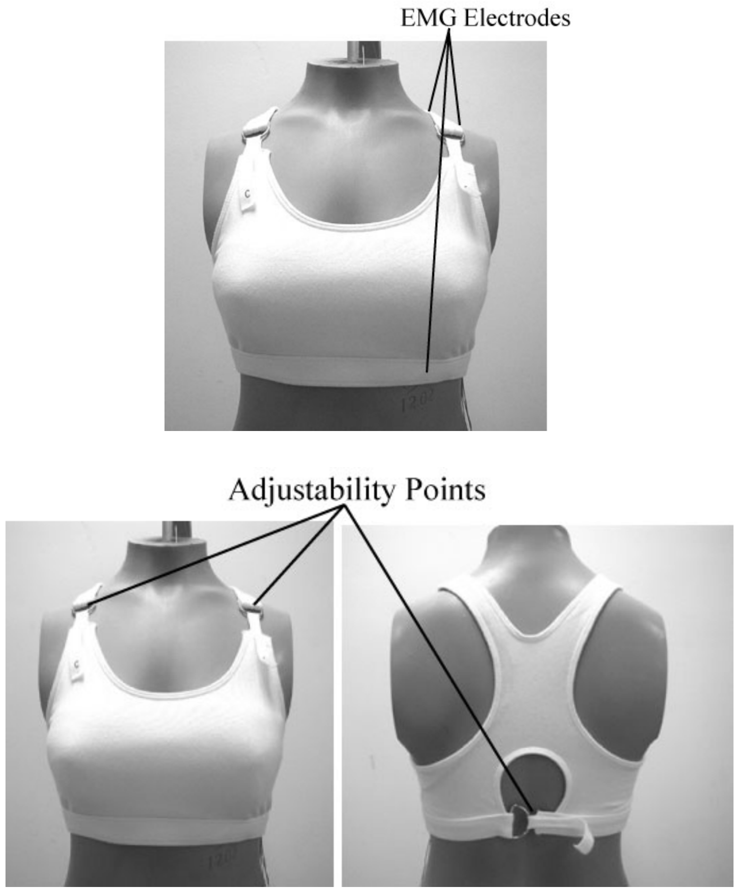


Figure 2.8: EMG Electrode Placement and Bra Adjustability Points

For each subject, each test garment was adjusted using a strain gauge, to obtain similar fit, as judged by the amount of pressure on the skin created by the garment.

2.1.8 Prototype Garments: ECG Configuration

Based on the background research, requirements similar to those of the EMG prototypes were identified. Requirements for the ECG collection garment were: three electrodes used to collect a full PQRST wave (the minimum number of electrodes necessary to record the full wave), arranged to form Eindhoven's triangle around the heart; electrodes held in constant contact with the skin; and data collection equipment shielded from external noise;

In the ECG configuration, all twelve subjects tested dry (no gel) contact electrodes in one test garment, and a control configuration of adhesive, pre-gelled Ag/AgCl electrodes in the same positions as the test electrodes. One single electrode size/shape was used for this test, because the sole variable of interest was the effect of movement on the signal quality. The test garment was of the same construction as the EMG test garments, adjustable on each shoulder strap and on the under-bust band. It contained three flat, circular electrodes, 2.2cm in diameter, shown in Figure 2.9.

Figure 2.9: Electrode, ECG Garment

The garment was adjusted using a strain gauge to obtain similar fit for all subjects. Figure 2.10 shows the electrode placement for the ECG configuration. Electrodes were placed in the traditional locations for 3-lead ECG measurement: one on each pectoral muscle near the shoulders, and one on the ribcage under the bust.

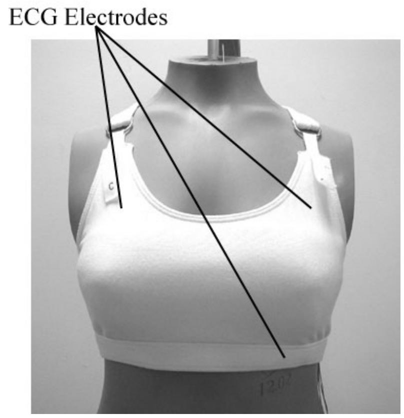


Figure 2.10: Electrode Placement, ECG Configuration

2.1.9 Experimental Procedure

Both groups of EMG subjects (gel and no gel) completed the same exercise in each of the four test garments and in the control configuration. Subjects were instructed to sit relaxed in a chair for ten seconds, and then flex their shoulders for five seconds. This was repeated, and concluded with ten seconds of relaxation, for a total of forty seconds per garment (relax-flex-relax-flex-relax).

For the ECG configuration, subjects donned the prototype garment, then completed a series of movement activities. Subjects first sat relaxed in a chair for 20 seconds, followed by a deep breath (inhale-exhale). They then stood, and were instructed to relax (arms at sides) for 10 seconds, then perform the following arm movements, each of which were held for 5 seconds, with 10 seconds of rest between: first, a ventral abduction to 90 degrees; second, a lateral abduction to 90 degrees; third, a dorsal abduction to 90 degrees; and fourth, a lateral abduction to 180 degrees.

2.2 Results: Bio-Monitoring Bra

In both the EMG and ECG tests, interference of external noise was a significant problem. Noise can be introduced from a number of sources. The primary sources in this test were ambient electrical noise, skin movement noise, peripheral muscle noise, and changes in the electrode contact with the skin (slippage, loss of contact, change in degree of contact).

2.2.1 EMG Test

In the EMG test, data was analyzed unfiltered; due to the complexity of creating a filter for EMG-type data. Whereas ECG data contains a consistent waveform of a lower frequency than most noise, making it relatively easy to remove noise using a low-pass filter, the EMG response is not a consistent wave, but rather a series of irregular peaks which are morphologically similar to noise. Thus the filtering process for EMG data is much more complex than it is for ECG data and was excluded from this test for this reason. Initial examination of the data revealed a significant variation between subjects, even in the control configuration. Figure 2.11 shows some examples of this variation in control data: differences in the response amplitude and in the morphology of the EMG response wave.

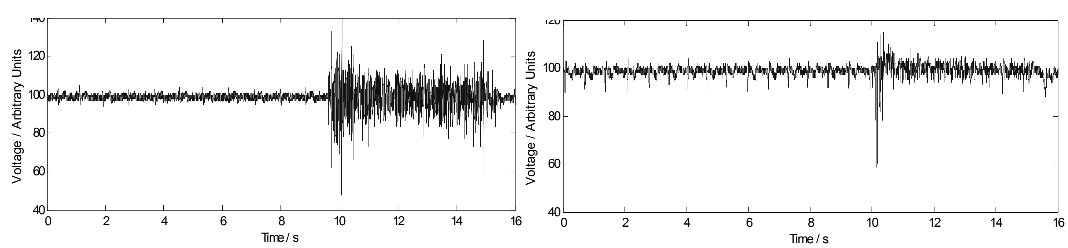


Figure 2.11: Inter-subject Variation in EMG Electro-Dermal Response

Because of the significant variation in subject data between subjects for the EMG test, subject data for each prototype bra were not compared to each other, but only to the control configuration for the same subject. A visual analysis was performed by the researcher and by an expert, to determine if any valid EMG response was present, and subsequently to determine differences in response quality between prototypes. A “valid” EMG response was characterized by a low-noise baseline signal, and an increased, irregular amplitude signal during flex periods.

Of sixteen total EMG subjects, 75% showed a valid response using the control electrodes. The group testing prototype garments using conductive gel showed better results than the group testing dry electrodes. In both groups, larger diameter electrodes in the prototype garments showed less noise in recorded signals, and flat large-diameter electrodes showed less noise than curved large-diameter electrodes.

2.2.1.1 No-gel EMG group

In the no-gel EMG group, five of eight subjects showed a valid EMG response in the control configuration (using adhesive, pre-gelled electrodes). No subject showed a valid EMG response in any prototype garment. All recorded responses from the prototype bras in the no-gel EMG group were deemed invalid, as signal recordings appeared to contain only contact noise, with no observable EMG response. An example of no-gel contact noise responses are shown in Figure 2.12.

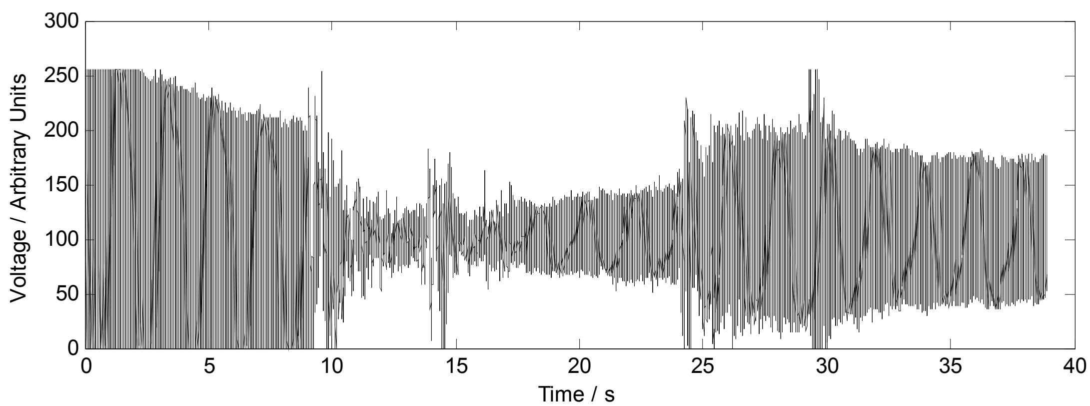


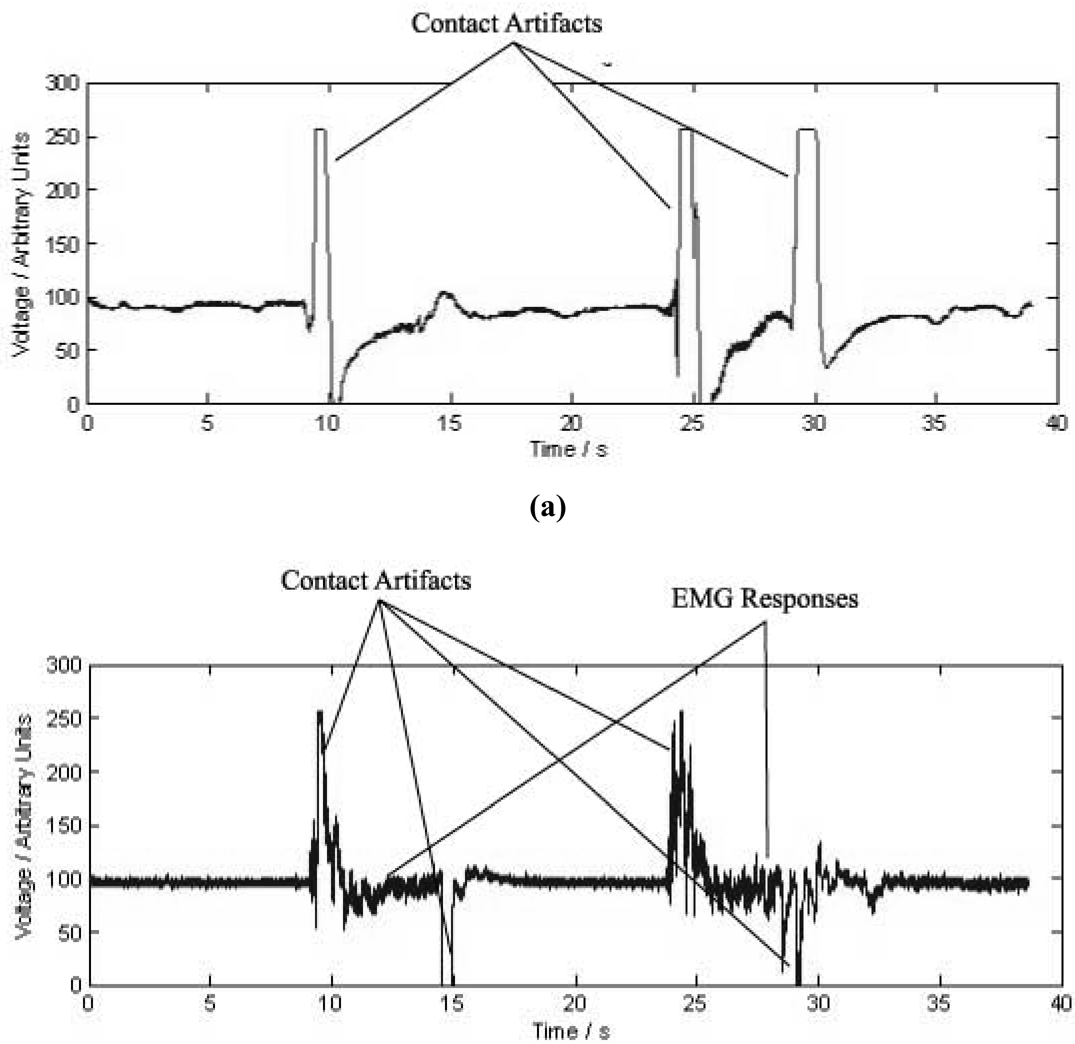
Figure 2.12: Contact Artifacts, No-Gel EMG Group

Subject responses showed a wide range of variation in amount of contact noise. Contact noise is the result of intermittent or inconsistent contact of the electrode with the skin. It can also include artifacts introduced by slippage of the electrode on the skin. Contact noise can be (but is not always) co-incidental with the flex action. Four subjects showed the least noise in the “A” prototype (flat 1.4 cm electrodes), and one subject showed the least noise in the “B” prototype (curved 1.4 cm electrodes). Three subjects showed an equal amount of noise in all four prototypes.

2.2.1.2 Gel EMG group

In the EMG gel group, seven of eight subjects showed a valid EMG response in the control configuration (using adhesive, pre-gelled electrodes). In noise levels, four subjects showed the least general signal noise in the “A” prototype, three subjects in the “B” prototype, and one subject in the “D” prototype. No subject showed a consistent, clear EMG response in any prototype; however, six signals were recorded which contained observable EMG responses, although these responses were combined with contact artifacts at the beginning and end of the signal. Three of these signals were recorded in the “A” prototype, and three in the “B” prototype.

In the gel EMG group, noise levels were generally much lower than in the no-gel EMG group. However, contact artifacts were still present. Figure 3.13 (a) shows a pure contact artifact, Figure 2.13 (b) shows a contact artifact combined with a valid EMG signal.



(a)

(b)

Figure 2.13: Contact Artifact (a) and Combined Artifact/Response (b), Gel EMG Group

2.2.2 ECG Test

In the ECG test, data was filtered using a low-pass filter. The filter program used a Fast Fourier Transform to divide the existing waveform into component sinusoids of different frequencies, which sum to form the existing wave. It used a Gaussian curve, centered at zero frequency to attenuate the high frequencies of the spectrum, eliminating noise that did not fall in the expected frequency range for the heartbeat (PQRST) waveform. An example of the filter's effect is shown in Figure 2.14.

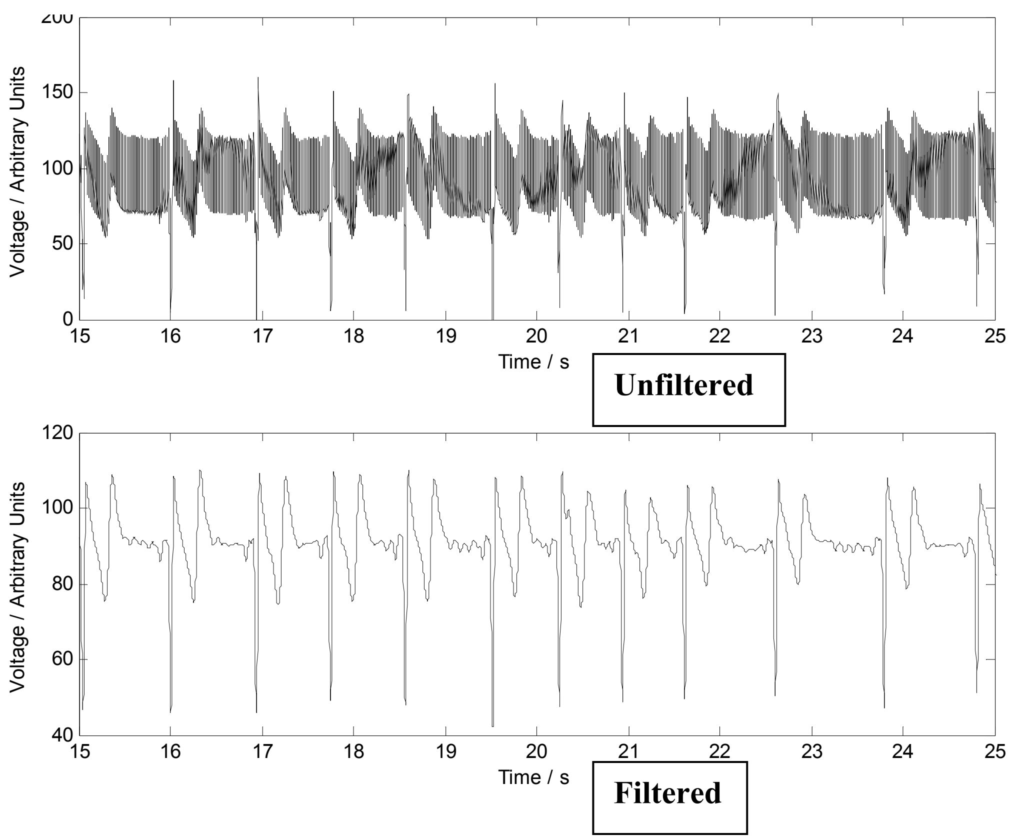


Figure 2.14: Noise Reduction in Filtered ECG Data

ECG subject responses once again exhibited significant differences between subjects, as illustrated in Figure 2.15. Accordingly, data was again analyzed by visually comparing test and control configurations within each subject, not to data collected on other subjects.

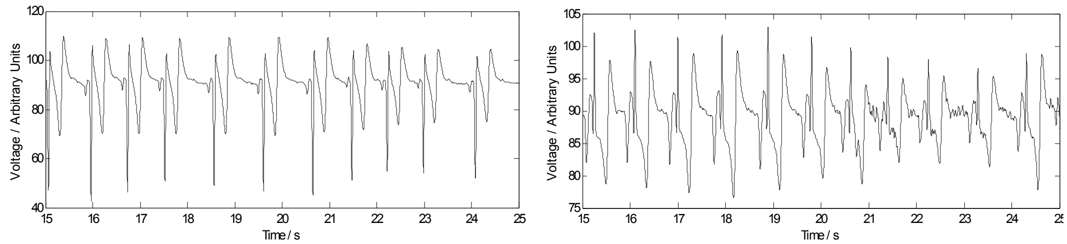


Figure 2.15: Inter-subject Variation in ECG Electro-Dermal Response

2.2.2.1 Baseline ECG Recording

In the baseline test, a valid signal (characterized by the presence of a full PQRST waveform) was recorded for every subject in the control configuration (using adhesive, pre-gelled electrodes). For six of thirteen, the baseline signal recorded from the test garment was similar in morphology to the control signal. In addition, two subjects showed a morphologically valid resting signal at some point during any ECG test. In the remaining five subjects, all heartbeat waveforms were obscured by noise.

The baseline test concluded with subjects taking a deep breath. The effect of this breath was visible at times both in the control and test configurations. However, in three of the six valid signals, the effect of the breath was more extreme on the test signal than on the control signal, whereas the effect on the control signal was never greater than the effect on the test signal. Figure 2.16 shows an example artifact introduced to a test signal as a result of the deep breath.

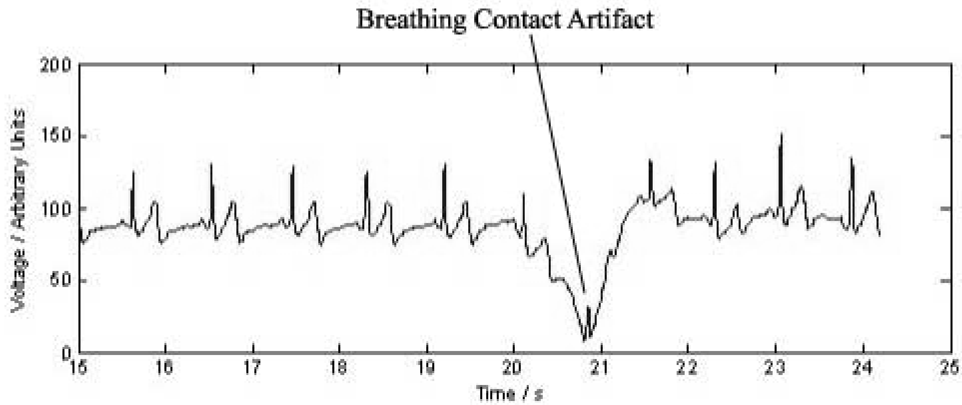


Figure 2.16: Breathing Artifacts in the ECG Test Configuration

2.2.2.2 Arm Movement Test

Arm movement introduced a significant amount of noise into both the control and test configurations; however, again, the effect was more severe in the test configuration, in four of five valid test signals. The most severe effects were seen in the dorsal arm abduction. A severe example of noise introduced by arm movement is shown in Figure 2.17.

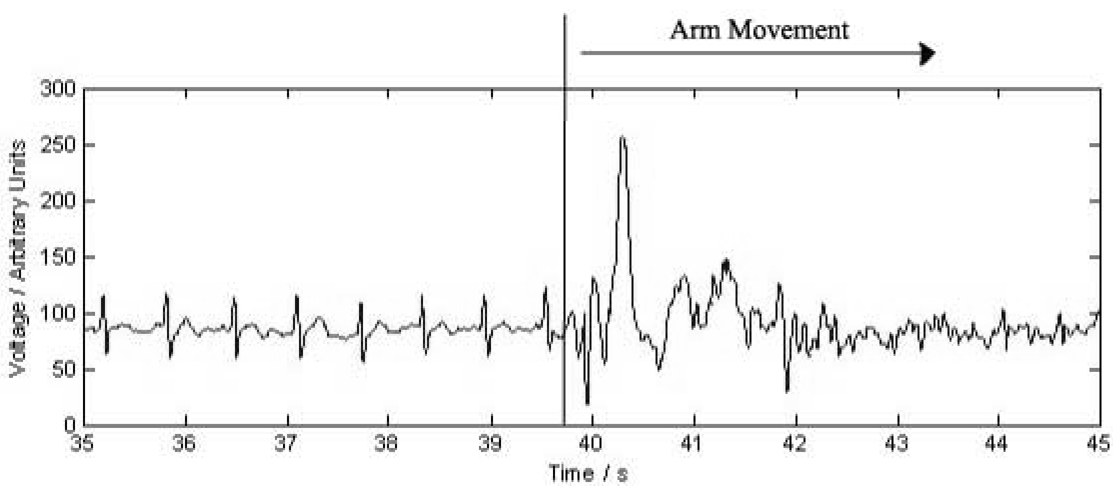
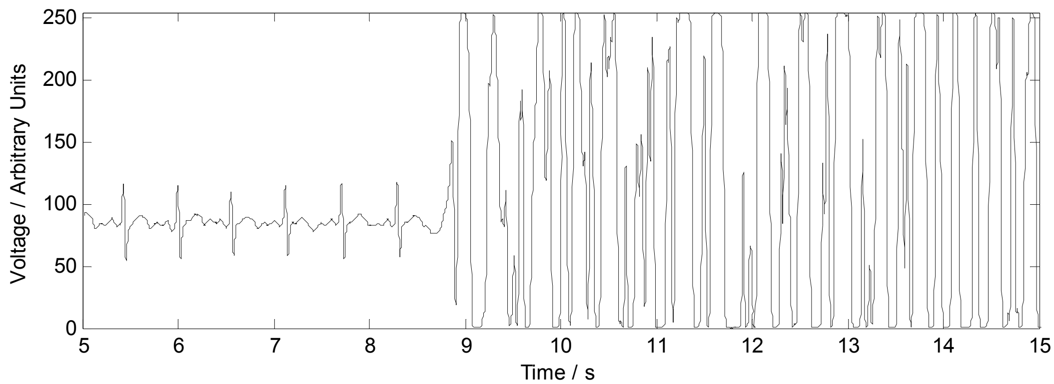


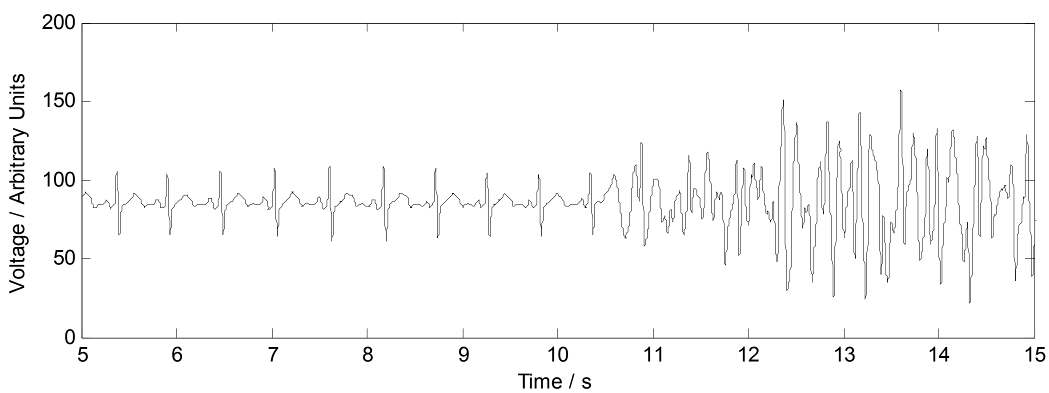
Figure 2.17: Arm Movement Artifacts in the ECG Test Configuration

2.2.2.3 Jogging Test

In the jogging test, for all but three subjects noise obliterated the ECG signal in the control configuration. For the three subjects with a regular waveform, the morphology of the waveform was lost leaving only a regular “R” section of the wave (the “spike” of the heartbeat). No regular wave or beat was discernible in any of the test configurations in the jogging test. Figure 2.18 shows noise introduced into a control configuration (a) and a test configuration (b).



(a)



(b)

Figure 2.18: Jogging Noise in the ECG Control (a) and Test (b) Configurations

2.3 Discussion: Bio-Monitoring Bra

The purpose of the bio-monitoring bra study was to investigate the possibility of integrating bio-monitoring sensors into a standard undergarment. The design of the bra demonstrates a distributed method of technology integration: rather than integrate the entire device into one garment, the sensors are located in the bra and the related computing device can be located in any number of other garments or body-mounted means of attachment. This design takes advantage of the bra's close proximity to the skin, but asks the question whether or not the bra can provide enough constant contact to permit electro-dermal bio-monitoring with simple metal electrodes that are not adhered to the skin. In this study, the garment is functioning as an input device. The biological input can then be used to trigger any number of output functions, based on physical or emotional states deduced from the biological input. For instance, a sustained state of muscle tension in combination with an increased heart rate could indicate a stress reaction. An output device could then be triggered to counteract the stress reaction with soothing music, or a light massage.

The primary source of variation in the recorded responses in both the EMG and the ECG configurations was quality and consistency of contact of the electrodes with the skin, evidenced by the inconsistencies observed in the recorded waveforms. Associating the observed inconsistencies with the physical changes that caused them led to the conclusion that the quality of the contact between the electrodes and skin was the primary source of variation. This variation was seen both in the test (contact) electrodes and in the control (adhesive) electrodes, and is caused by variations in the forces acting on the electrode. This factor was further complicated by the inter-subject variation, due to natural variations in the human population.

Recordings of electro-dermal responses such as EMG and ECG rely on a consistent contact with the skin (which prevents introduction of noise artifacts from the movement of the electrode over the skin, as well as maintaining a consistent measurement point on the muscle being evaluated). This is currently achieved through creative use of adhesives. However, even if the electrode is securely fastened to the skin, there is no way to securely fasten the skin to a consistent place on the muscle. Skin moves over muscles, and this too introduces noise into a recording, although not as severely as the noise created by inconsistent contact with the skin.

The hardware used to process the EMG/ECG signal was also very sensitive to ambient electrical noise. This effect was easily observed by unshielding the primary circuit board, which rendered it rarely able to record a useable signal. Shielding the board prevented the board itself from picking up noise, but it is reasonable to assume that other conductors in the system (like the lead cables) would also experience environmental noise, although to a lesser degree than the more sensitive processing chips. The lead cables used were not shielded, and thus could be responsible for some degree of electrical noise experienced. Electrical noise tends to be of a consistent frequency, higher than that of an ECG wave, and thus can be fairly easily filtered in the ECG analysis. As environmental noise could not be filtered from EMG data, it was of concern for collecting this type of data.

The evaluation process for this investigation identified several incorrect assumptions present in the design process. For instance, the assumption that contact electrodes would function in a similar fashion as adhesive electrodes was shown to be erroneous, when subject testing showed extensive interference due to noise. More extensive research in the preliminary stages of the design process may have helped to avoid this assumption. However, as most of the research that led to the design of adhesive electrodes (signal filtering, and current methods of electrode placement/affixation) has occurred in the commercial arena, much of this information is not recorded in published material.

2.3.1 Observations: EMG Test

In the EMG test, movement artifacts were particularly prominent in the test results. To record a response from the trapezius muscle, it is necessary to flex that muscle. Flexing the trapezius brings the shoulder upward, fairly dramatically. The test electrodes were incorporated into a garment which is secured under the bust and over the shoulders. Thus, flexing the shoulder necessarily increases the pressure between the shoulder strap (which contains electrodes) and the skin. For this reason, especially in the no-gel EMG group, the “EMG response” observed in most subjects appeared to be backwards. Instead of seeing a low-noise signal in the relaxed state, then an increased amplitude in the flexed state, the recorded response showed a high-noise signal in the relaxed state, and a lower-noise signal when the muscle flexed (Figure 2.19). This however does not represent a true EMG response. Because of the increased pressure during shoulder flexion, a better contact is established between the electrode and the skin, thereby reducing the noise in the signal. During the relaxed state, contact is reduced and more noise is introduced into the signal. So rather than seeing the amplitude of the muscle signal increase, we see a decrease in the level of noise present. The “flex” signal may represent a true EMG response, but since (due to the noise) there is no perceivable relaxed state to compare it to, it can not be evaluated.

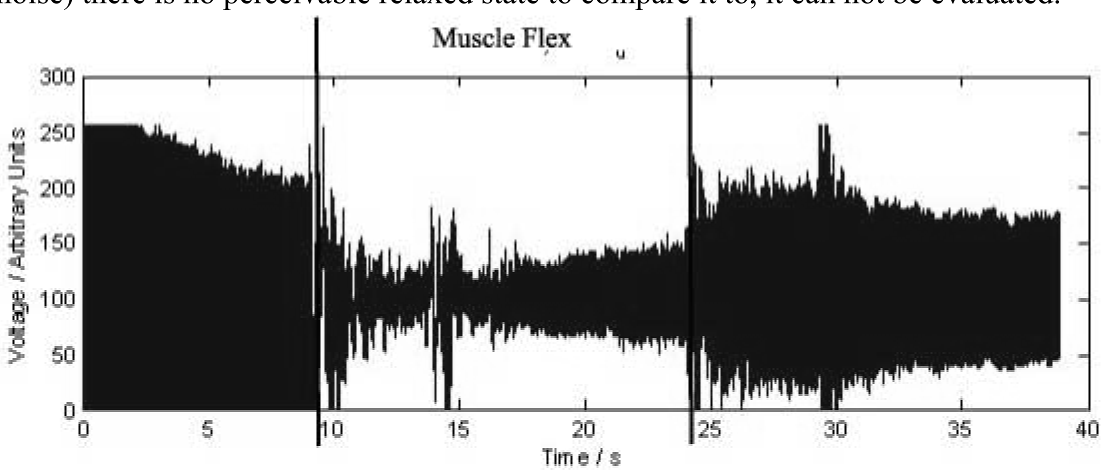


Figure 2.19: Improved EMG Contact in the Flexed State

In some subjects, the initial flex created a better contact that continued during the relaxed state, as seen in Figure 2.20. The band of noise narrows more following each muscle flex.

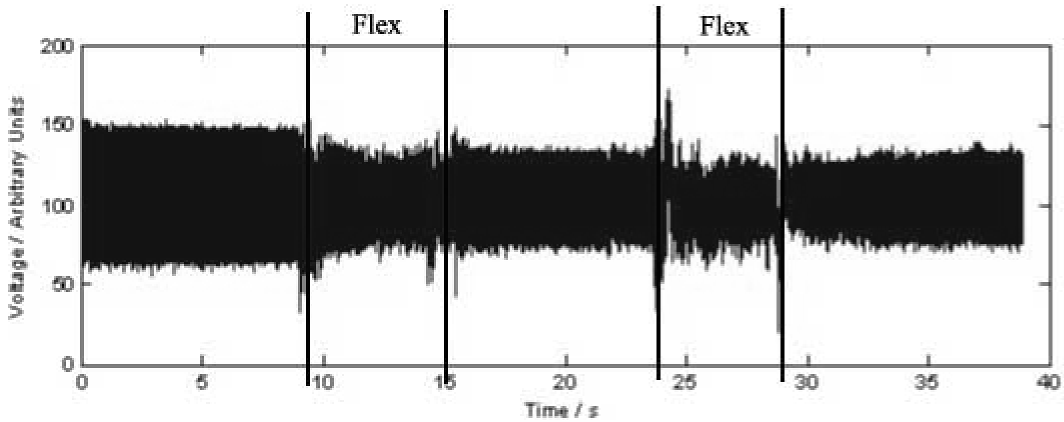


Figure 2.20: Sustained EMG Contact Improvement Due to Shoulder Flex

In the EMG gel group, the signals recorded were generally much better. The conductive gel adds a layer of viscous connection between the skin and the electrode, which allows for a slightly more flexible contact. However, movement artifacts still appeared to be present as the electrode moved within the gel area, especially as the body moved to flex or relax. (Changes in pressure and force applied to the adhesive electrodes during movement also affect the quality of contact.)

The EMG gel group showed a generally lower-noise response, but often with very sporadic data capture. This could be due to electrodes coming in and out of contact with a more highly gelled area, or perhaps could represent the same kind of motion artifacts that were present but buried in noise in the no-gel EMG group. Intermittent contact artifacts are shown in Figure 2.21.

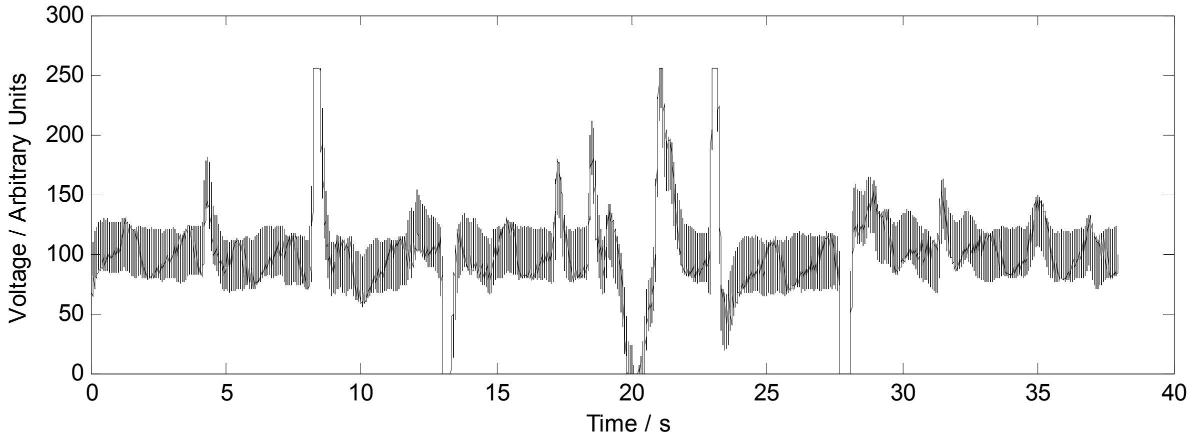


Figure 2.21: Intermittent Contact Artifacts, EMG Gel group

The lowest-noise signals were recorded most often in the "A" prototype for the no-gel EMG group (flat 1.4 cm electrodes), and fairly evenly between the "A" and "B" (curved 1.4 cm electrodes) prototypes for the gel EMG group. The "A" and "B" prototypes contained electrodes with larger diameters. Only one significant low-noise signal was obtained through the "C" (flat 0.6 cm electrodes) or "D" (curved 0.6 cm electrodes) prototypes, those with very small-diameter electrodes. This result is consistent with the theory that larger electrodes (spaced far enough apart) offer a better chance of good contact and therefore a clearer signal.

2.3.2 Observations: ECG Test

In the ECG test, clearer, more valid (not obscured by noise) signals were obtained than in the EMG test. This is mostly due to the circumstances of measurement—the ECG signal can be measured without physical movement of the user. This removes many contact artifacts and keeps the skin in a more or less consistent place over the muscle. However, introduction of as little movement as a deep breath resulted in sometimes significant artifacts in the response signal. More extreme movements, such as the dorsal arm abduction and the jogging test, resulted in a signal completely obliterated by contact and skin movement artifacts. The control configuration showed less movement noise and fewer artifacts, but still resulted in an obliterated signal during extreme movement. However, extreme movement such as jogging is not a factor in many environments where the user is more stationary (such as seated at a desk) and may not pose significant problems.

Electrode placement to create Eindhoven's triangle requires that the electrodes be located on the pectoral muscles near the shoulders. When using a bra test garment, this means that two of the three electrodes can not be placed on edges, suspension points, or anchor points of the garment—places where contact can be easily improved by tightening the garment. For instance, to create better contact in the lower (ribcage) electrode, the chest strap of the bra can be tightened. To create better contact in a trapezius electrode, the shoulder strap can be tightened. But there is no similar easy alteration that will secure a pectoral electrode more tightly to the body. Additionally, because of the complex morphology of that area of the body, it is not possible to integrate a constricting belt for the upper electrodes. This makes reduction of contact artifacts difficult. In female subjects, the added mass of the breasts introduces complex forces on the bra during extreme movement (such as jogging), which can lead to even more contact artifacts, slippage of electrodes, and movement of skin over muscle.

2.3.3 Sources of Error

In both tests, interference of external noise was a significant problem. The primary sources, which have been previously discussed, are ambient electrical noise, skin movement noise, peripheral muscle noise, and changes in the electrode contact with the skin (slippage, loss of contact, change in degree of contact).

Electrical noise is present in any environment. It comes mainly from electrical devices in the environment, or from local wall outlets. Wall outlet noise is a consistent 60Hz sine wave, and thus is fairly easy to filter out. Noise from other electronic devices can be at a variety of frequencies, and is more difficult to filter. Shielding of the recording device by encapsulating it in metal removes much of this noise.

However, other conductors (such as the electrode leads) which are not shielded can also act as antennas and pick up noise. In the ECG test, the low-pass filter removed most of the electrical noise in the data. However, an EMG signal looks very much like noise (an irregular sine wave of increased amplitude), and hence it is difficult to remove external noise from this type of signal. In this test, EMG signals were used un-filtered.

Skin movement noise, as previously discussed, occurs when the skin moves over the muscle being recorded. Surface recording of muscle activity relies on the electrical potential diffusing from the muscle through the skin to the electrode. Thus, when the skin moves, the point of contact moves, interrupting the signal

Peripheral muscle noise is the result of the activity of a nearby muscle being picked up along with the activity of the muscle of interest. This is a significant problem when recording ECG data. The heart muscles, (the "muscle" of interest) are buried beneath layers of other muscles. Therefore it is impossible to record the ECG signal without experiencing peripheral noise. Eindhoven's triangle helps to minimize this by placing no two electrodes on the same muscle and by taking the differences between pairs.

Changes in electrode contact with the skin were the most significant variable in this study. Adhesive electrodes were developed with the intent of reducing the effects of contact artifacts. However, in the day-to-day wearable environment, adhesives are not a reasonable request to make of the user. But because the electrode is not affixed to the skin, it is free to slide over and lift away from the skin. This can be minimized by holding the electrode tightly to the skin with an elastic strap (for instance, recordings made using an adhesive lower electrode show little change when that electrode is switched to the elastic chest-strap electrode), but in many body areas a tight elastic strap is not practical or even necessarily possible.

EMG and ECG data can be used to determine physical states (movement, activity, fatigue) as well as emotional states (anxiety, surprise, fear), both of which can be useful in triggering appropriate wearable applications, or as input to assist context awareness in wearable technology. In order to be used in wearable technology, an appropriate sensing technology must be found so that EMG/ECG data can be gathered reliably in the wearable environment, without requiring the user to significantly change their clothing habits. A method is required to maintain consistent, reliable contact between the conductor and the skin, without use of adhesives or requiring the application of a conductive gel. These are the user needs/architectural requirements determined by the pilot subject test, which can then be applied to a future prototype in the iterative design process. A next prototype might use a conductor with some sort of compressability, for example a conductive pad, a conductor composed of springs or a textile construction similar to terrycloth, which contains protruding, flexible yarn loops. This kind of mechanism might permit some movement in the garment without changing the contact with the skin.

2.4 Conclusions/Future Work: Bio-Monitoring Bra

2.4.1 Design Process

The functional apparel design process was used to initially identify the wearability problems inherent in adhesive electrodes. This pilot study investigated the utility of metal-plate contact electrodes as a functional substitute for adhesive electrodes. The analysis of user comfort requirements, leading to the subtle integration of minimally perceptible electrodes in a standard garment, was successful. However, inaccurate assumptions regarding the hypothesized functioning of contact electrodes were identified in the evaluation process. Contact electrodes were hypothesized to function in a similar way as adhesive electrodes, but subject testing proved that without the adhesive holding the electrode in place, movement artifacts significantly affected the clarity and consistency of the recorded signal. The requirements for contact electrode recording garments must then be modified to include some degree of maintenance of consistent skin contact during movement.

Similarly, several new requirements for the recording hardware and software were identified. Specifically, the need for electrical shielding of all components of the recording system, including electrode leads, became apparent. The need for a sophisticated, adaptive filtering algorithm was also identified.

2.4.2 Prototype Evaluation

The physical integration of metal-plate electrodes into the bra was successful. Subjects did not exhibit signs of discomfort when wearing the prototype bras, and some were even unable to locate the electrodes within the garment.

The integration of contact electrodes into a standard sports bra produced more successful results in measuring ECG than EMG, primarily because of the nature of the physical changes associated with creating the response (the change in body surface area and contour caused by certain muscle contractions).

In both tests, the largest problem was the amount of noise created by poor contact between the electrode and the skin, and inconsistencies in that contact due to movement of the bra over the skin and movement of the skin over the muscles.

ECG measurement was fairly reliable in the stationary environment. This kind of device may be useful in a hospital environment, or other environment in which subject movement is restricted, such as a sedentary office or desk environment. EMG measurement posed considerable difficulties, due to the fact that flexing a muscle inherently changes the size and shape of that body area, which changes the quality of the electrode contact.

Bio-monitoring sensors in wearable technology can facilitate a large variety of functionality. They allow the computing device to become aware of the physical and emotional state of the wearer. This can establish the potential for much more intelligent functionality, including context-awareness. Automated or context-aware functions can reduce the cognitive load of the wearer and allow the function to become more powerful.

Considerable further investigation is required in this area, in order to establish reliable bio-measurement techniques. The following parameters or variables are presented for consideration in future research:

- *Consistency of electrode contact:* A method for more consistent contact is necessary, without using adhesives or conductive gel.
- *Electrical shielding:* All conductors in a recording system, including connecting wires and leads, must be insulated as much as possible, to eliminate environmental noise.
- *Data filtering:* Investigation of more adaptive filtering methods may improve recording methods, and eliminate some degree of required contact consistency. An adaptive filtering algorithm could, for instance, be trained to disregard noisy elements of a signal, and differentiate noise from activity. In applications where absolute consistency is not required, this could permit much more variation in signal quality.
- *Electrode comfort:* In continuous-wear applications, the comfort of the electrode as well as the health implications of the configuration must be investigated. For instance, the application of conductive gel can improve electrode contact consistency, but it can also cause skin irritation.

- *Garment fit:* Pressure of the garment on the skin has a considerable effect on the strength and consistency of the recorded signal. In this study, the adjustability of the garment created a consistent pressure for every subject. In a mass-marketed scenario, however, this variable could need to be addressed in a different manner. Several options exist: a similar, adjustable garment, an extensive sizing system that takes into account the wide variation between individuals in the bust/torso area, or custom-fitting of garments to each subject.
- *Electrode elasticity:* Especially when gathering EMG data, a garment-integrated electrode must contain enough elasticity that the volume change in a body part caused by a muscle flex does not create a change in electrode contact.
- *User control of biological data:* As indicated by focus group subjects, control over the use and distribution personal biological data can be of utmost importance to the user. Any biological monitoring system must disclose fully to the user the means and manner of use and distribution of the gathered data. If possible, the user must retain control over these aspects of the device.

Although the contact artifacts experienced in both studies made recording of a consistent signal difficult, in other applications these artifacts might prove useful in deducing other information about the user's state and activity. For instance, the artifacts experienced in EMG recording due to the elevation of the shoulder, while problematic for EMG recording might be very useful in recording movement of the shoulder. Similarly, movement artifacts experienced in ECG recording could also be used to deduce movement on the part of the user in a wearable system.

As previously mentioned, a next prototype of garment-integrated contact electrode should provide a higher degree of contact consistency. To achieve this, a looped or compressible textile structure might be used, but conductive textiles also add resistance to the electrode, which must be taken into account in signal measurement. Other possible solutions include the use of larger electrodes, increased garment pressure, or textile electrodes that make use of materials with some ability to grab the skin—similar to the rubber materials used to hold stockings and bras in place. Additionally, future investigation may include user willingness to use conductive gel on a daily basis (as well as possible effects of daily use on skin health). A next prototype would also include better shielding in the recording system and the electrode leads.

The quality of data gathered from the prototype garments is immediately useful in stationary situations—situations like hospital monitoring, stationary desk jobs, or driving in a car. Combined with more sophisticated filtering, it may also be useful in more dynamic situations.

Most research in electro-dermal biosignals has involved only the collection of data, to be analyzed post-collection. Many wearable applications, however, require data to be analyzed in real time, so that it can be used to trigger a separate change. Real-time data analysis of biosignals poses new problems for the design of wearable technology. Data processing algorithms must be equipped to handle interruptions in signals, variations in individual threshold levels, artifacts in the data stream, and many other factors.

Recording of detailed biological data like EMG and ECG signals can be beneficial both for personal health and medical monitoring, and for less crucial applications like context aware information retrieval. The difference lies in the user's willingness to accept changes in personal habit: in a situation where bio-monitoring has significant effects on the individual's health or has the potential to prevent a life-threatening situation, the user is more willing to endure some discomfort and change certain personal habits. However, when the application is merely an added convenience, the cost of changing habits or comfort levels appears much higher. One end use of this kind of technology could be well-received by children in a hospital environment, who might be quite intimidated and frightened by adhesive electrodes, which can also cause skin irritation.

The applications of bio-monitoring in the wearable environment are immense in scope. Knowing the physical and emotional state of the user can be used to help the device "learn" the user's patterns, preferences, and needs, to improve the functionality of a wide range of personal devices like scheduling programs, information retrieval, purchasing, entertainment, or work efficiency. A significant change in emotional state can be used to trigger a response in the wearable device: for instance, a severe change in heart rate, combined with other signals like a quick muscle response can be categorized by the device as a startle or fear response, triggering a device to take a picture or start recording audio, in case the user is in a dangerous situation. A detection of a physiological response (or set of responses) identified as a stress response could trigger a function similar to the massage shirts: a gentle soothing massage. Biological information conveyed to other individuals (or devices worn by other individuals) can improve group and interpersonal communication, disseminate appropriate information, and facilitate group networking. A community of wearable technology users can communicate more effectively by using biological signals to determine the emotional state, location, or activity of each user, thereby allowing other users to make better judgments about how best to interact.

Without bio-monitoring, a device must rely on user input to learn information about a user's state or activity, increasing the cognitive load and attentional demands on the user as well as increasing the social weight of the device, and rendering the device more difficult to use and accept.

Real-world application of bio-monitoring, however, can also pose significant social issues. As previously discussed, the concept of one's physical state being recorded and potentially transmitted to others can be very threatening. The fine balance in wearable technology is between reducing the user's cognitive load and restricting their autonomy. The less the user has to do to make the device function, the less that user knows about how it functions. This decreases the cognitive load, but also decreases his/her autonomy of choice. Automated functionality is easier to use, but it may not always be desired by the user.

CHAPTER 3: OUTPUT DEVICES: THE SHOULDER PAD VIBROTACTILE DISPLAY

Existing output modalities in technology design show much more variety than input modalities. Whereas most input paradigms center around button-presses, output can take the form of text, sound, image, symbol, or tactile impulse. However, automated output can become socially intrusive, when an inappropriate modality is used. This is glaringly evident in the example of the inappropriate cell-phone ring, which can be very socially intrusive in many situations. Thus the designer must also take into account the effect which device output can have on social interactions.

When designing output devices for wearable technology, a designer can use the entire body space to receive output. Whereas many input modalities are not readily applicable to the wearable environment, many desktop and mobile output devices translate easily into wearable technology. The tactile alert is particularly useful in wearable technology, as it allows output to remain socially subtle, as well as offering the opportunity for intuitive user interfaces in several applications.

In addition to designing a device's output modality for social subtlety, the designer must make sure that the physical presence of the device itself also remains socially subtle. This requires the investigation of available integration spaces and techniques, because output technology is often significantly larger than input sensor technology.

The design of a wearable output device that maintains physical comfort, low cognitive load, and does not negatively impact social interactions is an inter-disciplinary design challenge requiring a thorough understanding of the human-device interface and the clothing concept. This study represents a pilot investigation into the physical, cognitive and social human interface issues involved in the development of a shoulder pad based vibrotactile display.

3.1 Methodology: The Shoulder Pad Vibrotactile Display

Vibrotactile displays on other parts of the body have already demonstrated a wide range of cognitive aids to improve situational awareness, navigation (Tan, Ertan, Lee, Willets, and Pentland, 1998) reckoning, balance (Wall, Weinberg, Schmidt, and Krebs, 2001), and to decrease confusion about spatial and directional orientation. The few applications which have incorporated the shoulder as a tactile display space have almost exclusively investigated applications for assistive technology for the disabled (Lee and Kwon, 2000; Wall et al, 2001). The exception is Osamu Morikawa's HyperMirror (Morikawa, 1999), which used a shoulder-worn single stimulator display to provide videoconference participants a vibrotactile cue for getting another person's attention. This cue literally provided a remote participant the ability to tap on the shoulder another remote videoconference participant who was at a different location.

Besides the benefits of pre-existing space created by a shoulder pad, the shoulder is also a prime location for a tactile display because of the established cultural norm of receiving tactile input through the shoulder—a tap on the shoulder, a guiding nudge.

In this test, the objective was to analyze the practicality of a vibrotactile display discreetly integrated into a standard garment, to determine whether or not such a display could be effective (and what kind of information could be transmitted) given the presence of several layers of fabric between the vibrating motor and the skin. Tactile displays in general have previously been shown to be effective in many situations. The question in this case was whether or not tactility was a useful display modality when the constraints of "normal" clothing interaction were introduced. In order to explore this question, the user and the user's needs with regard to daily apparel, as well as the user's needs with regard to a subtle technology interface, must be taken into account.

The first step in the design process is the identification of the user. In this study, the user was defined as female, between the ages of 18 and 35. She is expected to work in an environment which requires constant access to information or communication technology, as well as requiring a certain degree of formality: formality of dress, which necessitates wearing a business suit or similar garment system, and formality of comportment, which necessitates a very subtle technology interface, one that does not interfere with social interactions.

The user in this situation needs to appear "normal", to avoid the various forms of social weight that can be attached to a wearable technology: fear, apprehension, suspicion, or even interest, novelty, and excitement. All of these emotional connotations could at times be detrimental to a business interaction. Some of the users in this defined group may require that the technology remain completely covert in order to secure a competitive advantage, such as in the aforementioned group negotiation scenario. However, aesthetic requirements must not impede the functionality of the system. The user must also be able to perceive the output of the display with enough certainty to be able to interpret the delivered information.

Additionally, the architectural requirements of this system dictate that the system must preserve the clothing concept not only aesthetically, but also preserve the manner in which the user interacts with a typical jacket. Therefore, the shoulder pad unit must function in the same way as a non-electronic shoulder pad. It must provide the same degree of shape and support, feel the same against the body, and be removable for care and cleaning.

3.1.1 Physiology: The Cutaneous Senses

To design a tactile display, the designer must first understand the mechanisms of tactile sensation, or the cutaneous senses. This information can inform the functional requirements of the design process, to ensure that the device is capable of delivering a perceptible sensation. The average sized adult human has 1.8 square meters of skin surface, which comprises 16 to 18 percent of total body weight (Montagu, 1971). Within the skin, many different mechanoreceptors facilitate cutaneous sense (the sense of touch). They are outlined in table 3.1 below.

Table 3.1: Human mechanoreceptors and corresponding sensory modalities

Receptor	Sense modality
Meissner Corpuscle	Stroking, fluttering
Merkel Disk Receptor	Pressure, texture
Pacinian Corpuscle	Vibration
Ruffini Ending	Skin stretch
Hair tylotrich, Hair guard	Stroking, fluttering
Hair-down	Light stroking
Field A	Skin stretch

The Pacinian corpuscles are the mechanoreceptors responsible for most detection of vibrational stimuli. Vibration was chosen as the tactile modality for the display unit because it is the simplest stimulus to achieve in the wearable environment. Vibration is the only modality that does not require a fixed anchor point for the stimulator. Pacinian corpuscles are some of the deepest mechanorecptors in the dermis, and are the largest touch receptors. They are the fastest-adapting of the class of fast-acting receptors, meaning they respond quickly to changing stimuli. They can detect pressure changes up to .0002 inches per .1 seconds, frequencies between 25 and 600Hz, but have optimal sensitivity around 250-400 Hz. (Wilentz, 1968). Therefore, a vibrating tactile stimulator must operate within this range for optimal perceptibility.

Mechanoreceptors are not distributed uniformly over the body surface: rather they are concentrated more densely in some areas than in others. Figure 3.1 shows a homunculus, or humanoid representation for cutaneous sense. The human figure is drawn along the perimeter of one hemisphere of the brain, enlarging body parts relative to their degree of sensitivity, an intuitive depiction of skin sensitivity. From the diagram we can see that the lips, hands and genitals are among the most sensitive areas of the body.

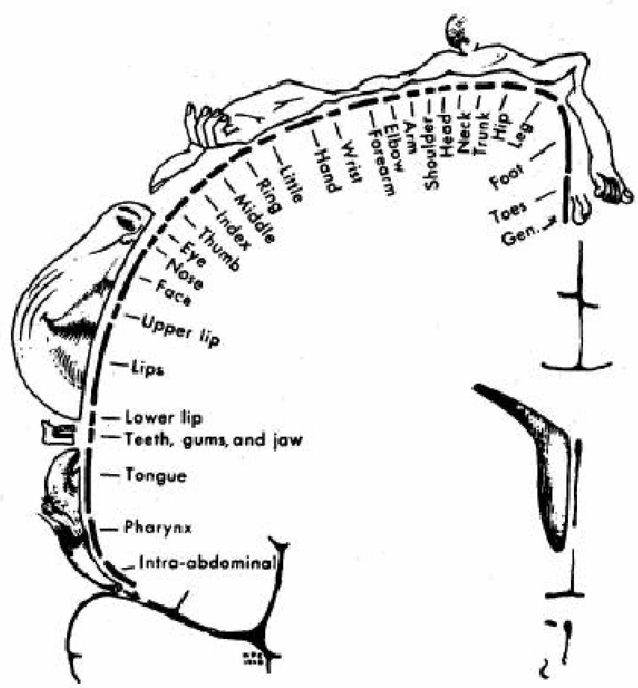


Figure 3.1: Sensory Homunculus (Penfield and Rasmussen, 1950)

The skin of the hand is characterized as “glabrous”, or non-hairy. It is highly enervated, resulting in a very high sensitivity resolution. On the fingertip, two concurrent stimuli must be at least 2 mm apart to be perceived as two separate stimuli. On the forearm, where the skin is characterized as “hairy”, this threshold increases to 30 mm, and on the back (also “hairy” skin), to 40 mm (Weinstein, 1968).

The most sensitive areas of the body (the fingers, toes, genitals, and tongue) are unfortunately not the most convenient for body-mounted technology. Additionally, the design of a tactile display relies on more than just the use of the most sensitive body area. It must take into account social norms and expectations for tactile communication. Therefore, it is necessary to take into account the areas of the body in which it is socially customary to receive tactile stimuli. These areas can be generalized as including the hands, arms, and shoulders.

Verillo found that contactor area for vibrational stimuli had an effect on threshold perception levels, only when the contactor was smaller than $0.02cm^2$ in diameter. Upwards of $0.02cm^2$, optimal detection of stimulus occurred at 250 Hz, but when diameter was smaller than $0.02cm^2$, changes in frequency of vibration had no effect on detection levels (Verillo, 1963). Furthermore, the skin has little ability to detect changes in frequency of vibration. Steps 70-90Hz apart can be detected as different frequencies (Rovan and Hayward, 2000), but as frequency increases, sensitivity to differences decreases (Verillo and Geschider, 1992).

Where changes in frequency are not easily detected by the skin, changes in amplitude or intensity are much more discernable. The smallest recorded perceptible change in amplitude is 0.4 decibels (dB). Amplitude thresholds are unique to the individual; however the skin can perceive vibrations with an intensity of up to 55 dB over the perception threshold. Amplitudes of over 55 dB become annoying and painful (Verillo and Geschider, 1992). A level of 15 dB over the perception threshold is generally considered distinctly perceptible, a comfortable sensation level (Gunther, 2001).

The geographic location of the stimulus also has an effect on the perceived stimulus. Figure 3.2 represents the perceived change in stimulus intensity as amplitude is increased (frequency held constant). Body parts with lower sensitivity (i.e. the forearm) show much steeper curves, indicating that the perceived stimulus intensity grew at a greater rate on more sensitive areas than on less sensitive areas (Verillo and Chamberlain, 1972).

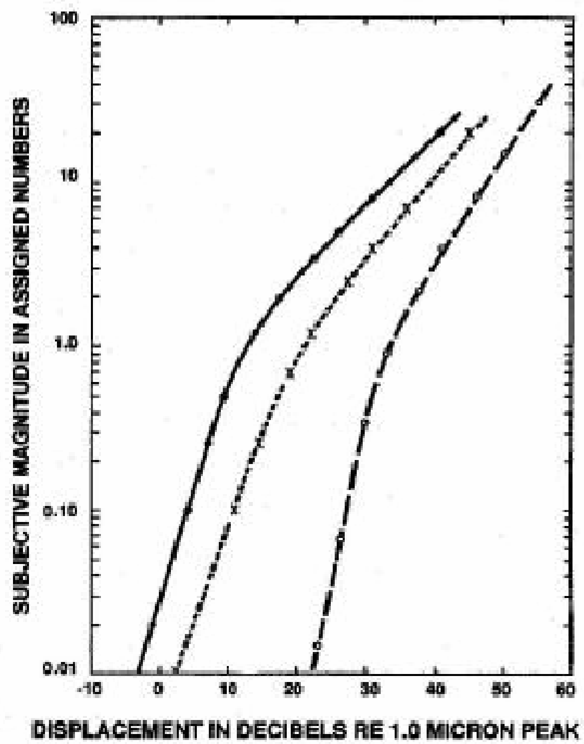


Figure 3.2: Subjective Intensity as a Function of Amplitude for Three Body Parts. Filled circles=fingertip, x's = palm, open circles=forearm (Verillo and Chamberlain, 1972)

Adaptation effects in the mechanoreceptors can substantially alter threshold perception levels. For instance, stimulating a skin area for 10 mins at 6 dB over the threshold perception level will result in an increase in the sensation threshold amplitude of 2 dB. The same 10-min stimulation, this time at 40 dB over the threshold level will raise the threshold by 20 dB (Kaczmarek, Webster, Bach-y-Rita, and Tompkins, 1991). During the adaptation period, the threshold will be increased gradually until it hits a saturation threshold, at which point prolonged stimulation will not result in any further increase of threshold levels. Cessation of stimulus results in a post-adaptation period, during which the threshold is gradually reduced to the normal level. The recovery period ranges from a few seconds to several minutes, depending on the duration and intensity of stimulus exposure (Verillo and Gescheider, 1992). The saturation threshold level is reached with a stimulus of 7-25 mins (Hahn, 1973). A situation in which skin is exposed to a variety of changing frequencies for an extended period of time could result in a more pervasive adaptation, as different frequency ranges would have de-sensitizing effects on the mechanoreceptors most sensitive to that particular frequency (Verillo and Gescheider, 1992).

Areas with larger threshold values exhibit a particular phenomenon when stimulated in spatial succession. For instance, when the skin of the forearm is stimulated with three tactile impulses in one location, followed by three in a second location, and three in a third location following the same tangential line, instead of feeling stimuli in three distinct loci, the subject feels a series of stimuli following the tangential line, spaced equally along that line. This sensory phenomenon is referred to as “sensory saltation.” (“Saltation” is the Latin word for “jumping.”) (Tan, Lim, and Traylor, 2002).

From the existing research on tactile perception, display device requirements were derived. These include: frequency of vibration between 250 and 400 Hz, tactors at least 40mm apart, and impulse duration of less than six minutes. Additionally, vibration amplitude (but not frequency) variations can be used as perceptible stimuli, as well as the saltation effect.

In this study, the shoulder was chosen as the tactile display area for two reasons: first, because the shoulder is a culturally familiar body location for reception of tactile impulses, and second, because the shoulder pad as a garment insert creates the largest amount of pre-existing volume on the body.

3.1.2 Garment Inserts

The wearable integration of technology into a garment requires the acknowledgement and preservation of existing norms in the clothing concept. One of the most visible areas of change caused by integration of technology is in garment silhouette and contour: bulky, solid shapes integrated into a flexible textile garment create noticeable bulges and stiff areas in a garment.

However, examination of the current clothing concept reveals the presence of pre-existing areas of added volume and stiffness within many common garments. These areas are defined here as "garment inserts", and include garment areas that are padded, interfaced, or otherwise given stiffness or volume to create a garment silhouette. Garment inserts are very common in a wide variety of garment styles. Figure 3.3 shows common areas of garment padding and interfacing, for both men's and women's clothing.

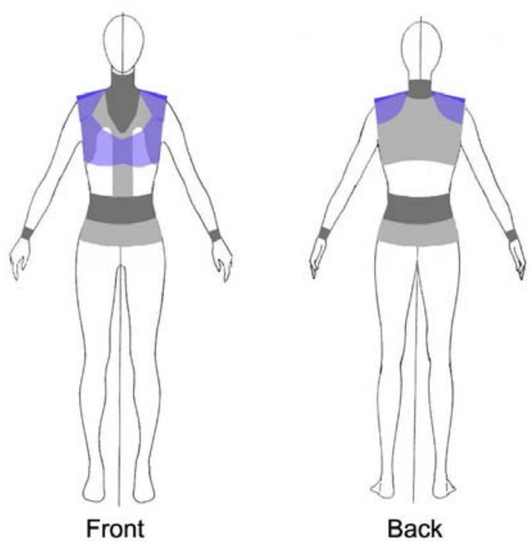


Figure 3.3: Common Areas of Garment Padding and Interfacing

Besides the bra cup, the shoulder pad is the largest pre-existing volume that is common in garment systems.

3.1.3 Sizing: Determination of Pad Size and Shape

To place electronics on the body, it is important first to determine the maximum available space in a given area. In the application of vibro-tactile units especially, it is important that the electronic piece fit the body it is placed on, so that constant contact is maintained to assist perception. The available space in a shoulder pad graded to fit the entire female population represents, in the design process, the architectural requirement influencing the physical configuration of the electronics in the shoulder pad. In order to determine the available space on the shoulder and the number of sizes that would be necessary to fit the entire population, several measurements from the ANSUR database of anthropometric measures were first analyzed. The ANSUR database is a survey of the body measurements of about 4000 subjects, male and female. The subset of female subjects was used, approximately 2000 subjects (Gordon, Churchill, Clauser, Bradtmiller, McConville, Tebbetts, et al., 1988). This data pool is not ideal, as it consists of subjects enlisted in the US Army, not civilian subjects. These subjects are regulated with respect to age, height, and fitness level. In this case, the age restrictions of the Army database are similar to those imposed by this study's definition of the user, which then leaves disparity only in the size and the shape (fitness level) of the subjects. However, as no similar civilian database was available, and since conducting an anthropometric study of the shoulder of similar scope was too large a task for the time frame of this study, the ANSUR database proved the best option.

The measures derived from the available measurements were shoulder length, vertical distance from the horizontal plane, and shoulder curve length, a measure from front to back mid-armscye over the shoulder. These measurements are illustrated in Figure 3.4.

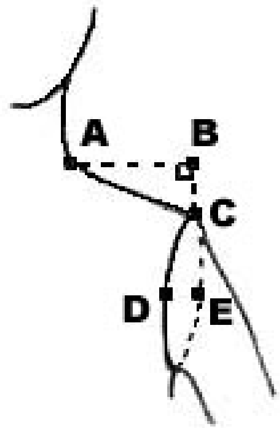


Figure 3.4: Desired Dimensions for Shoulder Pad
(Shoulder length A-C, vertical distance B-C, and curve length D-C-E)

To obtain these measurements, the measurements for seated axilla height, seated neck height, seated acromial height and shoulder length were used. These measurements are illustrated in Figure 3.5.

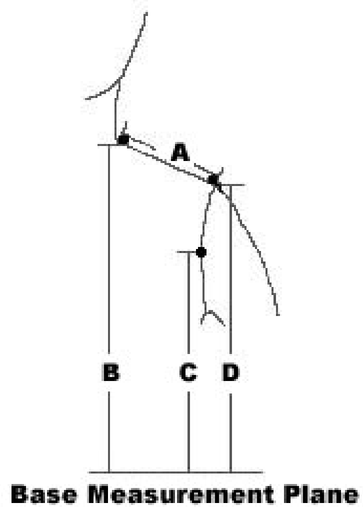


Figure 3.5: Available Body Measurements Used
A: Shoulder length, B: Cervicale Height, C: Axilla Height, D: Acromial Height

The shoulder length measurement was the only measure that was used directly with no modification. For each subject, the acromial height measurement was subtracted from the neck height measurement, to obtain the maximum vertical distance for a shoulder pad. This measure was the vertical height that would produce an absolutely horizontal line from the base of the neck out to the end of the shoulder. To obtain the pad curve length against the shoulder, the axilla height was subtracted from the acromial height. The result was multiplied by two, for the front and back curve. This measure is a linear measure, not a curve, but the amount of length added by the slight curvature was deemed not significant enough to create a problem.

The new measurements (pad height, pad curve) that had been derived were then statistically analyzed to determine the number of sizes needed to fit the entire population. Two statistical measures were used, histograms of each measure and correlations of length versus height. Length was used in the correlation because it is the most important sizing measure in a shoulder pad. As the pad tapers to nothing at the edges, the lower edges of the pad have few adverse effects with a less than optimal fit. The shoulder length measure, however, has a more significant visual effect. A too-small fit results in a broken line in the silhouette of the shoulder. A too-large fit results in turning under or bunching of the pad on the neck, or in a protruding edge at the sleeve cap.

The correlation of length versus height resulted in a fairly strong relation between the variables. The scatterplot is shown in Figure 3.6.

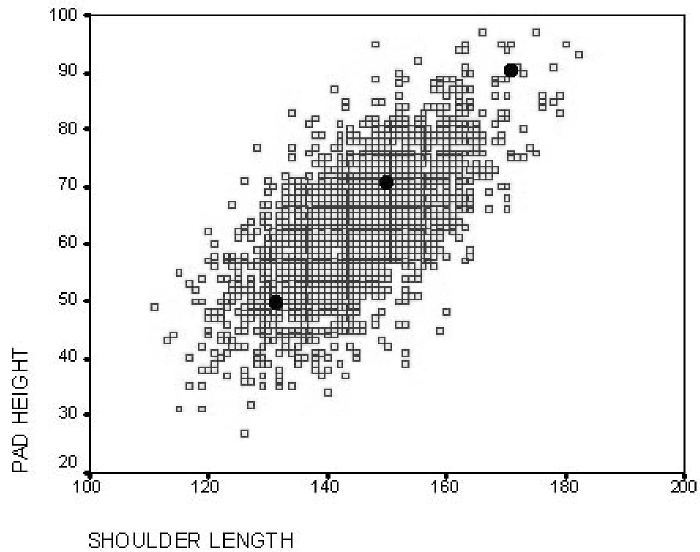


Figure 3.6: Scatterplot of Pad Length versus Pad Height

Using the histograms of each measure, it was determined that the entire population could be effectively fitted using only three sizes of shoulder pads, that vary by only 2 cm in each dimension. The body sizes for each pad are shown in Table 3.2.

Table 3.2: Body Sizes for Shoulder Pad Grade

SIZE	LENGTH	HEIGHT	CURVE
1	13cm	5cm	22cm
2	15cm	7cm	24cm
3	17cm	9cm	26cm

The shoulder pad grade was then determined by subtracting 2 cm from the length and curve (to allow for wearing ease) and at least 2 cm from the height (to allow for a less-than horizontal line). The height of the middle size was reduced by 3 cm, as a height of 7 cm was deemed too severe when tested on the body, and the height of the largest size was reduced by 4 cm. Experimentation with the actual shapes led to further decreases in pad height for all sizes to create a more traditional silhouette. The resulting grade for the shoulder pads is shown in Table 3.3. These sizes are indicated on the scatterplot of pad length versus pad height in Figure 3.7.

Table 3.3: Shoulder Pad Grade

SIZE	LENGTH	HEIGHT	CURVE
1	11cm	3cm	20cm
2	13cm	4cm	22cm
3	15cm	5cm	24cm

The small number of sizes needed to fit the population are evidence of the small amount of variation present in shoulder measures. This is why, for instance, conventional shoulder pads often come in only one size.

3.1.4 Materials: Development of Shoulder Pad

The next step in the design process for this application was the investigation of materials and construction methods to create the shoulder pad. The appropriate structure for embedding electronics needed to be identified, which would meet the user needs of both providing the functionality and comfort of a standard shoulder pad, as well as allowing the user to adequately perceive the output of the display. As defined by the background research, the functional requirements of the vibrational stimulus included vibration frequency between 250 and 400 Hz, tactor spacing of at least 40mm, and impulse duration of less than six minutes. In order to investigate the resolution of a multi-tactor display, tactors must be allowed to vibrate independently, without mechanical coupling effects. Besides the functional requirements of the embedded technology, the display must retain its functionality as a shoulder pad: it must provide support and shape for the garment. Several different fabrication techniques were explored, to arrive at the best-fit solution.

The concept for embedding electronics into this type of garment insert centers around the use of the padding already present in the insert to provide both structure and support to protect the electronics and conceal their shape. For this application, a flexible foam was first chosen for its ability to be easily molded into a shape and for its similar physical properties to materials used in conventional shoulder pads.

The foam, manufactured by Smooth-On, is made from a two-part product. When mixed, the two parts react to create a foaming liquid. The mixture is immediately poured into a mold prepared with a coating of a chemical release agent, and within five minutes, the foam expands to ten times its original volume, forming a uniform five lb per cubic foot cell structure to fill the mold. The foam develops handling strength in five minutes, and cures fully in 30 minutes. The one-to-one mix ratio specified by the distributor of the product created a nice foam, but it was fairly stiff, and did not meet the requirement that the display retain the properties of a standard shoulder pad. Through experimentation, it was found that a mixture of two parts to three parts created a softer foam, more appropriate for shoulder pad construction, but less volume.

The first obstacle to overcome was the process of molding the foam into an appropriate shape. In the interest of simplifying production, the goal was to replace the chemical release agent with a fabric layer. The foam would then adhere to the fabric, but not to the mold. This proved slightly more complicated than anticipated, due to the propensity of the foam to soak through most porous fabrics in its liquid stage. Through experimentation, it was discovered that fabrics that were porous or absorbent allowed one of the mix components to soak into the fabric, resulting in a stiffer, flatter foam as it cured. In addition, in some non-absorbent fabrics, a smooth surface finish caused the foam to retract as it cured, causing the exterior fabric to wrinkle and resulting in a smaller than desired final product. Experimental prototypes are shown in Figure 3.7.

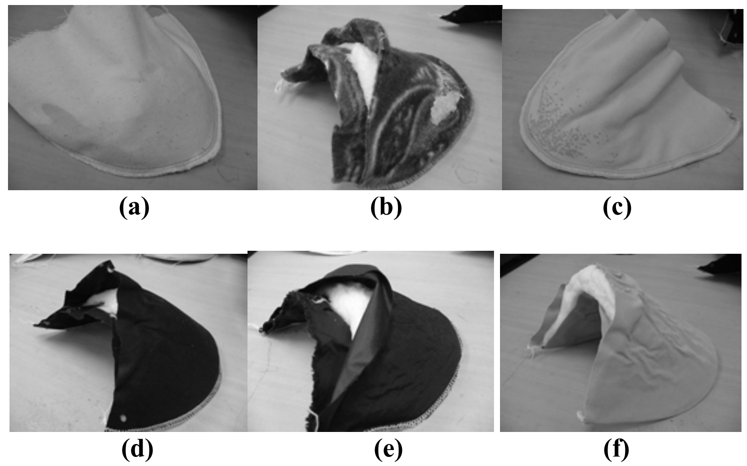


Figure 3.7: Experimental Prototype Shell Fabrics
a, b, and c show soaking through of liquid foam. d, e, and f show shrinkage due to smooth interior surface.

The optimal fabric found for use with molding foam was a 100% polyester fabric, a tight plain weave with a brushed, suede-like surface on one side. The prototypes were constructed so that the sueded finish was on the inside of the pad as it was filled with foam, as seen in Figure 3.8.

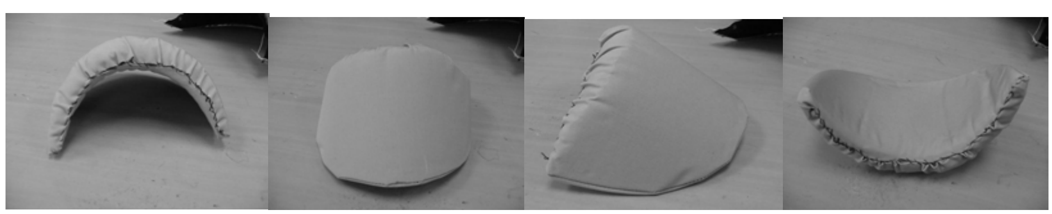


Figure 3.8: Optimal Fabric for Foam Mold

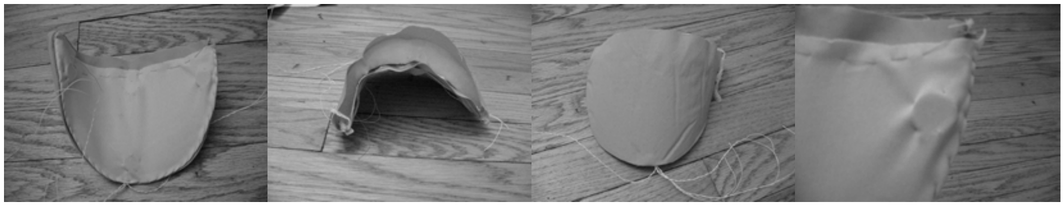
Additionally, the foam would not fill the molds to the very edges. As a shoulder pad optimally tapers to almost nothing at the edges, a very flat edge was desired. However, the gas bubbles that created the foam in the final product were too large to allow the liquid to fill the mold to the very edges. Thus a different solution was adopted: the fabric shells were sewn together on an industrial serger, creating a

¼" sewn edge. These shells were then turned inside out, so that the ¼" of sewing filled the edge of the pad, and the foam could expand to meet this on the inside.

Once motors were embedded into the pad, the functional operation did not meet the desired parameter of independent vibration of each tactor. The vibrating motors, when in contact with the foam, caused the entire unit of foam to vibrate. In the desired application, it was necessary for the subjects to be able to distinguish between motors, and to be able to localize where each vibration was initiated. If the entire pad were to vibrate when any one motor was active, this kind of localized perception of individual motors would not be possible.

To find the best-fit solution to this problem, as specified in the design process, multiple alternative solutions were generated. First, a pocket of airspace was formed around the motor itself, so that it could vibrate freely without coming into contact with the foam. Two types of airspace were developed, a pocket of stiff vinyl fabric, with a fleeced interior to provide some cushion, and a metal enclosure that separated the motor from the foam interior. Neither configuration was successful in preventing transmission of the vibration of one motor to the entire pad.

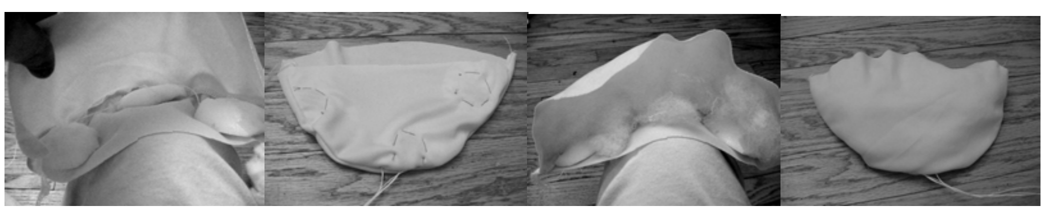
In the next experiment, the motors were isolated from the pad unit by molding a pad without embedded motors, then attaching the motors to a layer of loose polyester jersey knit fabric underneath the pad (Figure 3.9). The theory behind this prototype was that the knit would allow the motors to vibrate independently, and removing them from the interior of the pad would prevent transmission of the vibration into the pad. However, it was discovered that if the motors were at all in contact with the foam, the entire unit vibrated.



(a) (b) (c) (d)

Figure 3.9: Foam Pad Prototype with Knit Underlay (a)Underside (b)Inside (c)Top view (d)Detail of Motor Attachment

In the next prototype the motors were embedded into islands of foam, which were shaped to fit the pad (Figure 3.10). The shell for this prototype was constructed out of the knit fabric rather than the sueded polyester plain weave. The shell was then filled with polyester fiberfill, an amorphous filler that would absorb any vibrational energy. This prototype did localize the vibration to each motor, but the foam islands in which the motors were embedded only served to increase the tactor area, by increasing the area of vibration from the area of the motor to the area of the island. This caused the space between tactors to decrease, not meeting the requirement of at least 40mm between tactors in every configuration.



(a) (b) (c) (d)

Figure 3.10: Foam Islands Prototype (a)Inside, no fill (b)Underside, no fill (c)Inside, with fill (d)Top view, with fill

At this point, the foam concept was discarded. Since the amorphous fiberfill had performed the best at absorbing vibration, this material had some of the necessary properties. However, the fiberfill by itself would not accomplish the requirement that the display retain the properties of a standard shoulder pad, which include adding structure and shape to a garment. Using fiberfill instead of a more compact padding added the necessary volume, but not the structure or shape. To accomplish all design goals, the next prototype was constructed out of layers of polyester and cotton batting (Figure 3.11). The polyester batting is of a loose construction, providing similar cushioning effects to the fiberfill. Two layers of this batting were placed directly on top of the motors, which were affixed to the fabric shell, constructed out of the knit fabric. On the top side of the pad, two layers of cotton batting, a thinner and more compact padding, were pad-stitched (a tailoring method of using hand or machine stitches to attach two layers of textile and create a three-dimensional shape) together to create the curved shoulder shape and provide the structure necessary for the pad. The wires supplying power to each motor were coiled slightly within the pad, to prevent the transmission of vibration through the wires. This prototype proved most functional. This combination of materials and construction method allowed the motors to vibrate independently, while providing the structure desired from the shoulder pad.

From a manufacturing point of view, however, the foam pads would have been much easier to manufacture. They would offer more durability and protection for the motors, as well as a one-step construction process. However, apparel manufacturing techniques that could be used to simplify the construction of the prototype shoulder pads (such as using fusible materials instead of pad-stitching) could add too much stiffness, and result in similar motor coupling effects.

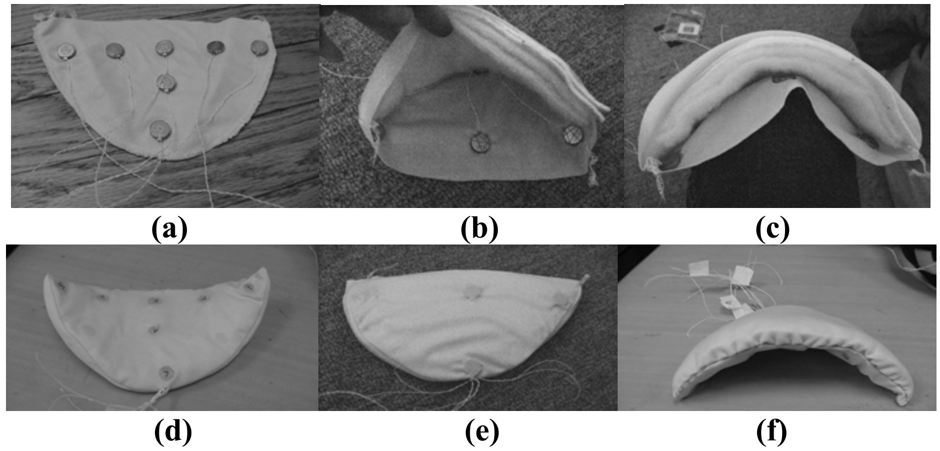


Figure 3.11: Final Protoype, Layered Batting Construction (a) Attachment of motors, 8-motor configuration (b) Interior of pad showing layers and motors, 4-motor configuration (c) Layering of pad (d) Underside of completed pad, 8-motor configuration (e) Underside of pad, 4-motor configuration (f) Pad closure, showing curvature.

3.1.5 Selection of Stimulator

The next step in fabricating the prototype tactile displays was the selection and determination the type of motors to be embedded in the shoulder pad. Within the wearable context the current vibrotactile actuator options of appropriate size and shape are solenoids, speakers, piezoelectric actuators and electromagnetic motors.

Solenoids are electromagenets, which create tactile stimulation by starting and stopping an electrical current to move a metal core or "slug" back and forth. The maximum firing frequency of the solenoid is limited by the mechanical travel of the solenoid "slug". As a result solenoids would not be able to display across the desired range of 250-400 Hz. Small solenoids suitable for garment integration also have a correspondingly small "slug" cross section and thus the tactile signal from suitably small solenoids would also be too easily muted by garment layers insulating the skin.

A broad range of speakers have been used to provide vibrotatile display for wearable applications. The speakers used range from rather large conventional speakers, with a diameter of 101.6mm to much smaller electromechanical and piezoelectric speakers (speakers made of crystals with electro-mechanical properties which allow them to change shape when a voltage is applied) and elements approximately 25.4mm or less in diameter. In addition to having a small diameter piezoelectric and electromechanical elements have the benefit of being very thin, approximately 1-3mm in thickness.

Piezoelectric stimulators are commercially available, thin, small, and flexible, making them an excellent candidate for future implementation of garment integrated vibrotactile displays. Piezoelectric stimulators have the drawback of requiring high driving voltages. For a garment integrated display this presents a risk to the user that must be addressed in any design.

The use of small counterweighted mechanical motors in consumer electronics such as pagers, cellular phones, PIMs, and PDAs means that a wide assortment of sophisticated devices are small, cheap, and readily available. These motors are similar to a regular servo-type geared motor, but they contain an off-center weight attached to the spinning motor shaft. As the shaft spins, the off-center weight causes the motor to vibrate back and forth.

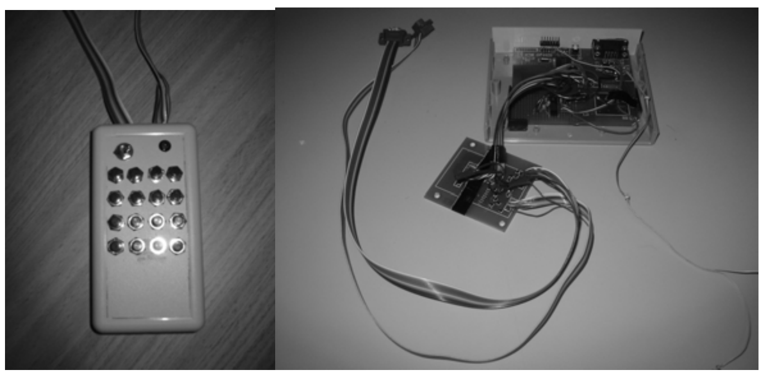
Motors also benefit from being easy to interface with, as they require only the application of voltage for operation. Motors also generate vibration with relatively large amplitude when compared against other vibration generating technology.
Small counterweighted electromagnetic motors come in two general package types: cylindrical or disk (“pancake”) motors.

Pancake motors provide a low-profile package, and occupy less volume and area than cylindrical motors. Additionally, they create a smaller tactor area, which in this application helps to maintain tactor spacing of at least 40mm. These motors were selected for use because of their small size, ease of integration, and ability to deliver appropriate levels of tactile stimulus. However, they are not ideal tactors. Their vibrational amplitude and frequency can not be precisely adjusted, nor was any information available on their operational frequency/amplitude. However, since the primary application for these motors is in tactile alerts for pagers, phones, and other devices, it can be assumed that their frequency and amplitude of vibration is within the human perceptible range.

3.1.6 Functionality: Development of electronics

The critical architectural requirement and user need in designing motor spacing was that of perceptibility. Motors must be spaced in such a way that they are far enough apart to be distinguishable by the sensory receptors as two distinct locations, but close enough together to provide the maximum amount of resolution in the display (maximum number of motors in the pad). Upon review of the literature, an initial estimate of the shoulder's two point threshold, or the minimum perceivable distance between two stimulation points, was made at 40mm. This estimate was made based on two-point threshold data for the torso. (Weinstein, 1968). Given the overall display space presented by the smallest size of shoulder pad, and using packing topologies where motor distribution remains relatively uniform and farther apart than the estimated two point threshold, six motors per shoulder pad was established as the maximum number of motors. Motor spacing between sizes was not maintained uniformly. Motors were placed in each size of shoulder pad relative to the dimensions of the pad. However, because of the small distances between motors and small differences between pad dimensions in the size range, these differences in motor spacing were negligible, and well within the two-point threshold. Enough flexibility as to the number and location of motors per shoulder pad to permit a 6-motor and a 4-motor configuration was required. To achieve this all shoulder pads were constructed with a standard DIN9 connector interface using a consistent motor to pin number mapping that could support up to eight motors and serve either as a right or left shoulder pad.

To facilitate initial prototype testing a simple battery powered “button-box” (Figure 3.12a) was constructed to drive the motors. However, for subject testing, it was necessary to have a generic and flexible motor-based vibrotacile testing system. For subject testing, a stimulator control program and a motor-driving “controller-box” (Figure 3.12b) were designed to interface with the shoulder pads.



(a) (b)

Figure 3.12 (a) “Button-Box” (b) “Controller-Box”

The “controller-box” is built around a TI MSP-430 microcontroller. A separate board is used to implement an array of Darlington amplifiers with kickback diodes to enable the microcontroller to drive the motors. The microcontroller interacts with the stimulator control program, a Microsoft Windows application used to set firing patterns. The control program allows the tester to specify up to seven different states for motor firings. In each firing state the tester selects which motors are fired, how long all the selected motors fire, and the duration to wait between states. The resolution provided for the motor firing and wait states is in units of 25mS and provides the tester a range of 0-254 units. This provides the user the ability to create both fine-grained and course testing patterns ranging in duration from 50mS to 89S. Once a pattern is constructed and "fired" it is sent to the microcontroller for execution.

3.1.7 Subjects

The twelve subjects in this study were between the ages of 19 and 34, almost the full age range of the intended user. They represented a range of body types, and their shoulder lengths ranged from 9 cm to 14.5 cm. Because this was not a field test, subjects were not controlled for occupation, work environment, technology needs, or social perceptions of technology. In this pilot study, subjects were responding only to the physical sensation of the vibrotactile display.

Subject participation met the requirements of the Cornell Committee on Human Subjects: subjects were informed of the requirements of their participation in the study, their anonymity was preserved, and they were permitted to discontinue participation at any time.

3.1.8 Testing Apparatus

Subjects tested the shoulder pads inserted into lined jackets in five sizes. The jacket and shoulder pad sizes were chosen for each subject based on their neck-to-shoulder measurement. To simulate a standard garment system, subjects wore a standard single-ply jersey knit cotton t-shirt underneath, with a thickness of 0.56mm. Jackets were donned first with conventional shoulder pads (those designed to go into the jackets) to allow the subjects to judge whether there were perceptible differences between standard and electronic shoulder pads. Testing Setup is pictured in Figure 3.13.

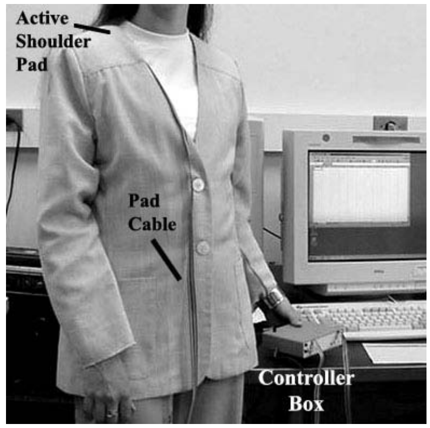


Figure 3.13: Testing Setup

Shoulder pads were constructed in two configurations, with either four (4-configuration) or six (6-configuration) motors. Motors were arranged in a t-shape, as shown in Figure 3.14.

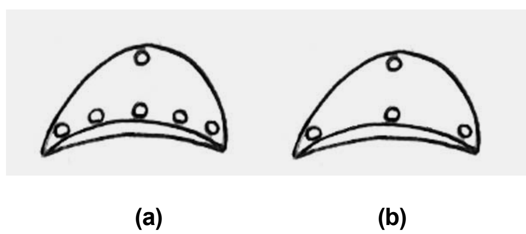


Figure 3.14: Motor Locations for 6-Configuration (a) and 4-Configuration (b)

The pads were inserted into the jackets using hook-and-loop (velcro®) fasteners. Connecting wires protruded from the neckline edge of the shoulder pad, exiting the garment and falling down the front of the jacket to connect to the driving interface. Although the available volume in the shoulder pad would have permitted a wireless prototype, at this point such development was not necessary. This test focused on how perceptible various motors in a vibrotactile shoulder display would be, not on its actual use in a mobile environment

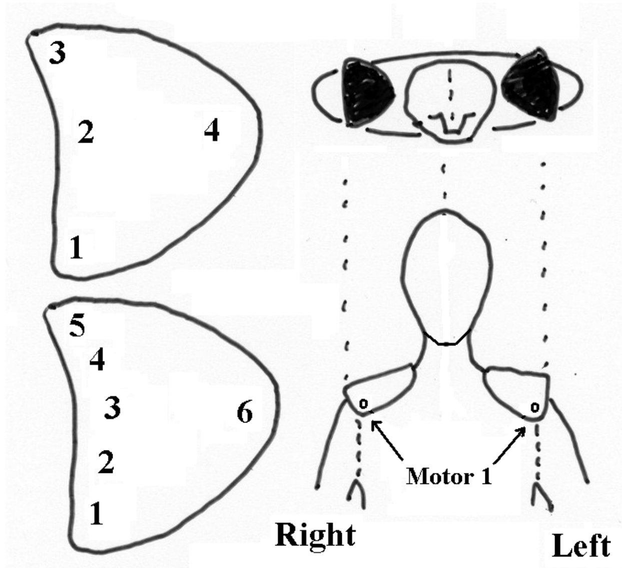


Figure 3.15: Motor Locations for Right Shoulder, 4- and 6- Motor Configurations Pictured Against the Shoulder. (Image courtesy Aaron Toney)

Right and left shoulder pads were given a mirrored motor numbering configuration. In both the 4- and the 6-motor configurations motor number 1 is the most anterior position on the body. Motor numbering then increases as the motors progress back over the shoulder. Figure 3.15 shows the motor numbering for both 4- and 6-motor shoulder pads.

3.1.9 Experimental Procedure

The twelve subjects were separated randomly into two groups, an informed group and an uninformed group, to determine if prior knowledge of motor locations would influence perception abilities. These groups were then further subdivided randomly into a group testing the 6-configuration shoulder pad and a group testing the 4-configuration shoulder pad.

Both groups were first asked to don a test jacket in the selected size with standard shoulder pads. They then rated the comfort of the jacket in their relaxed standing position on a five-point descriptive scale from very uncomfortable to very comfortable. The jacket was then removed and the shoulder pads replaced with two electronic shoulder pads. The subject rated the new configuration on the same comfort scale.

Uninformed subjects were not shown the motor configuration, but were only told that the electronic shoulder pads contained several vibrating motors, and that they would be asked to draw the area of their shoulder where they felt vibration.

Informed subjects were shown the configuration of the motors within the electronic shoulder pad by using a shoulder pad with numbers showing the placement of each motor. They were told that motors would be activated in various combinations, and that they would be asked to draw the area on their shoulder where they felt vibration.

All subjects were tested by activating only the motors in the pad on the shoulder of their dominant hand. The vibrational stimulus was first presented by activation of all motors at once to orient them to the feeling of the motors generally. Once oriented, the testing consisted of a series of trials in which motors were activated first individually, then in pairs, in threes, and in fours, and finally fives and sixes for the 6-configuration groups. Subjects testing the 4-motor configuration had a total of fifteen trials each, and subjects testing the 6-motor configuration had a total of twenty-four trials each. Patterns were randomly ordered from a predetermined set of patterns for each number of motors.

Each stimulus was activated for a period of 2.5 seconds. Subsequent patterns were activated after the subject finished drawing their response to the stimulus. (Response time varied among subjects.) Subjects recorded their responses to each trial on an illustration of a gender-neutral body outline shown in Figure 3.16. They were told to indicate what they felt in a manner that would best communicate it, by drawing points, shaded areas, arrows or x-marks, or any other depiction they felt was more suited to their experience.

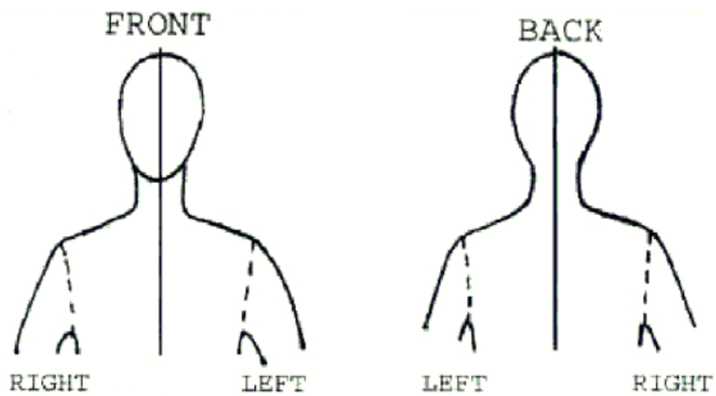


Figure 3.16: Subject Scoring Target

Following pattern trials, the subject was asked a series of qualitative questions to determine their general reaction to the tactile stimulus. They described the quality of the vibrational stimulus, the comfort level of the stimulus, and the amount of mental effort required to localize the origin of stimulus. The uninformed group was then debriefed and shown the actual location of tactors within the pads.

3.2 Results: Shoulder Pad Vibrotactile Display

3.2.1 Data Analysis

The testing procedure required subjects to map perceived vibration onto a graphic human torso, to record the subjective mapping of sensation onto the body outline shown in Figure 3.16.

In order to minimize any interpretational bias in analysis of these data an independent scorer mapped the user responses to motor positions. The scorer was provided a key of points across the shoulder that corresponded with motor location within the 4 and 6 motor configurations. For each subject the scorer was only informed as to which configuration (four or six motors) was being tested and whether there were one or multiple motors active during each trial. The scorer then recorded by number the motors that each subject appeared to feel based on her responses. These results were then compared to the actual active motors for each trial. These data were then compiled and used for the analysis.

3.2.2 Quantitative Results

3.2.2.1 Perception

Most subjects' responses followed consistent patterns through their individual testing period although the perceived location of active motors varied between subjects. There was much variation among subject's responses in mapping sensation on to the torso outline.

Even when they were provided with prior knowledge concerning the size and position of the shoulder pad and the position of the motors, the subjects also reported a much wider range of perceived stimulation area than would be expected. Figure 3.17 shows a sample subject response, where the perceived activation area is significantly outside of the area that is covered by the shoulder pad: the response extends into what can be considered the armpit of the torso figure.

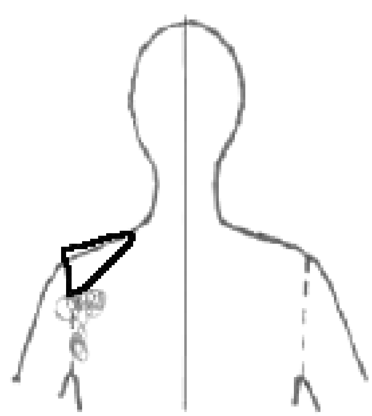


Figure 3.17: Inaccuracies in Response Mapping

3.2.2.2 Detection

During testing, for 15% of all trials, users reported the inability to detect any vibration, although all trials contained at least one active motor. For the four motor configuration, subjects felt no detection of signal in 44% of 26 single-motor firings, 13% of 47 double-motor firings, and 0% of the three- and four- motor firings. For the six motor configuration, subjects felt to 27% of the 26 single-motor firings, 15% of the 13 dual-motor firings, 8% of the 25 triple motor firings and 0% of the four-, five-, and six-motor firings.

Results identifying motors that subjects consistently did not detect through their complete testing period were compiled and are shown in Figure 3.18. This compilation shows the frequency with which each motor location was consistently missed. Tests firing three or more motors have 100% detection for the forty randomized 4-motor configuration tests and 95% detection rate for 72 randomized tests of the 6-motor configuration, indicating that although some motors were difficult to detect, multiple-motor combinations insured a higher degree of perceptibility.

All subjects experienced at least one motor that they consistently had difficulty feeling but the problematic motor varied across the subjects. All subjects could detect motor 2 in the 4-motor configuration (located at the outer shoulder tip) and motors 2 and 4 in the 6-motor configuration (located on the upper front and back of the outer shoulder edge).

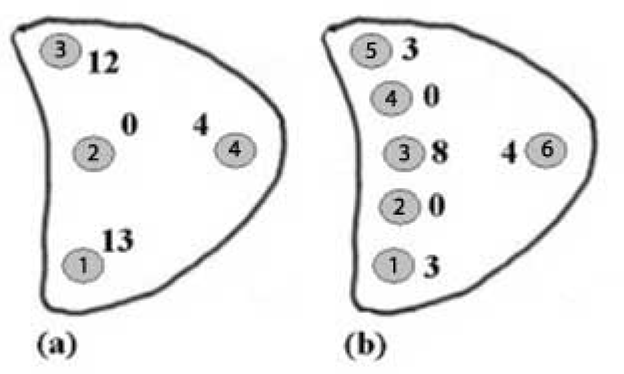


Figure 3.18: Motor Miss Frequencies, (a) 4-Configuration and (b) 6-Configuration

In many cases, the motors that could not be perceived individually were also not felt in the multiple-motor trials; these trials were perceived as if the missed motor(s) were not active. However, in some cases the missed motor made a small contribution to the multiple-motor patterns, by extending the perceived area of stimulus in the direction of the missed motor.

The responses of the informed and uninformed groups were similar in both number and identity of motors that were not perceived. However, the informed group drew more focused areas of stimulus in their response diagrams.

3.2.3 Qualitative responses

As part of the study subjects were verbally asked several open response questions. The external scorer sorted the open response comments into categories reflecting the perceived quality of vibrational sensation, degree of comfort, concentration required, and perceived ability to distinguish between sensation locations.

There was a large variation in the subject observations reported concerning the quality of the sensation they experienced. The question “what does the stimulus feel like?” was posed, and subjects responded with comments ranging from comforting or soothing to annoying or ticklish, and one subject reported that some trials were painful. Grouping the subject comments on perceived degree of comfort with the vibration (“how comfortable is the stimulus?”) the external scorer rated seven of the responses as showing a high degree of comfort, five as medium, and one as very low. The subjects’ reports of the quality of the vibration are similarly distributed with five medium responses and eight high responses.

A trend was observed in cognitive load that merits further testing; subjects who tested the 4-configuration in both groups (informed and uninformed) appeared to indicate a lower cognitive load than subjects testing the 6-configuration, based on their verbal responses to this question and on observation of their response time during the trials.

The user's perception of their own ability to distinguish between sensation locations was generally low or very low. This subject reaction appears to be in agreement with these data. Viewing just the single and dual firing tests we see only 32% and 34% perfect matches for the 4-and 6-motor configurations respectively.

The subjects generally reported no difference in comfort between the garment with normal shoulder pads and the garment with electronic shoulder pads. Three subjects reported an increased comfort level when wearing the electronic shoulder pads.

3.3 Discussion: Shoulder Pad Vibrotactile Display

The goals of the shoulder pad vibrotactile display study were to examine the utility of exploiting pre-existing volumes within a garment to integrate technology by way of garment inserts, and to investigate how perceptible a tactile display on the shoulder is in the wearable environment, taking into account layers of textile between the display and the skin. In this test, the garment is functioning as a display or output device. This introduces a variety of social and cognitive variables, but we focused in this investigation on the physical variables, perceptibility and comfort.

Given the small combined size of the subject population, data was compiled based on observations of our subjects and their response to the display. The subject pool is not large enough for rigorous statistical analysis, but trends have been successfully identified in the data for further study.

3.3.1 Development/Design Process

A detailed definition of the user and the user's needs can help to eliminate ambiguities in the rest of the design process. In this study, the user was defined as a young female (22-40 years of age), working in a somewhat formal social environment. Given this user group, a size range could be established and appropriate social parameters could be considered. The user's functional needs for the device, simultaneous perceptibility of motors and shape/structure of the shoulder pad, defined the parameters within which the physical form of the device was designed.

The materials experimentation process for prototype development helped to clarify some incorrect assumptions (for instance, that moldable foam would have enough elasticity to absorb vibration and prevent mechanical coupling) so that they could be corrected prior to fabrication of the test prototypes.

The subject evaluation process, however, also assesses the validity of design assumptions. The design of the shoulder pad display must be modified so the signal is more consistently perceptible by all subjects. This is the manner in which the design process becomes iterative: the lessons learned from the pilot study will be applied to the next generation prototype.

3.3.2 Observations

Generally the most-missed motors were those on the lowest and medial edges of the pads, those at the front and back axilla and at the intersection of the neck and shoulder, positions 1, 5, and 6 of 6-motor configuration, see Figure 3.15. This could be due to several factors: 1) the fit of the jacket in the shoulder area, which will influence the amount of pressure applied to the pad affecting the amount of skin contact; 2) the posture of the subject within the jacket, which can cause more or less pressure in an area of the shoulder; 3) the weight of the cables attached to the pad, which may pull the pad away from the body at the base of the neck; and 4) the fit of the shoulder pad, affecting the location of the axilla motors on the body.

The shoulder itself has a complex curved shape with much variation in the population. Generally the ball of the humerus and the musculature over it creates a convex curve in the front and back of the shoulder, the outer-most edge of the shoulder curve. Underneath the ball joint, there is a concave hollow in the front of the body and a shallower convex curve in the back of the body. When the lower motors on the pad fall beneath the ball of the humerus, they are more likely to sit further from the body and not be perceived, particularly in the front where the body curves away from the contour of the shoulder pad. The jacket construction does not provide a lateral force in these locations to push the motor against the body.

Motor number 3 (at the acromium) in the 6-configuration, which was not consistently perceived by subjects, corresponds in location to motor number 2 in the 4-configuration, which was always perceived by subjects. The 6-motor shoulder pad configuration is stiffer than the 4-motor shoulder pad configuration because of the proximity of the motors. This increased stiffness may be responsible for the difficulty many subjects experienced in perceiving motor 3 in the 6-motor configuration, in contrast to motor 2 in the 4-motor configuration. The increased stiffness of the 6-motor configuration may cause the pad to lift slightly away from the body as it curves over the top of the shoulder.

Misperceived motors on the pad edges often seemed to have an effect on the perception of multiple-motor patterns, expanding the area of stimulus beyond the perceived motor, but not as far as the missed motor. One possibility is that the vibration of the motor is transmitted through the batting layers within the pad to some extent, and thus the mechanical coupling of the batting is felt by the subject at an intermediate point between motors where the body is in closer contact with the pad. The result is an expanded area of perceived stimulus.

3.3.3 Sources of error

As Figure 3.17 shows, there was a very wide range of area that the subjects felt to constitute the active area on the shoulder. There are two possible reasons for this:

subject variation in the mapping process of identifying physical perceptions on the body outline and/or the vibrotactile display in conjunction with the garment produced a perceived tactile sensation away from the shoulder pad insert for some subjects. Future work is required to understand variation in subject responses.

Once the subjects had been familiarized with the operation of the shoulder pads and had recorded some initial perceptions, the recorded responses generally increased in precision without any apparent corresponding increase in accuracy. The increase in subject precision was reflected in an increased number of marking locations and specificity of location. A corresponding increase in accuracy would have resulted in fewer missed or mischaracterized responses during testing. No such trend was found. The smaller-sized markings meant a greater number of locations were chosen, making the data hard to evaluate. Given the problem of mapping physical perception onto the body outline and the difficulty of interpreting these marks, improvements to the data collection regime are required for further studies.

One possibility is to specifically instruct subjects to mark x's or dots where they felt activation (instead of having subjects self-identify appropriate marks). However, this may not be optimal for this kind of study, because one of the influencing criteria on tactile perception in the shoulder is the degree of enervation of the skin in that area, or the sensory resolution of the shoulder. A low sensory resolution would make it difficult for subjects to pinpoint a specific location where they felt a stimulus, and a small specific mark would not necessarily accurately reflect the actual perception of the subjects (who may have felt a larger area than was actually stimulated).

The variables involved in perceptibility, from this study, appear to be the layers of textile between the motors and the skin, and the fit of the shoulder pad on the body (which affects the amount of contact between the display and the body). To maximize contact and minimize the intermediate textile layers, perhaps a similar tactile display might be integrated into a close-fitting undergarment, such as a t-shirt layer, or a bra layer like the bio-monitoring bra. There is another complicating variable however, when dealing with vibrating motors and skin contact. Increasing the pressure applied on the motor to hold it in contact with the skin may have the effect of restricting the motion of the motor, preventing it from providing the tactile stimulus. Thus a configuration would be necessary that allowed the motors to remain close to the skin surface, but still retain the lateral mobility to vibrate.

3.4 Conclusions/Future Work: The Shoulder Pad Vibrotactile Display

3.4.1 Design Process

The functional apparel design process was used to identify the issues involved in socially subtle device output, and to generate the solution of a shoulder pad vibrotactile display. The iterative, exploratory design process used in the development of the display itself was very successful, and illustrates the utility of this process in identifying incorrect assumptions (such as the assumption that the pourable foam product would provide structure and allow independent motor activation), and correcting them to arrive at a functional solution. However, incorrect assumptions about motor perceptibility were identified in the evaluation phase. Specifically, the assumption that six motors would be distinctly perceptible through several textile layers was shown to be slightly inaccurate. At least four motors were reasonably perceptible, but users showed significant variation in their individual abilities to perceive motors. These findings would be applied to the next phase of a continuing iterative design process.

3.4.2 Evaluation Process

This study showed a strong positive subject comfort response to integration of technology in the shoulder pad. Garment insert integration was successful in minimizing visual and comfort effects of technology integration. The shoulder pad insert also allowed the easy removal and interchangeability of pads in a standard suit jacket.

Conventional clothing inserts offer an exciting new form factor for socially covert body-worn devices. Device integration into standard garment inserts, such as the shoulder pad integrated tactile display, allows intelligent clothing to be practically indistinguishable from conventional clothing while the device is not in use. Further design consideration can minimize the external perceptibility of the device during device usage. Ultimately these optimizations lead to clothing-integrated technology usable in the same manner as “off the rack” clothing, including issues related to care and cleaning. Integration into a stand-alone unit allows the device to be moved from one garment to another, and removed to allow the garment shell to be washed in a conventional manner. It also allows the device to be manufactured as a unit, reducing the additional cost related to interfacing the technology and apparel manufacturing processes.

Integration of devices - particularly display devices - into commercially viable clothing in a visually unobtrusive manner, results in minimal degradation to the social interaction which occurs between users and others when the device is not in use. While the relative social weight of the shoulder pad was not measured in this testing, one can assume that by combining minimal physical presence with the potential to operate within existing social conventions and with a minimal increase in the visibility of technology to observers, such garment-integrated devices have an inherently low social weight.

The tactile displays mounted in the shoulder pad were shown to have some degree of perceptibility, although not as much perceptibility as tactile displays that are in direct contact with the skin. Subjects were able to distinguish more than one general area of stimulus, and the chance of perception increased with number of active motors. Some effects on cognitive load were observed between the 6- and 4- motor configurations. The larger number of active motors required more attention from the subject in order to discern location of activation, indicating that a lower-resolution display would present a lower attentional demand.

The subjective perception of haptic interfaces is affected by several design considerations. Design issues are multiplied when the interface is embedded into a garment. The perceptibility of the interface is affected by the form and the fit of both the garment and the display device. In order to help facilitate further development in the area of shoulder-mounted tactile displays and garment-insert integrated electronics, the following guidelines are proposed:

- Vibro-tactile stimulators require garments to be constructed such that an even and adequate force is applied by the stimulators. The force bearing the stimulators' mechanical energy into the skin is related to garment weight, display device (shoulder pad) shape, and garment fit (taking into account subject posture).
- Display applications which require user perception of distinct activation areas increase the importance of insuring that stimulators continually have the best possible contact with the body, even when additional garment layers come between the stimulator and the skin. Such applications therefore must either take into account optimal fit, or be equipped to apply a degree of pressure to the area activated, in order to ensure perception of active motors.
- Care must be taken that mechanical coupling of motors within display enclosure materials do not blur the boundaries of specific vibration regions.
- Shoulder-mounted garment integrated displays and their applications should be limited in the number of discrete stimulating regions the user is expected to

distinguish. Users seem able to accurately distinguish at least four discrete stimulation regions on one shoulder with the degree of skin contact afforded in our testing set-up. However the number of discernable regions is directly affected by the proximity of the motors to the skin and the magnitude of motor vibration. The relative importance of these contributing factors seems to increase proportionally to the number of discernable stimulation regions.

Key design issues remaining to be tackled include moving the stimulus closer to the body, optimizing number and placement of motors, and optimizing garment weight. Future wireless shoulder pads will allow for a more open response to testing and a broader range of subject responses and allow the authors to move from a static to dynamic testing paradigm.

In a next iteration of the design process for this prototype, the resolution of the display would perhaps be decreased, using the 4-motor configuration but coupling the vibration of each motor with a larger tactor area (similar to the foam islands prototype from the initial development stages) to increase the perceptibility of vibration. Experimentation with altering the amplitude and frequency of the motor vibration may help to optimize perceptibility.

Future applications of this kind of garment-integrated shoulder-mounted tactile display include assisted navigation, motion guidance, subtle communication alerts, and communication of low-bandwidth information. One promising end use is the implementation of moving tactile stimuli on the shoulder to elicit physical movement for navigation or motion control.

CHAPTER 4: AESTHETICS AND IDENTITY: THE MASSAGE SHIRTS

Technology mounted directly onto the body is assimilated as part of the user's personal space. Body-mounted technology that is worn continuously becomes part of the user's visual identity. Therefore, the decision to adopt an innovation that possesses that degree of influence on an individual's identity involves more emotional risk, and thus a user is more likely to adopt a gradual innovation that is more observable, compatible, trialable, and offers more competitive advantage.

The design of the aesthetic display of embedded technology represents one of the most complex design challenges in the field of wearable technology, because of the scope and nature of the variables involved in the decision. These variables relate to the user's perception of their own personality, their interactions with others, the situations in which the device will be worn, and their interest in the function of the device, among other things. The visual display of technology is the focal point of the interface between the user/device combination and other individuals in a society, and therefore has a significant impact on the user's definition of self. Whereas input and output devices impact the physical and cognitive interfaces between the human and the device, the visual representation of the technology embodies the social interface.

This study represents a pilot investigation into the introduction of a wearable technology innovation to a broad user group. The function of the device must be attractive to a broad range of users. The variations in aesthetic display of the embedded technology are used to analyze user responses to the display or concealment of the embedded technology.

4.1 Methodology: Massage Shirts

As previously discussed, the emotional and social connotations that are attached to a visual image have distinct effects on an individual's interest or lack thereof in an object, garment, or device. This is especially relevant in wearable technology, which has the added uncertainty of being a new and innovative product. In this study, a series of garments was constructed with identical functionality, but different degrees of display of the embedded technology. Each garment displays or conceals the component technology to a different degree. The goals of the study were to explore the relationship between an individual's self-perceived personality and their attraction to each level of technology display. Although the relationship was explored using one prototype technology, a similar relationship between individual personality and attraction to subtle or overt technology is hypothesized to be present in any wearable application.

Because the user in this scenario is defined not as an individual, but as a group or target market of individuals, the first requirement for the design of the prototype garments was the identification of a low-cost, simple application of technology that would be attractive to a wide variety of individual personalities. (However, in order to simplify the design process of multiple garments, the user group was restricted to female users.) During testing of the vibrotactile shoulder pad display, a common subject response to the tactile stimulus was that the stimulus felt "relaxing" or "comforting" or "soothing". Thus it was hypothesized that a massage function, based on the use of the same vibrating motors used in the shoulder pad, would be an attractive functionality. To explore this aspect of the tactile impulse, two focus groups were conducted on the topic of wearable technology and stress in the workplace. Two groups of four women each met for one hour to discuss their experiences with stress in the workplace, their use of technology, and their reactions to the idea of a soothing massage device.

The purpose of conducting focus groups is to open up a discussion among members of a target group to gather information about their ideas, thoughts, and opinions on a topic or set of topics. Small group size ensures that each participant has adequate opportunity to contribute to the discussion. (Recommended focus group size is between four and six participants).

4.1.1 Focus Group Subjects

Subjects were all female, between the ages of 22 and 40. Each group contained four participants. These participants in each case were acquainted with one another and worked for the same organization, although not all in the same office. One group worked in university administration, and the other in local government administration. Conducting focus groups with subjects who are well acquainted can help to ease the flow of conversation and discussion, allowing subjects to freely speak their minds and express differing opinions.

Subject participation met the requirements of the Cornell Committee on Human Subjects: subjects were informed of the requirements of their participation in the study, their anonymity was preserved, and they were permitted to discontinue participation at any time.

4.1.2 Focus Group Procedure

Discussion topics covered three major areas: clothing choices and use in the workplace, experiences with stress in the workplace, and use of technology in the workplace. (See Appendix 1: Questions for Focus Groups.)

Conversation was guided by open-ended questions and follow-up questions where needed. Focus groups were tape-recorded, and transcribed following the focus group. The transcriptions were then analyzed in two parts: first, relevant sentences and phrases were separated from filler or no-content speech. The relevant sentences were then classified using a series of codes (See Appendix 2: Focus Group Data Codes.) Generating the codes themselves provided initial insight into the gross categories of responses, and applying them to the text then allowed similar responses to be pulled together for comparative analysis and frequency analysis. The transcripts from both groups were analyzed using the same set of data codes by the primary researcher and by an independent evaluator, and compared for consistency.

4.1.3 Prototype Garments

The massage shirts are designed to use vibrotactility for a far simpler application than that required for communication or information display. They are constructed using common manufacturing methods used in the apparel industry: machine embroidery, adhesives, and lining.

This kind of simple but attractive application represents a way to gradually introduce wearable technology into the mass market. The added cost beyond the garment cost is minimal, manufacture requires little adaptation on the part of cut-and-sew garment manufacturers, and the garment retains its aesthetic and functional roles whether or not the electronic application is used.

To achieve the vibrating massage, each shirt contained six to eight flat pancake-style vibrating motors, the kind that is used in pagers and cell phones. These motors were identical to those used in the shoulder pad vibrotactile display. The set of motors is powered by one 9-volt battery. They are activated by an on-off slide switch.

The three shirts were designed to represent a spectrum of aesthetic references to the technology and end use. Because of the focus group responses regarding aesthetic preferences, a sheath tank-top style shirt was used. This garment style provides aesthetic adaptability and maintains full mobility. The “subtle” shirt looks outwardly like a normal sheath tank-top. No evidence of technological function (the vibrating units) is visible, as motors are concealed beneath appliqués and wires are covered with embroidery. The “moderate” shirt alludes graphically to the embedded technology, through zig-zag lines that evoke an image that references the vibrating function. Motors are adhered to the inside of the shell garment, and both motors and wires are concealed between the shell and the lining layer of the garment. The “overt” shirt takes the shirt’s function from the tactile modality into the visual modality, by using the vibration of the motors to physically stimulate an added surface embellishment. For this mode, each motor is enclosed within a flexible, clear plastic hemisphere or “bubble”, half-filled with iridescent beads. When the shirt is operated, the beads bounce within the bubble. Wires in this prototype are adhered to the inside of the face fabric using a color-matched adhesive. In all three shirts, the battery and switch are integrated into the wide hip-level hem panel, which minimizes their bulk and outward appearance. The design for these shirts is shown in Figure 4.1.

(a) (b) (c)

Figure 4.1: Designs for Subtle (a), Moderate (b), and Overt (c) Integration

4.1.4 Testing

4.1.4.1 Pilot Test

A pilot test was conducted during a showing of student work. Subject responses to all three prototypes were gathered using a brief survey (see Appendix 3: Massage Shirt Pilot Test Survey). Survey questions were designed to elicit the subjects' views of their own personality, their level of affinity towards gadgets and technology, and their reactions to each prototype. Specifically, questions were included about which (if any) of the shirts they would wear or buy, reasons why/why not, and their perceptions of the massage function. The three prototype shirts were displayed on mannequins, and subjects were told to turn the shirts on and feel the vibrating massage with their hands. Subjects did not try on the prototypes. Subject responses were collected from 34 participants in the pilot study, from subjects ranging in age from 18 to 60. This range of subjects includes the same general distribution of subjects in the focus groups. Four of these responses were from male subjects; these were discarded prior to data analysis.

Subject participation met the requirements of the Cornell Committee on Human Subjects: subjects were informed of the requirements of their participation in the study, their anonymity was preserved, and they were permitted to discontinue participation at any time.

4.1.4.2 Survey

Following the analysis of the results of the pilot test, the survey and the experiment were re-designed and the test conducted a second time (see Appendix 4: Massage Shirt Survey). The responses from the pilot test survey were used in re-designing the survey, to make it more precise and eliminate variables based on the specific aesthetics of the prototype garments. The second survey was conducted over a period of three days, as part of a second exhibition of student work. 31 responses were collected. Respondents to this survey were female, between the ages of 21 and 60, again a similar distribution as subjects participating in the focus groups and pilot test. Responses from three male subjects were discarded prior to data analysis.

Subject participation met the requirements of the Cornell Committee on Human Subjects: subjects were informed of the requirements of their participation in the study, their anonymity was preserved, and they were permitted to discontinue participation at any time.

In the second survey, subjects were shown each prototype shirt on a dress form, along with a set of design sketches for each (see Appendix 5: Massage Shirt Design Sketches). The sketches offered subjects alternatives to the specific aesthetic of each shirt, grouped into levels of expression of technology. Subjects were also asked to judge each shirt without reacting to its color: they were asked whether they would wear any shirt in a given group if they could have it in any color combination. These two changes helped to prevent subjects from reacting only to the surface design, garment style, or color of each prototype. As each subject could imagine the shirt in their preferred style and color, they could then concentrate on their reaction to the degree of expression of the technology.

Open-ended questions from the pilot survey were replaced with multiple choice options, to help identify specific reactions from the subjects and eliminate responses based on variables related to specific garment aesthetics.

4.2 Results: Massage Shirts

4.2.1 Focus Group Results

Focus groups were conducted to obtain opinions from target market regarding their needs in the area of a massage shirt. To determine their wearability needs in a wearable device, subjects were questioned about their normal daily clothing choices, and the ways in which they used or modified their clothing during a work day. To explore the sources of the need for a massage device, they were questioned regarding the sources of stress in their work lives. To investigate their feelings toward technology, they were questioned regarding their uses of technology at work. And finally, subjects were presented with the concept of a massage function embedded into a shirt, and questioned about their reactions to the idea of wearing such a device.

4.2.1.1 Subjects

Each subject brought a different set of experiences to the discussion. Some subjects were in their first job out of college, and others had been working in offices for 15 or more years. Some had only worked in one office; others had experienced several different environments. Subjects had different job requirements and office environments.

4.2.1.2 Clothing Discussion

The clothing discussion was focused on determining the levels of formality of dress experienced by the subjects, the degree of versatility required of their clothing, and the kinds of tasks performed at work.

In terms of formality of dress, there seemed to exist a wide variety of acceptable dress choices. However, most subjects seemed to have encountered some degree of social pressure regarding their clothing choices. This pressure came primarily from superiors or colleagues, as well as internal pressure (a desire to feel good about one's self) and pressure to appear professional to customers or outsiders. Pressure from superiors was the most common, and often seemed to come from age differences. In the words of one subject, "…when I first started, I felt discounted all the time, and I didn't know if it was because I was dressing incorrectly or if it was just because I was so much younger than they were. Like if I wear a button down shirt and a blazer, and a straight skirt and pumps, will I be taken more seriously?" In this example, the subject seems to be using dress as a visual expression of occupational competence, but also as a way of departing from her own age group to identify with an older group. The subjects returned to this theme of difference of clothing choice between their age group and the older group. In the words of another subject: "I think it's a generational thing. I see everybody in my group wearing pantyhose or supportive undergarments or slips! Some of them still wear slips! And I'm like, slips? I *never* wear slips!"

The blazer and the dress were recurring examples of "formal" dress, items of clothing that would be worn on occasions where the subject wished to appear more businesslike, more capable, or more serious. Dressing up would allow the subject to impress superiors and clients, and to be taken more seriously.

Although the spectrum of formality in everyday work wear was broad, the delineating example that was continuously brought up was that of blue jeans. Subjects cited jeans as the stereotypical example of "informal" dress. Such dress would perhaps be acceptable on a "casual Friday" in the office, but not at other times. Other examples of dress that would be considered too informal in the office included shorts and t-shirts. Shorts, in particular, were given as an example of dress that would be considered too informal even for a casual Friday.

The topic of appropriate levels of formality of dress brought up another, related problem. Both groups complained of pressure to dress more formally than their salaries allowed: "...at an entry-level position where you're younger, you're not making the kind of money that it costs to afford the wardrobe that they expect. Yeah, I would go out and buy a full wardrobe at Ann Taylor if I could, but you're going to have to up my salary a little more."

The younger subjects seemed to like the prestige and other social implications of wearing formal garments such as blazers, but complained of the physical restrictions imposed by such garments. “I feel like I can’t move my arms.” Some subjects had jobs which required a mix of stationary desk-work and more physically demanding tasks, such as putting up bulletin boards or other displays.

4.2.1.3 Stress Discussion

The discussion of stress was concerned with the factors that caused stress in the workplace, the ways in which stress was experienced by the subjects, and the methods subjects used to deal with stress.

The stressors experienced by focus group subjects generally fell into two categories: interpersonal relationships and task-related stress. Interpersonal relationships, including relationships with bosses, co-workers, or clients/customers/the public, were the largest source of stress. Subjects cited relationships with their superiors often, complaining of the frustration of trying to please superiors, and of the accomplishment of their own responsibilities being impeded by a superior’s actions (or inaction): “It’s kind of the stress of being like powerless, in the sense of getting your boss to get you something on time.” Similarly, interpersonal relationships between colleagues also caused stress: “I think I get stressed the most when I’m having a difficult interaction with co-workers.” “I feel a definite pressure of trying to create harmony.”

In certain jobs, the primary stressor is the constant interaction with individuals outside of the office environment, with clients, customers, or members of the public. “It can be very stressful, the way that people, I get a lot of verbal abuse…it does stress you out, because even though it’s not attacking you personally, they are yelling…” This, for several subjects, was also magnified by their lack of authority: “Not only that, but we’re not in power to do anything about it anyways.” “We’re just sounding boards.”

Task-related stress often came from a work overload or from an unexpected problem, like a technological breakdown. “I think a lot of us have high points of the year when we have tons of events going on…I think those days are stressful, when you’re just not quite sure if you’re really going to make it through the day, and get everything done the way it needs to be done.” However, it can also come from a combination of tight deadlines and problems with co-workers on collaborative projects. “You’ve got this deadline and all of the sudden not all of the pieces are together, and this group over here hasn’t submitted what they need to…you spend a lot of time doing work, that ends up being for nothing”.

The physical experience of stress for the focus group participants was primarily manifested in the form of headaches and muscle tension, mostly in the neck and jaw area. However, some subjects also claimed they experienced stress more emotionally than physically, as evidenced in their interactions with others. (“I get very bitey in conversation.”) Extreme stress experiences brought on more severe physical reactions in some subjects, such as gastric problems, vomiting, or shaking.

Although some subjects had come into contact with stress-management techniques, the most common method of counteracting stress was avoidance of stress situations. Subjects often gave examples of techniques they used to remove themselves from a stressful situation: (“I personally find the hold button works pretty well.”…“My thing is just getting up and going for a walk, and just remove yourself from the situation: I’ll count to ten…”); or to prevent a stressful situation from happening: (“I try to plan things in advance…and think of everything.”…“I’ve actually ducked out of my office and gone into someone else’s just hoping that the person will just go away.”) Other ways of dealing with stress included calling a family member (including small children) on the phone, “venting” to friends, listening to music, and working out. One subject was medicated for her tension headaches, and others used over-the-counter pain relievers to reduce headache or muscle ache. Relaxation techniques, although familiar, were not used. The most common reason offered for this was the nuisance of remembering to perform relaxation exercises.

4.2.1.4 Technology Discussion

The technology discussion was concerned with the ways in which subjects used computer technologies during the workday. All subjects used the computer a large portion of the day, many up to 80-90% of the day. They used the computer primarily for communication, data processing, and word processing. None of the subjects used a laptop or PDA, although all but one subject expressed a desire for increased mobility in her work. Many subjects complained of the physical effects of being tied to the computer. “Just the physical of getting up from the computer, I mean I don’t mind working on documents, but like I said, I do welcome the activity.” “When I’m just staring at the screen, sometimes I have to close my eyes and look away because I feel like my eyes have become part of the screen.”

Other subjects expressed the need for a portable computer to take to meetings or other non-office locations where they might need to take notes or record things. Communication with direct superiors was also a desire expressed: “I’d like for my boss to use a PDA. I’d love it. Because then, I can hot-sync that thing with my computer, and upload, download do everything…” The idea of being able to work in more pleasant environments than the office was also appealing to subjects: “To have the capability of getting up and…go hang out at the commons for half an hour…I think you would still have your break time, ‘cause you’re actually working.”

Although almost all subjects expressed a clear desire for a portable computer to improve the quality of their workday as well as to improve their efficiency, many subjects also expressed at the same time an aversion to computers at home. “I don’t like sit at home on the weekends wanting to type away on the computer, I don’t think so." "I actually refused to own one, but I had my own little side-business, and I had to have one for that. Otherwise, I never use it. I have no desire to even look at the computer." Subjects seemed to enjoy and recognize the utility of computers in their worklife, but not for entertainment or social functions.

One subject was consistently opposed to any kind of mobile computing device. For her, a mobile device represented work following her around, and she enjoyed being able to leave the work behind when she left the desk. "…when I leave the office, that work is staying there. I don't want to be bothered with it until I have to get back into the office."

When introduced to the idea of wearable computers and specifically a massage shirt, subject reactions were mixed. One group reacted very positively, despite their earlier aversion to using computers at home or outside of work. The other group had a mixed reaction. Subjects were concerned about the security of wearing a computing device: "…big brother watching my bra…"… "But as far as anybody being able to contact me just by wearing clothes, that scares me."… "I would be concerned mostly with who gets the data and how it's being used." This was due to the participant's lack of knowledge about the functionality of the system, as it was never suggested that the device contained any communication capability (and therefore, "big brother" or anyone else for that matter would have no way of finding, tracking, or getting data from the system).

Subjects were also concerned with the physical impact of wearing a device. "When you said it would be on your body, I didn't find it to be very appealing, that it would be attached to me somewhere"… "…if it was bulky, if you were wearing a tight shirt…" and with the social implications "…but you'd probably have other people sittin' there looking at you, like what is wrong with you…"

The massage device functionality seemed to be the most appealing. Subjects responded very well to that particular function, regardless of their reaction to other aspects of wearing technology or to computers in general. “It would be nice every now and then just to have a little shoulder massage, not even on a stressful day!”, “I could handle a shoulder massage all the time…”, “I’d use it in my personal life too, if it fit the criteria of being easily worn, not bulky, because I have just as much stress out of work as I do in work.”

4.2.2 Prototype Development

Based on the responses from the stress discussion and the introduction of the massage garment concept, the massage function was considered to be a useful and attractive function for users with a wide variety of personalities. Other user needs included the need for maintenance of the levels of physical mobility and comfort provided by loose-fitting (non-constrictive) clothing, a versatile garment aesthetic (above a certain threshold), social subtlety of both the embedded technology and the technological functioning, and autonomous control over the garment function.

Although the focus group discussion was limited to the environment of a particular office workplace, even within that constricted environment, subjects exhibited varied needs and wants in the area of garment aesthetics. For this reason, and to expand the potential target environment and market, multiple options for garment aesthetics were generated in the test prototypes. The design of the “subtle” shirt focused on eliminating all visual evidence of the embedded technology. This garment is pictured in Figure 4.2.

Figure 4.2: “Subtle” Massage Shirt Prototype

The “moderate” design contained no outward appearance of the physical technology, but used graphic surface design (using zig-zag patterns) to allude to the garment’s functionality. This garment is pictured in Figure 4.3.

Figure 4.3: “Moderate” Massage Shirt Prototype

The “overt” garment used the technology in a very visible manner. This prototype used the technology in a more traditional “wearable technology” aesthetic—high-tech, innovative, attention-grabbing. The surface embellishment (bubbles of iridescent beads) displayed in a very prominent manner the activation of the vibrating motors. When the motors are active, the beads bounce inside the bubbles, adding both a visual and an enhanced audible element to the motor function. This garment is pictured in Figure 4.4.

Figure 4.4: "Overt" Massage Shirt Prototype

Color images of all three prototypes can be found in Appendix 6: "Massage Shirt Prototype Images".

4.2.3 Pilot Test

Survey responses were collected from 30 subjects in the pilot test. Because of the open-ended nature of many of the survey questions, responses were extremely varied, and because of the environment in which the survey was conducted (public exhibition), many responses were incomplete. These factors made data analysis very difficult, but provided valuable insight to assist the modification of the survey for a subsequent test.

Subjects generally enjoyed the massage function. 82% responded positively to the massage function in general. This result was consistent with the general reception of the prototypes at exhibition: they generated a lot of positive attention, and were attractive and exciting to attendees. Similarly, although subjects' attraction to any one prototype was not consistent, only three subjects responded that they had no interest in wearing any of the three prototypes. The "overt" shirt was the most popular, a favorite in most levels of every personality response.

As shown in Figures 4.5, 4.6, and 4.7, there was little relationship between subject responses to personality questions and attraction to a given prototype.

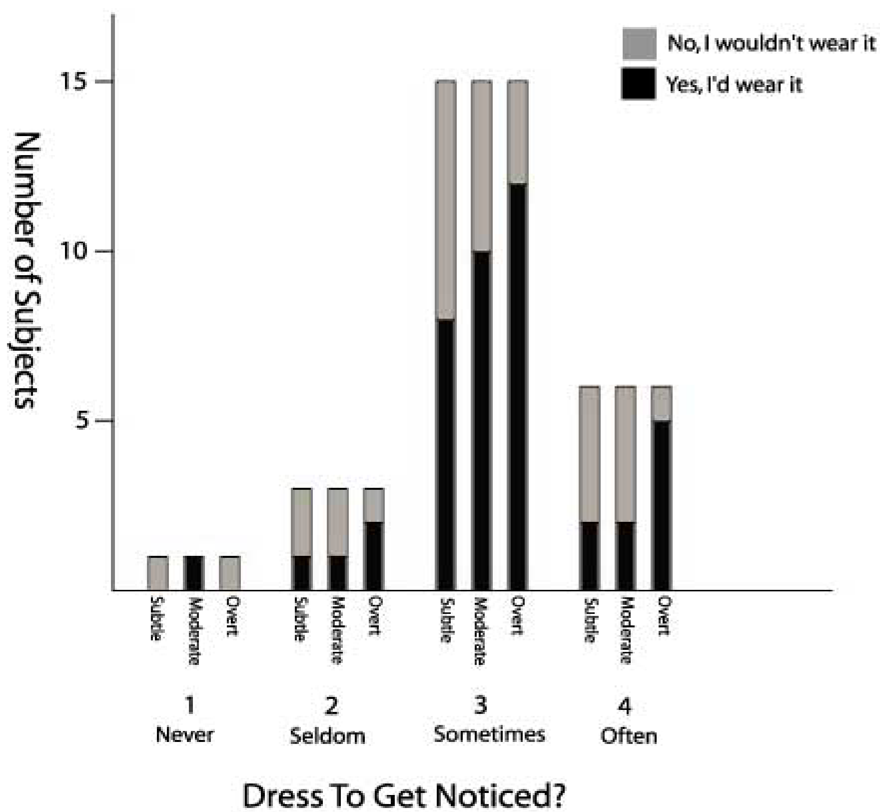


Figure 4.5: Subject Interest in Test Prototypes, by Dress Factor

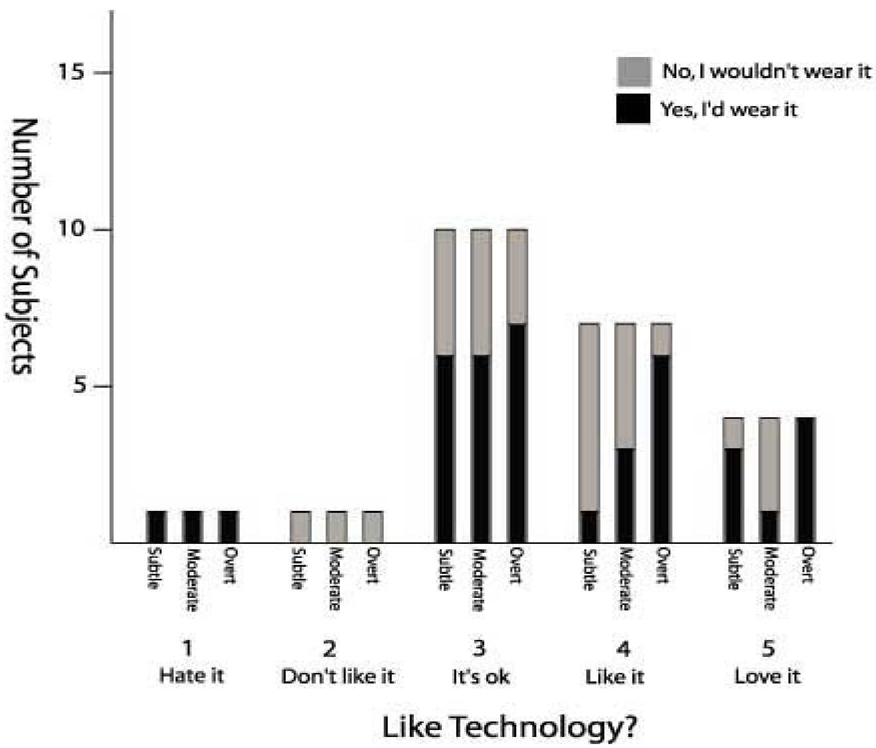


Figure 4.6: Subject Interest in Test Prototypes, by Technology Factor

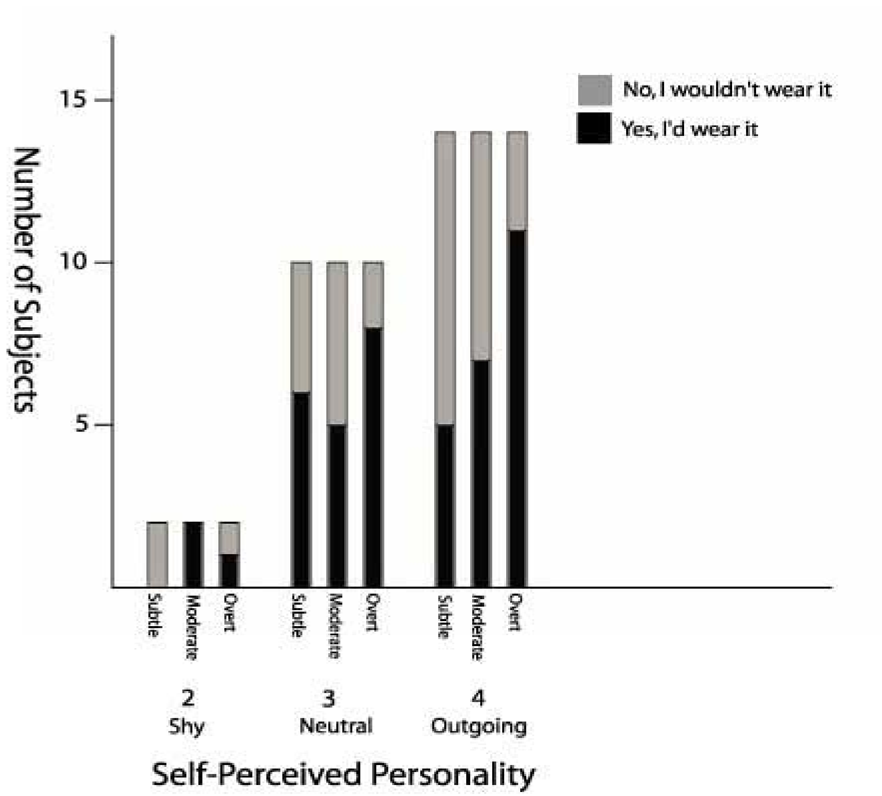


Figure 4.7: Subject Interest in Test Prototypes, by Personality Factor

Subject perceptions of the value of the prototype garments ranged from $0-10 to over $80, with the majority between $30 and $50, as seen in Figure 4.8.

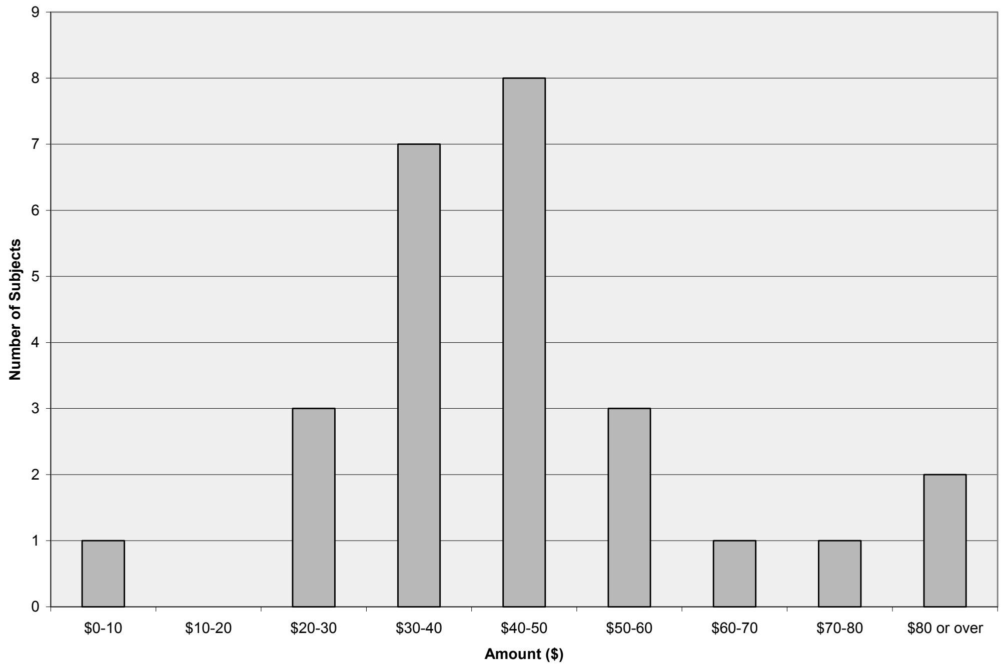


Figure 4.8: Perceived Value of Prototype Garments, Massage Shirt Pilot Test

Besides the survey responses to each prototype, the open-ended responses identified external variables that are likely to have had significant effects on subjects' affinity towards (or lack thereof) each prototype. The most predominant of these variables were the role of color, garment style, and surface embellishment/graphics. Many subjects qualified their decision to not wear a given prototype with reasons such as "I don't like the color", "I don't like zig-zags", or "it's not my style". This kind of response was interpreted as having been significantly influenced by variables other than the display or concealment of technology. However, the visual presentation of the technology was also a factor. Subjects also qualified their responses with reasons such as "technology is too subtle", or "this one is too obvious".

4.2.4 Massage Shirt Survey

The pilot test, concluding in three physical prototypes, provided the test-environment feedback necessary for the next iteration of the design process. The feedback from the pilot test was used to re-design the study in order to focus more precisely on issues more directly related to the technology.

From the pilot test qualitative results, it appeared that while display of technology was a factor in determining a subject's degree of affinity toward a given prototype, the response was significantly complicated by the extraneous variables of garment style, color, and surface embellishment. To remove these variables in the second test, the study was re-designed so that subjects reacted to each of the tangible prototypes along with an associated group of drawings. The group of drawings which corresponded to each prototype varied in their style and graphics/surface design, but contained three distinct levels of visual representation of the technology. These design sketches can be found in Appendix 5: "Massage Shirt Survey Design Sketches".

In the second survey, 87% of subjects responded they would wear the subtle garment. 74% responded they would wear the moderate garment, and 61% responded they would wear the overt garment. The number of subjects in each level of each personality response that would wear a garment in each group are shown in Figures 4.9, 4.10, and 4.11.

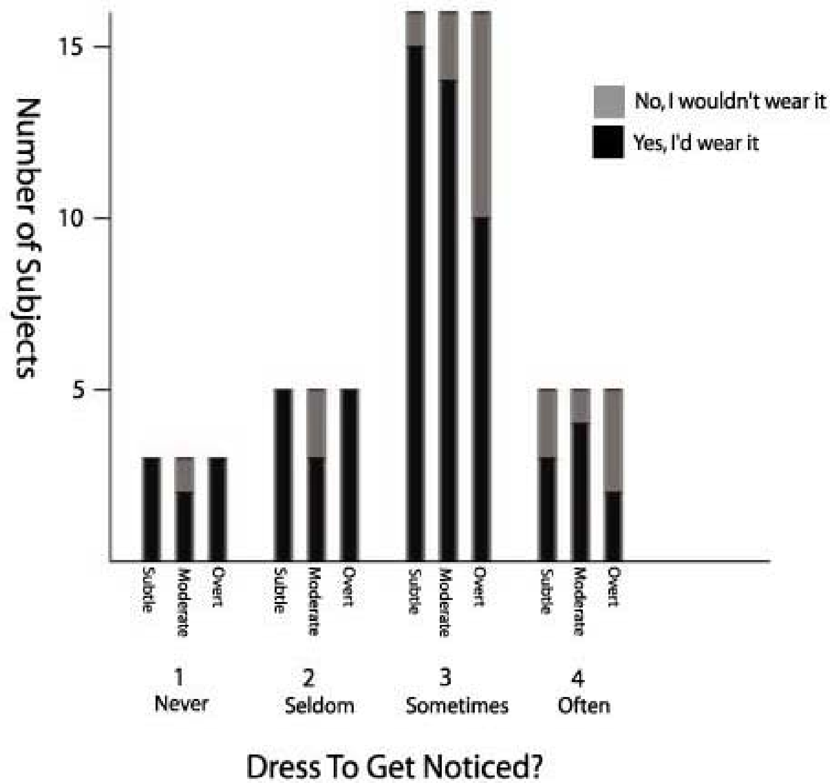


Figure 4.9: Subject Interest in Design Groups, by Dress Factor

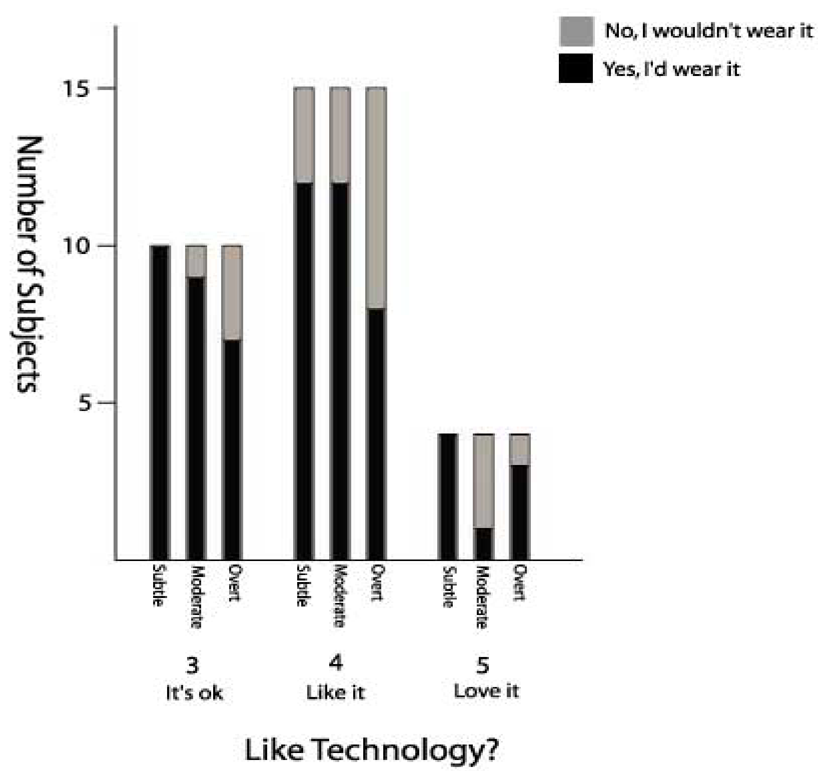


Figure 4.10: Subject Interest in Design Groups, by Technology Factor

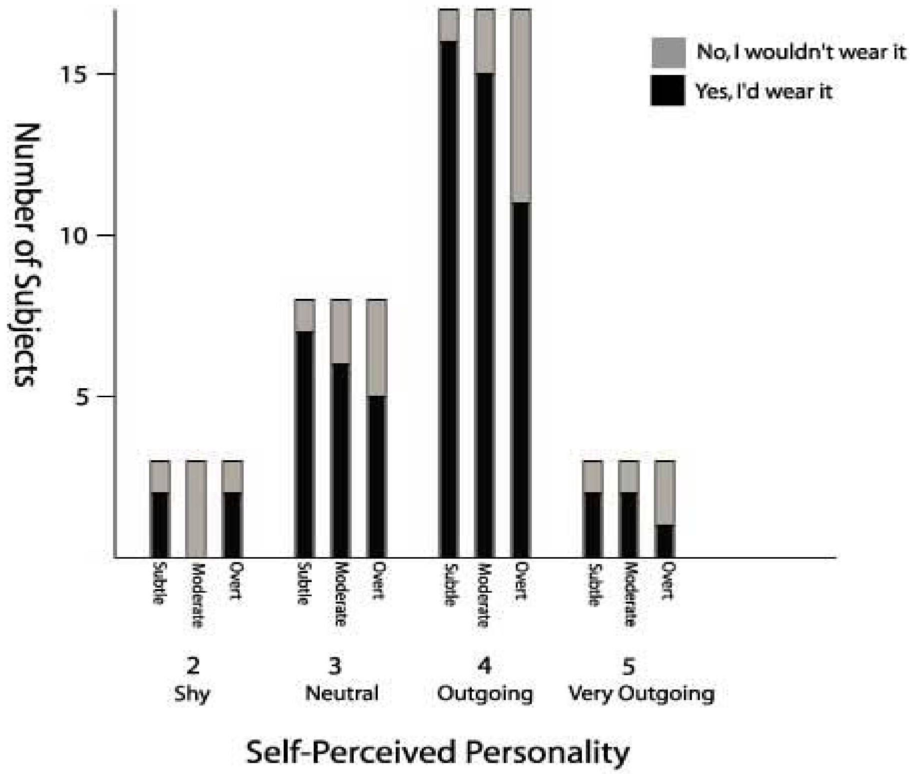


Figure 4.11: Subject Interest in Design Groups, by Personality Factor

In the second survey, the overt group was a clear favorite in almost all response levels of the personality questions regarding self-perceived personality and manner of dress. However, the subtle prototype was the favorite in all levels of the personality question regarding interest in technology. The combination of these results shows no clear pattern or relationship between these aspects of personality and affinity for a given group of prototypes.

The multiple-choice responses in the second survey allowed responses based on specific garment aesthetics to be eliminated. Sixty-one percent of subjects responded that they would wear the subtle garment for reasons related to the display of technology. Thirty-nine percent of subjects would wear the moderate garment for reasons related to the display of technology, and 42% would wear the overt garment. Six percent of subjects would not wear the subtle garment because of the degree of visibility of the embedded technology, 10% would not wear the moderate garment, and 32% would not wear the overt garment.

Subjects in the second survey found the garments to be of less value than subjects in the pilot test. As seen in Figure 4.12, subject responses ranged from $10 to $70, with most subjects willing to pay between $10 and $30 per garment.

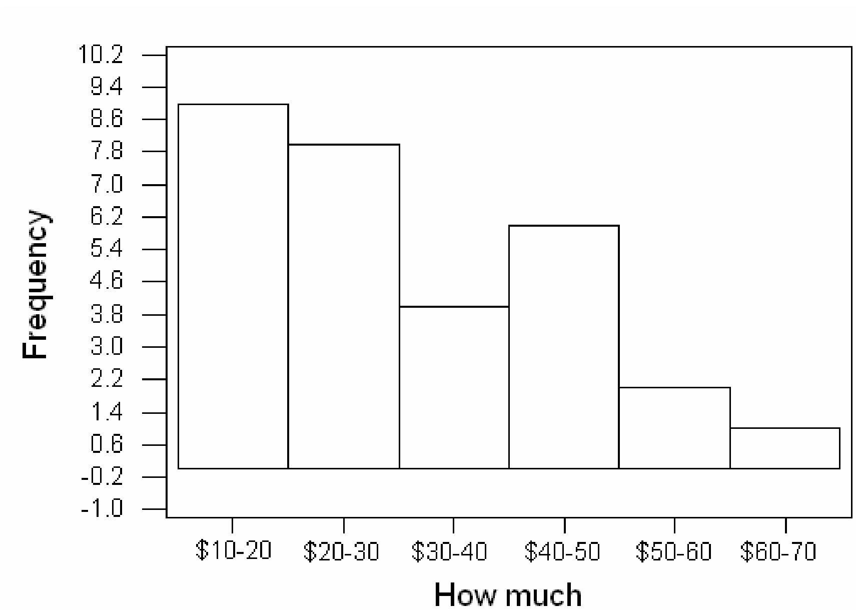


Figure 4.12: Perceived Value of Garments, Massage Shirt Survey

In the second survey, 75% of subjects responded positively to the massage function in general. In their open-ended responses, however, a new variable emerged. In the pilot test, the garments were presented to subjects during a crowded showing of student work. Ambient music and conversation drowned out the buzzing noise of the active motors. In the second survey, subjects experienced the functionality of the shirts generally in a quiet gallery, with very little ambient noise. Many subjects in the second survey commented in a negative manner on the noise created by the activity of the motors. This was often deemed to counteract any visual subtlety of the integration of the technology. Subjects gave comments like "too noisy for work" or "it would be nice if the motors made less noise, then you could activate it anywhere".

4.3 Discussion: Massage Shirts

4.3.1 Observations: Focus Groups

The focus group discussions provided valuable insight that helped to define the target user, and determine the user's functional, physical, and emotional needs. This information was used in the design of both the design of the prototype garments, and the design of the survey evaluation.

4.3.1.1 Clothing Discussion

Subjects often expressed concern about socially appropriate dress. Their offices had a range of "appropriate" levels of formality (business casual to formal dress), and appropriate levels of formality often depended on presence or absence of superiors or outsiders, and on the tasks to be performed on a given day (meetings, dealings with the public, et cetera). However, many subjects reported that they dressed to feel better about themselves. There was a definite threshold of informality that subjects felt they could not cross. Specific examples included wearing jeans or shorts.

Physically, subjects did not like the restrictions placed on their physical mobility by formal articles of clothing such as blazers. They often felt that formal clothing did not afford enough mobility for the tasks they were required to perform.

4.3.1.2 Stress Discussion

Subjects experienced stress primarily from interpersonal interactions or from occupational tasks. Physically, stress was manifested mostly in muscle tension, in the neck and jaw. Emotionally, it was exhibited through short tempers, and impacted interpersonal interactions and relationships. They dealt with stress in two ways: a few used medication, but most counteracted stress by attempting to avoid it. When stress was unavoidable, subjects used a variety of techniques to relax themselves: talking to loved ones, listening to music, or taking a break. Relaxation techniques were familiar to subjects, but they did not consider them useful enough to remember to use them.

4.3.1.3 Technology Discussion

Although all subjects used computers and other technologies extensively in their work, they generally had a negative opinion of using technology. This, however, seemed to be more because subjects associated the use of technology only with doing work, thereby generating a negative impression of the use of technology.

To contrast the apparent negative impression of technology, subjects were very interested in the target application, the massage function. Only one subject responded negatively to the concept of a massaging garment.

Subjects exhibited apprehension about the possibility of other people being able to see or record their biological signals. They also expressed the need for a wearable device to remain visually subtle, so that others would not know that the device was active, or that they were wearing a device.

4.3.2 Development/Design Process

The design process in this study was most valuable in its exploration of the use of standard apparel production processes to integrate electronics into clothing. Machine embroidery, when applied using a layer of interfacing to prevent buckling of the face fabric, was strong enough to hold two wires in place, and dense enough to mask their appearance from the inside of the garment. Wires were placed between inside of the the face fabric and the interfacing layer, which aided in concealing the wires from view. Embroidery, however, was difficult for an inexperienced operator, because of the difficulty of maintaining the precise positioning of the wires on the garment. Positioning was made more difficult because the wires could not be seen during embroidery (as they were concealed between two textile layers). An initial application of fast-drying adhesive to hold wires in place, or the use of a routed template, may assist this process in commercial manufacture. The use of machine embroidery to attach wires and electronic components does, however, require that the garment’s aesthetic design incorporate elements that can serve as machine-embroidered pathways. Engineering surface design so that machine embroidery can support the wires wherever they need to travel can be a design challenge.

The use of color-matched adhesive to affix wires was an easier process, but less traditional to apparel manufacturing. The wires were attached directly to the inside of the shell fabric layer, with no additional textile layers. Therefore they could easily be positioned by the operator during attachment. The drying time of the adhesive is a drawback to this process, but it does not require that exterior visual elements be included in the aesthetic design to allow for the integration of wires and connectors.

The easiest integration method was the use of a complete lining in the garment. Motors were attached to the inside of the face fabric using adhesive, and wires were allowed to hang between the face fabric layer and the lining layer. There are two major drawbacks to this manner of integration: first, the wires and motor connections may experience more strain during garment donning and doffing, and second, the use of a full lining in a garment increases the garment cost and may create negative comfort effects, by increasing the garment’s heat retention and decreasing its breathability.

4.3.3 Observations: Pilot Test

The purpose of the survey evaluation of the prototype garments was to measure the relationship between subjects’ self-perceived personality and their interest in various levels of technology display in the wearable environment, and to explore the range of user needs in the aesthetic expression of an electronic garment.

Subjects exhibited a good distribution of personality factors. The massage function was well-received, with 81% of subjects responding positively. This reinforced the findings of the focus groups, that a massage garment was a relatively universal application, attractive to a wide variety of users.

In the pilot survey, however, there was little relationship between personality factor and affinity toward a particular prototype (Figure 47). This could be due to many factors, including the specific aesthetics of the garments, which complicated user responses, the calculation of personality factor, or a lack of relationship between the two variables. The overt shirt was the most popular in the pilot test, in all but the lowest two personality factors. This may have been influenced by the social environment present during testing: the overt prototype generated the most interest from passers-by, and most of the interest was strongly positive. Therefore, the strong positive response surrounding that particular prototype may have increased the attraction of subjects to the overt shirt. Alternatively, in both surveys the evaluation environment was that of an exhibition of new work: therefore participants may have arrived at the exhibition with an expectation of seeing new and innovative garments (or, participants could have been influenced toward this expectation by other aspects of the exhibition), and thus showed more interest in the prototype garment that was visibly the most innovative and different. The subtle shirt was the least popular. This again could have been influenced by the aforementioned variables.

4.3.4 Observations: Massage Shirt Survey

In the second survey, the massage function was again very well-received, with 75% of respondents indicating a positive reaction. The use of alternative design drawings in conjunction with the constructed prototypes eliminated a considerable amount of reaction based purely on specific garment aesthetics, but not all. 42% indicated their reason for wearing or not wearing garments in Group 1 (“subtle”) was due to reasons other than the integration of technology (either garment style or surface design). 52% cited aesthetic reasons for wearing/not wearing garments in Group 2 (“moderate”), but only 26% for wearing/not wearing garments in Group 3 (“overt”). This perhaps is due to the lack of ambiguity of the integration in the overt prototype. Because the technology features so dominantly in the design, it overpowers other factors like garment style or surface design: either subjects are interested in visible technology, or they are not. The novelty of obviously having an electronic garment is much stronger than the other elements of the aesthetic design. In the other two prototypes (and groups of designs), the technology is not immediately visible, so subjects must respond to a wider variety of less divisive design elements.

Again in the second survey, there was no clear relationship between any personality response and attraction to a given prototype. However, in this survey the subtle group (Group 1) was the most consistently popular in the personality response related to interest in technology, while the overt group (Group 3) was the most popular in the other two personality questions (self-perceived personality and manner of dress). Group 1 contained the most neutral designs, and therefore would have been expected to be more popular to a wide variety of subjects. However, as previously discussed, this result could have been skewed by participant expectations of experiencing distinctly new and innovative garments in an exhibition setting.

The variability in subject responses indicates a further complicating factor that was not specified in this test: that of environment (social and physical). Subjects indicated that they would be interested in different prototypes for different environments: the overt integration for a nightclub, party, or other special event; and a subtle or moderate integration for work or every-day. Social environment is very difficult to define, because of its dependence on a large number of intangible factors: physical condition, group composition, activity, presence/absence of spectators, perception of self, and many others. A worn device impacts the individual's self-perception as well as their perception by others. Therefore, this variable is very difficult to control, but very clearly impacts the individual response.

4.1 Conclusions/Future Work: Massage Shirts

4.4.1 Design Process

The functional apparel design process initially was used to identify the problem addressed in this study: the issue of the impact of visual display of technology on the social interface between the human and the device. The process was successful in identifying a function that was attractive to a broad range of different users, and in creating prototypes that were also attractive to a broad range of users. Following the first pilot test evaluation process, additional variables were identified for examination: those of the specific aesthetics of the prototype garments. These variables were addressed in the second study, but new variables were also identified in that evaluation process. The assumption that user attraction to a given level of technological display would not be influenced by context of device usage was shown to be inaccurate, and was believed to have affected the outcome of the second survey. In a future iteration, each level of display of technology would be presented along with a specific usage scenario.

4.4.2 Evaluation Process

The focus group discussions undertaken at the beginning of this sequence provided the foundation for a more successful design. Subject responses indicated that the prototype garment needed to be aesthetically versatile, maintain mobility, retain user control over functionality, and provide some degree of technological subtlety.

To address varied user interests, meet the needs of multiple situations, and provide the desired aesthetic versatility, three prototypes were developed. Each prototype embodies a different degree of visual display of technology, although all have the same functionality. Through a short survey, subjects were questioned regarding their self-perceptions of personality and their interest in each prototype garment.

The results of the pilot survey, as the evaluation phase of the design process, emphasized some areas of improvement for the prototypes. Subjects responded more to the specific aesthetics of each prototype (surface embellishment, color, garment style) than to the general aesthetics of display of technology. At this point, were the prototypes being developed for market, more prototypes would be designed, either with more neutral aesthetics and surface design or with a greater variety for subjects to choose from. However, since the goal of the study was to explore the relationship between degree of display of technology and individual self-perception of personality, the need to remove specific aesthetics from the subject evaluation process was achieved by generation of a series of alternate aesthetic design drawings. This encouraged subjects to imagine any number of color combinations and design execution methods, removing many of the reactions based on specific aesthetics. The second survey also employed multiple-choice responses rather than open-ended questions, allowing responses based on specific aesthetics to be identified and eliminated.

In the first survey, there was a strong positive response to the massage function, indicating that the functionality of the shirt was successful and attractive to a wide variety of consumers—large age span and personality variation. The prototype garments were perceived as fairly valuable: most subjects felt they would pay between \$30 and \$50 per garment, a slight increase from the market price of a similar non-electronic garment.

In the second survey, the massage function was again positively evaluated. The garments were perceived as less valuable, with most subjects willing to pay between $10 and $30: roughly the cost of a similar garment without augmentation.

There was no significant relationship between personality factor and desire to display or conceal technology in either survey. In the first survey, the overt garment was the most popular, and in the second, the subtle garment was the most popular. However, in the second survey subject responses indicated that the decision to wear or not wear a garment with overtly integrated technology was based primarily on the presence of the technology (not on the specific aesthetics of the design), which can be seen as a simplification of the decision-making process. The prototypes that contained less overtly integrated technology caused variables such as garment style and surface design to become more important in the decision-making process.

In the second survey, the subtle group was the most popular overall (across personality factors, regardless of reason for decision), followed by the moderate group. The overt group was the least popular. This is also not surprising, because the subtle group contained the most generic aesthetic designs, and the overt group contained the most aesthetically specific designs.

The process of development and testing of these prototypes raised many important issues in socially accommodating design of wearable technology. The following specific variables are proposed for consideration in future design processes:

- *Integrated adaptability or multitude of choice:* Because of the large number of influencing factors in user decisions to wear an electronic garment, it is not always practical to introduce a limited number of aesthetic options. In the design of a carried device, the device aesthetics are not as integral a part of the user's self-image as body-worn devices and garments are. Therefore it is necessary to either embed adaptability, customization, or other means of aesthetic modification into the device, or to present the user with a multitude of aesthetic options. This can be achieved through adaptable design or through a mass-customization production scenario.

- *Production efficiency:* Subject responses in this study indicated that a massage function raised the perceived value of the garment only slightly, if at all. Because of this, and because of the necessity of maintaining user choice in aesthetics (either through multitude of choice or through adaptability), which creates an additional expense in garment production, it is essential that technology integration does not significantly raise the production cost of the garment. Use of standard apparel production techniques for technology integration can help reduce additional costs.
- *Other sensory perception variables:* As seen in the second survey, other peripheral sensory variables may influence the perceptibility of the embedded technology, either by the user or by others. In this study, the noise of the vibrating motors was of concern to subjects, who wondered how others would respond to the noise. In other kinds of applications, lights, sounds, or even added heat may render a subtle application noticeable, and must be taken into account during the design process.

The next set of prototypes and alternate design options in this design process would most likely be geared toward very specific social contexts, and toward a narrower user age group. This would permit the analysis of personality factors without the complicating element of ambiguity in social situation. A real-world user field test would also help to identify other variables involved in actual use of wearable technology in a day-to-day situation.

The issues involved in this study are directly related to consumer buying choices, and therefore can be applied to many different kinds of garment-integrated technologies available on the commercial market. The way in which a body-worn technology affects self-perception as well as perception by others, must be taken into account when designing a wearable device. These variables are often ignored, primarily because of their complexity. In this study, social acceptance variables were imagined by each subject: prototypes were not worn by subjects in social settings. A more complete investigation is necessary to thoroughly evaluate the ways in which wearing a subtle or overt technology affects social interaction, self-perception, and garment functionality.

CHAPTER 5: CONCLUSION

This work has used the functional apparel design process and design culture to inform the design of wearable technology as it relates to the human-device interface. The three components of this study have been conducted to investigate and to experiment with some of the important emerging issues in the design of input devices, output devices, and the visual expression of embedded wearable technology, with a focus on the analysis of the physical, cognitive, and social variables that influence good design in each area. Approaching the design problem from an apparel or functional apparel perspective can raise new issues as well as propose novel solutions to existing problems.

The focus in this study was the investigation of wearable technology issues as complex, interrelated issues relating to physical, cognitive and social needs of the user. Each component prototype and evaluation was designed to investigate a different aspect of the wearable integration of technology, the approach to wearable technology applications, and the needs of the user in the wearable environment. No one study provides a comprehensive solution to any issue, but they individually raise important issues and offer preliminary solutions.

In a traditional design process, one problem would be addressed from start to finish, with as many iterations of the process as necessary. However, in an emerging field, there is often not sufficient awareness of the issues involved in designing for a new context or functionality. Therefore, a complete process becomes difficult and less successful. Because of this, an exploration into multiple important issues of wearable technology design was conducted, making use of the structure of a traditional design process to help ensure as thorough an analysis as possible.

The three investigations undertaken in this work have provided valuable insight for the designer of all kinds of wearable technology. They have offered new variables for consideration in the areas of application design, garment-integration of technology, and socially accommodating design. These variables are related to the physical user (the way in which the physical form of the device relates to the body of the user), the emotional/psychological/cognitive user (the way in which the user cognitively interacts with a device, and the impact the device has on the user's normal patterns of behavior), and the social user (the way in which the physical and functional form of the device impacts the user's self-perception, and the user's interaction with others—be they users or non-users). All of these variables are unique to the design of wearable technology, although they may have counterparts in the design of functional clothing or the design of computing devices. The set of issues and variables presented here is by no means complete: it represents an initial exploration into the multitude of issues present in a new field, and offers a new perspective to designers to help expand the scope of variables that are considered in wearable technology design.

The functional apparel design process and design culture is uniquely qualified to approach the intangible and complex variables that effect the intimate relationship between a human user and a technological device. The culture of functional apparel design is accustomed to analyzing the needs of human users. These needs have traditionally been physical or social in functional apparel design, but the relative similarity of cognitive needs renders other areas of human factors expertise applicable. While the technology design culture is well-equipped to carry out the successful design of the technology itself, this is often not sufficient when the real-world factors of physical, cognitive, and social interactions are introduced. Successful design for a mass-market, real-world application requires a detailed and informed analysis of the human-device interface.

The immense array of complex variables related to this interface, while familiar to the functional apparel designer, are not yet completely identified. This is due to the novelty of the field of research: an established body of knowledge does not yet exist that can sufficiently inform the design process. For this reason, it is important that the designer conduct pilot investigations and engage in an iterative design process to identify the specific new variables that exist for a particular design problem. This work represents three such pilot investigations, intended to identify some major variables related to the human-device interface in the areas of device input, device output, and visual representation of embedded technology. The major new variables that have been identified include:

- *Structural Garment Design*: the location of components (weights and volumes) within a garment structure; the maintenance of garment-skin contact; dynamic interaction of complex shapes; and the manner of integration of technology components within the garment structure.
- *Preservation of Clothing Concept:* the investigation and understanding of the factors that make up the current clothing concept, and the elements of that concept that must be preserved to facilitate evolutionary design and consumer acceptance of innovation; the creation of garment-appropriate applications; and the maintenance of comfort and usability standards.
- *Construction of the User:* the conscious awareness of the designer's choices and their impact on the physical, cognitive, and social construction of the user

Good design is crucial to user-acceptance of a new technology. Wearable technology requires a more dramatic shift on the part of the user than any previous technological advance, because it exists on the user's body and as a part of the user's self-image to a much higher degree than technologies that are left on the table or slid into the pocket. Technology that becomes a "second skin" takes on all of the power and influence of the skin: physically, psychologically, and socially. It is only through a very complete design process that the designer of a second skin can hope to address the magnitude of the problem.

APPENDIX 1: QUESTIONS FOR FOCUS GROUPS

Questions for Focus Groups

Introductions: around the table—give your name, and your background—especially any kind of work experience you've had in an office environment. Give us a little description of the kinds of offices you've worked in: how formal was it? How many people? How old were they? What kind of work atmosphere was there?

Clothing Questions

What do you usually wear to the office? [Is there a dress code at the office? Describe a typical outfit, including accessories.]

Where do you do most of your work in the office? [Do you sit, stand, walk? Are you often in one location? How much do you move around?]

Stress Questions

Working in an office, how often did you find yourself becoming stressed? [Did this change depending on the kind of office you were in? (Try to generate discussion of different kinds of office environments, and how they induce stress)]

What kinds of things make you stressed?

How do you know you are getting stressed? [What do you feel physically? How long does it take you to realize you're getting stressed? How do you usually first know?]

Describe some of the ways you deal with stress. [Have you ever learned any relaxation techniques? Do they help?]

Describe some measures you take to avoid or counteract stress. [How successful are you in avoiding stress?]

Do you think it would be helpful to be alerted to your rising stress levels before you become aware of them?

Personal computing questions:

What kind of a computer do you use most often?

Do you ever use a laptop or PDA? [Why not?]

What do you use mobile computers for most often?

What if you could have constant access to your computer files, the web, and your personal data? Would that be useful to you?

What would be your reaction to wearing a computer?

Introduce idea of massage device. Solicit comments, questions, reactions. How would you make this better? How else would you like it to function?

APPENDIX 2: FOCUS GROUP DATA CODES

Codes for Focus Group Data

SP=social pressure; modifiers: D=dress, T=technology

BG=background

CW=computing work; modifier: E=example

PW=physical work

CE=clothing example; modifiers: F=formal, I=informal

FC=financial constraint

PI=physical impact; modifiers: C=clothing, S=stress, T=technology

SE=stress experience; modifiers: C=co-worker, B=boss, W=work/task related, O=other interaction

SM=stress management; modifiers: R=removal, T=therapy/technique, M=medical, P=prevention

CP=computer-related comment, positive

CN=computer-related comment, negative

APPENDIX 3: MASSAGE SHIRT PILOT TEST SURVEY

Massage Shirt Survey

You are invited to participate in a survey concerning the shirts in this display, as part of a Masters Thesis research. Your response to the survey will remain completely anonymous. Your decision whether or not to participate in this study will not affect your future relations with Cornell University or the Department of Textiles and Apparel in any way. If you have any questions about the research, please call Lucy Dunne (Graduate student, primary researcher) at 262-0779, email address led6@cornell.edu, or Susan Ashdown (Faculty advisor) at 255-3151, email address spa4@cornell.edu. If you have any question about your rights as a study participant please contact the University Committee on Human Subjects at (607) 255-5138.

Your completion of the survey indicates that you have read the information provided and that you wish to participate in the study. You may withdraw from the study at any time without prejudice.

Age:_____ **Sex:** _________

I would consider myself: (circle one)

1-------------2--------3-----------4------------5

very shy shy neutral outgoing very outgoing

I dress to get noticed: (circle one)

1---------2----------3-----------4----------5

never seldom sometimes often always

I like technology and gadgets: (circle one)

1------------2-------------3----------4----------5

hate it   don't like it   it's ok   like it   love it

Please examine the three prototype massage shirts. Feel free to turn them on and feel the vibrating massage.

Would you wear any of these three shirts? Why/why not?

Shirt #1   Shirt #2   Shirt #3

Would you buy any of these three shirts? Why/why not?

Shirt #1   Shirt #2   Shirt #3

If you would buy any of the three shirts, how much would you pay for each?

$0-10 $10-20 $20-30 $30-40 $40-50 $50-60 $60-70 $70-80 Over $80

What do you think of the massage function?

____

____

____

____

Is there anything else you'd like to tell us? Please tell us below!

APPENDIX 4: MASSAGE SHIRT SURVEY

Massage Shirt Survey

You are invited to participate in a survey concerning the shirts in this display, as part of a Masters Thesis research. Your response to the survey will remain completely anonymous. Your decision whether or not to participate in this study will not affect your future relations with Cornell University or the Department of Textiles and Apparel in any way. If you have any questions about the research, please call Lucy Dunne (Graduate student, primary researcher) at 262-0779, email address led6@cornell.edu, or Susan Ashdown (Faculty advisor) at 255-3151, email address spa4@cornell.edu. If you have any question about your rights as a study participant please contact the University Committee on Human Subjects at (607) 255-5138.

Your completion of the survey indicates that you have read the information provided and that you wish to participate in the study. You may withdraw from the study at any time without prejudice.

Age:_____ Sex: _________

I would consider myself: (circle one)

1--------------2--------3------------4-------------5

very shy shy neutral outgoing very outgoing

I dress to get noticed: (circle one)

1----------2-----------3------------4-----------5

never seldom sometimes often always

I like technology and gadgets: (circle one)

1------------2-------------3----------4----------5

hate it   don't like it   it's ok   like it   love it

Please examine the three prototype massage shirts, and the group of alternate designs for each. Feel free to turn them on and feel the vibrating massage. Please answer one question from each pair. (Circle all that apply)

If I could have it in any color combination, I would wear at least one shirt in group #1 because I like:

a) the shirt style b) the surface design c) that the technology is obvious d) that the technology is subtle

I wouldn't wear <u>any</u> of the shirts in group #1 because I don't like:

a) the shirt style b) the surface design c) that the technology is too obvious d) that the technology is too subtle

If I could have it in any color combination, I would wear at least one shirt in group #2 because I like:

a) the shirt style b) the surface design c) that the technology is obvious d) that the technology is subtle

I wouldn't wear <u>any</u> of the shirts in group #2 because I don't like:

a) the shirt style b) the surface design c) that the technology is too obvious d) that the technology is too subtle

If I could have it in any color combination, I would wear at least one shirt in group #3 because I like:

a) the shirt style b) the surface design c) that the technology is obvious d) that the technology is subtle

I wouldn't wear <u>any</u> of the shirts in group #3 because I don't like:

a) the shirt style b) the surface design c) that the technology is too obvious d) that the technology is too subtle

If you would buy any of these shirts, how much would you pay for each?

$0-10 $10-20 $20-30 $30-40 $40-50 $50-60 $60-70 $70-80   Over $80

What do you think of the massage function?

____

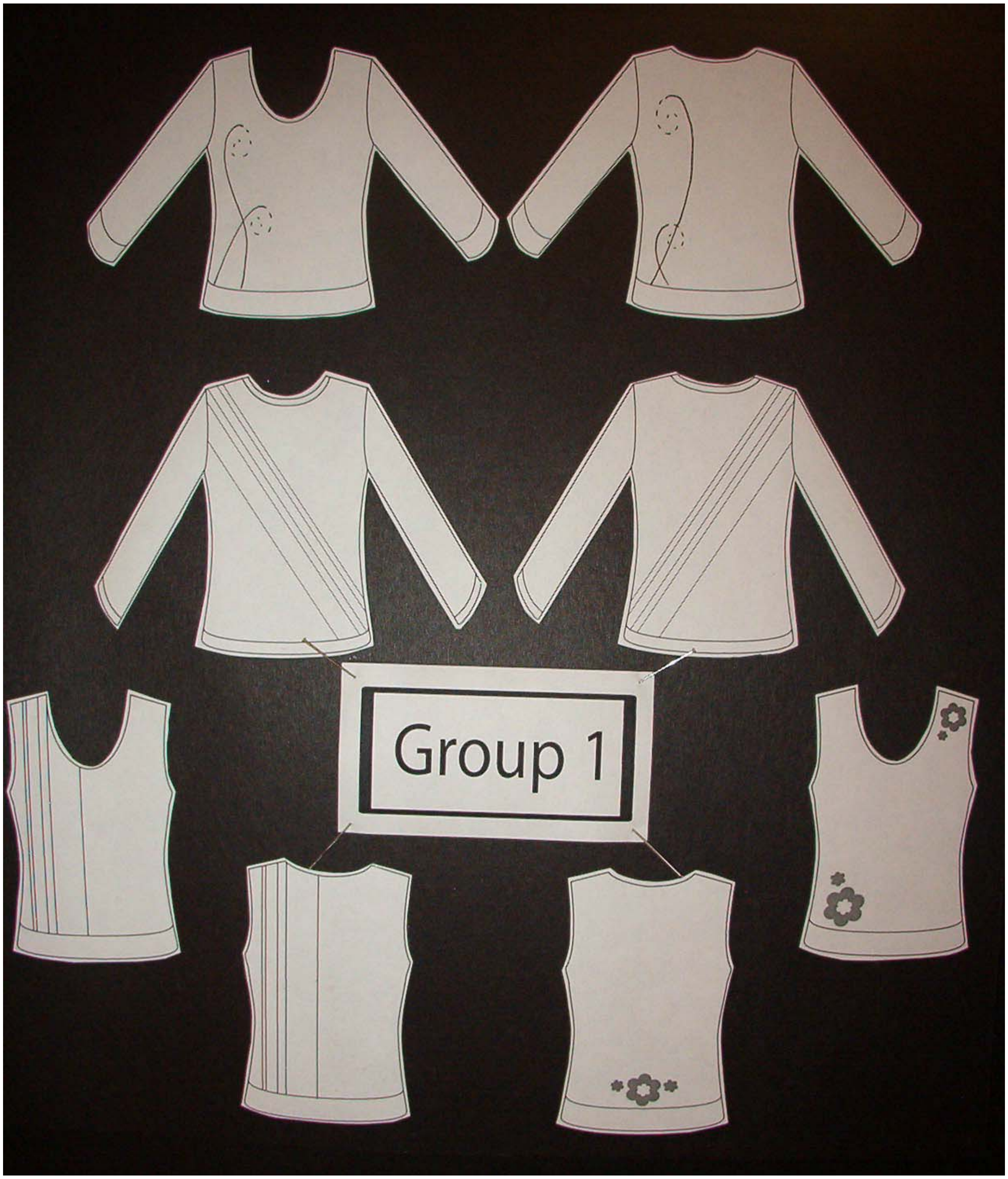
____

____

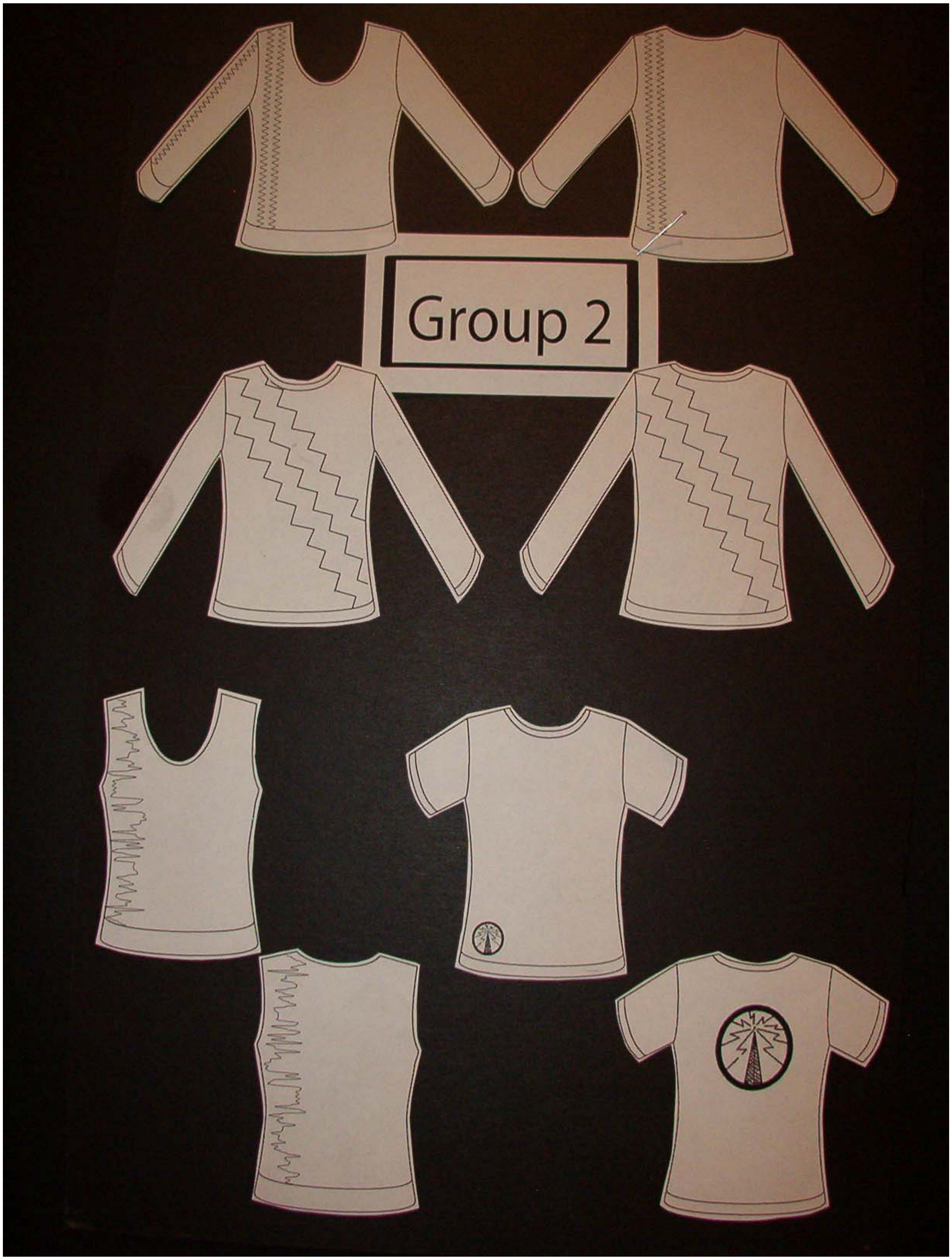
____

Is there anything else you'd like to tell us? Please tell us below!

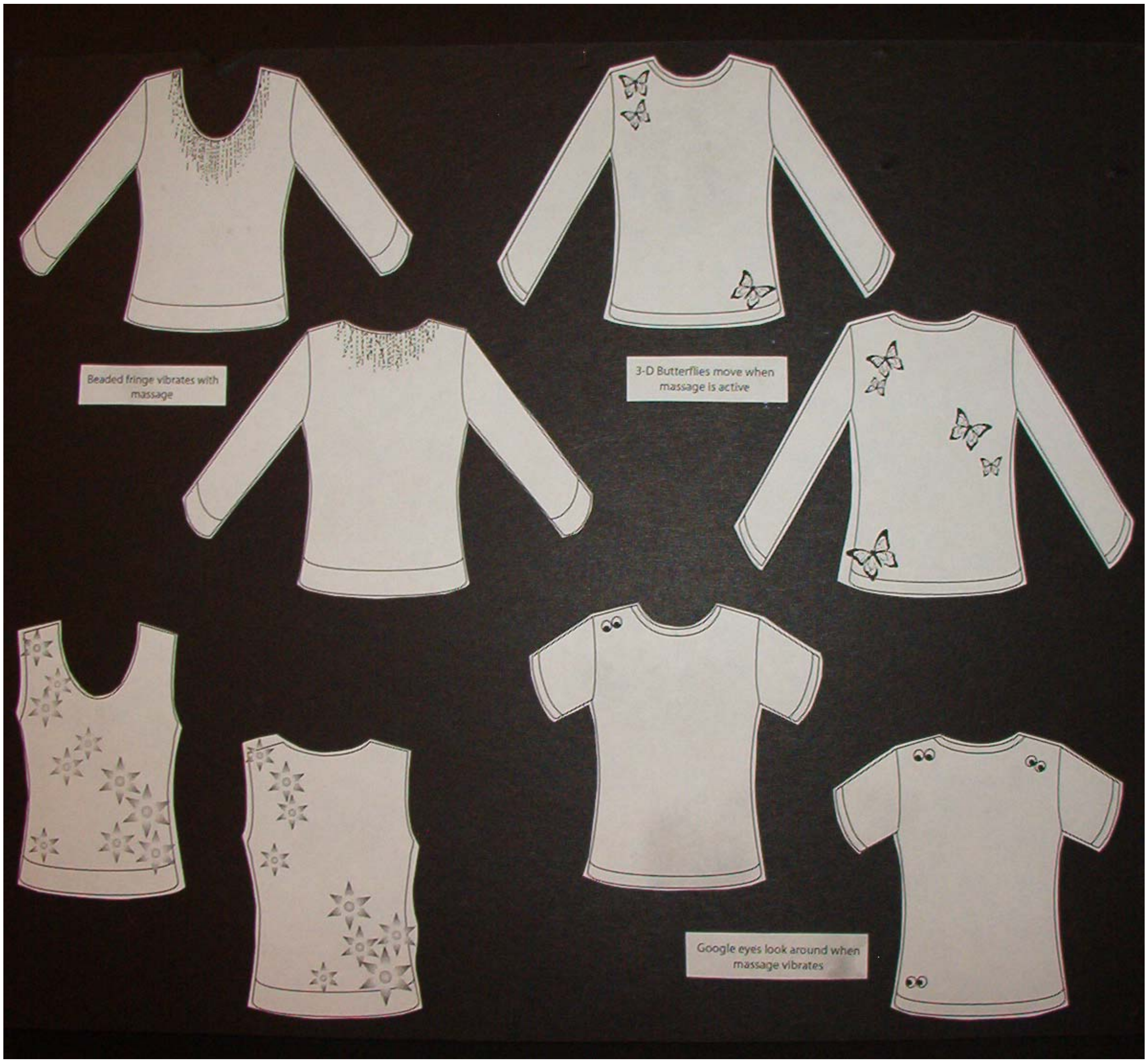
APPENDIX 5: MASSAGE SHIRT DESIGN SKETCHES



Group 1 (Subtle)



Group 2 (Moderate)



Group 3 (Overt)

APPENDIX 6: MASSAGE SHIRT PROTOTYPE IMAGES

Subtle Prototype, Front and Back

Moderate Prototype, Front and Back

Overt Prototype, Front and Back

REFERENCES

Abend, J. (1996). Custom-Made for the Masses: Is it Time Yet? *Bobbin, 42*(52).

Accenture. (2003). *Human Performance Enhancement: Personal Awareness Assistant*. Retrieved January 15, 2003, from http://www.accenture.com/xd/xd.asp?it=enweb&xd=services%5Ctechnology%5Cresearch%5Ctech_personal_aware.xml

Agre, P. (1995). Conceptions of the User in Computer Systems Design. In P. J. Thomas (Ed.), *Social and Interactional Dimensions of Human-Computer Interfaces*. New York: Cambridge University Press.

Anderson, L. J., Brannon, E. L., Ulrich, P. V., Marchall, T., & Staples, N. J. (1998). *Discovering the process of mass customization: A paradigm shift for competitive manufacturing*: National Textile Center Research Briefs.

Ashdown, S. P. (2003). Watkins, Susan M. In J. R. Miller, R. M. Lerner, L. B. Schiamberg & P. M. Anderson (Eds.), *Encyclopedia of Human Ecology* (Vol. 2, pp. 705-708). Denver, CO: ABC-CLIO.

Bardini, T., & Horvath, A. (1995). The Social Construction of the Personal Computer User. *Journal of Communication, 45*(3).

Barfield, W., & Caudell, T. (2001). Basic Concepts in Wearable Computers and Augmented Reality. In W. Barfield & T. Caudell (Eds.), *Fundamentals of Wearable Computers and Augmented Reality*. Mahwah, NJ: Lawrence Erlbaum Associates.

Barfield, W., Mann, S., Baird, K., Gemperle, F., Kasabach, C., Stivoric, J., et al. (2001). Computational Clothing and Accessories. In W. Barfield & T. Caudell (Eds.), *Fundamentals of Wearable Computers and Augmented Reality*. Mahwah, NJ: Lawrence Earlbaum Associates.

Basmajian, J. V. (1974). *Muscles Alive: Their Functions Revealed by Electromyography*. Baltimore: Williams and Wilkins.

Charmed Technology, I. (2002). *Industrial and personal wearable computer development and sales*. Retrieved April 13, 2002, from http://www.charmed.com

Childers, C. (1999). *Master Wristwatches*. New York: Rizzoli International Publications, Inc.

Davis, F. (1992). *Fashion, Culture, and Identity*. Chicago: University of Chicago Press.

DeVaul, R., Sung, M., Gips, J., & Pentland, A. S. (2003). *Mithril 2003: Applications and Architecture.* Proceedings of the 7th International Symposium on Wearable Computers, White Plains, NY.

Diffrient, N., Tilley, A. R., & Bardagjy, J. (1991). *Humanscale 1-9*. Cambridge: MIT Press.

Eyetop. (2003). *Eyetop Head-Mounted Display*. Retrieved January 15, 2003, from http://www.eyetop.net

Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., & Martin, R. (1998). *Design for wearability.* Proceedings of the 2nd International Symposium on Wearable Computers, Pittsburgh, PA.

Georgia Tech. (2003). *Wearable EPSS*. Retrieved January 15, 2003, from http://wearables.gatech.edu/EPSS.asp

Glock, R. E., & Kunz, G. I. (2000). *Apparel Manufacturing: Sewn Product Analysis* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

Gordon, C., Churchill, T., Clauser, C. E., Bradtmiller, B., McConville, J. T., Tebbetts, I., et al. (1988). *1988 anthropometric survey of U.S. Army Personnel* (No. Natick-TR-89-004). Natick, MA: U.S. Army Natick Research and Design Center.

Gray, S. (1988). *CAD/CAM in Clothing and Textiles*. Brookfield, VT: Gower Publishing, Ltd.

Gunther, E. (2001). *Skinscape: a tool for composition in the tactile modality.* Unpublished Masters thesis, Massachusetts Institute of Technology, Cambrige, MA.

Guyton, A. C. (1977). *Basic Human Physiology: Normal Function and Mechanisms of Disease*. Philidelphia: Saunders.

Hahn, J. F. (1973). *Vibratory adaptation.* Paper presented at the Conference on Cutaneous Communication System Devices.

Hall, E. T. (1969). *The Hidden Dimension*. Garden City, NY: Doubleday.

Hoffman, J. (1999). Writers, Texts, and Writing Acts: Gendered User Images in Word Processing Software. In D. MacKenzie & J. Wajcman (Eds.), *The Social Shaping of Technology* (2nd ed.). Philidelphia: Open University Press.

Hoffman, K., & Rush, H. (1988). *Micro-Electronics and Clothing: The Impact of Technical Change on a Global Industry*. New York: Praeger.

Horn, M. J. (1975). *The Second Skin: An Interdisciplinary Study of Clothing*. Boston: Houghton Mifflin Company.

Kaczmarek, K. A., Webster, J. G., Bach-y- Goldstein, I. B. (1972). Electromyography: A Measure of Skeletal Muscle Response. In N. S. Greenfield & R. A. Sternbach (Eds.), *Handbook of Psychophysiology*. New York: Holt, Rinehardt and Winston, Inc.

Kaiser, S. B. (1997). *The Social Psychology of Clothing*. New York: Fairchild Publications.

Kidwell, C. B. (1974). *Suiting Everyone: The Democratization of Clothing in America*. Washington, D.C.: Smithsonian Institution Press.

Kortuem, G., Schneider, J., Suruda, J., Fickas, S., & Segall, Z. (1999, October 18-19). *When Cyborgs Meet: Building Communities of Cooperating Wearable Agents.* Proceedings of the 3rd International Symposium on Wearable Computers, San Fransisco, CA.

Lee, K., & Kwon, D. S. (2000, November). *Sensors and Actuators of Wearable Haptic Master Device for the Disabled.* Proceedings of the International Conference on Intelligent Robots and Systems, Takamatsu, Japan.

MIT. (2002). *MIThril Wearable Computer*. Retrieved January 15, 2003, from http://www.media.mit.edu/wearables/mithril

Montagu, A. (1971). *Touching: The Human Significance of the Skin*. New York: Columbia University Press.

Morikawa, O. (1999). *Shoulder tapping illusion by vibrator in HyperMirror.* Proceedings of the ICCS/JCSS '99.

Payne, B., Winakor, G., & Farrell-Beck, J. (1992). *The History of Costume: From Ancient Mesopotamia Through the Twentieth Century* (2nd ed.). New York, NY: HarperCollins.

Penfield, W., & Rasmussen, T. (1950). *The Cerebral Cortex of Man*. New York: The Macmillan Company.

Post, E. R., & Orth, M. (1997). *Smart fabric, or 'washable computing'.* Proceedings of the 1st International Symposium on Wearable Computers.

Renbourn, E. T., & Rees, W. H. (1972). *Materials and Clothing in Health and Disease*. London: H.K. Lewis & Company.

Rhodes, B. (2000). *Just-In-Time Information Retrieval.* Unpublished Dissertation, MIT, Cambridge.

Rhodes, B. J., & Starner, T. (1996). *Remebrance Agent: A continuously running automated information retrieval system.* Proceedings of the First International Conference on the Practical Application of Intelligent Agents and Multi Agent Technology.

Rita, P., & Tompkins, W. J. (1991). Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Transactions on Biomedical Engineering, 38*(1).

Rovan, J., & Hayward, V. (2000). *Trends in Gestural Control of Music: Typology of tactile sounds and their synthesis in gesture-driven computer music performance*. Paris: Editions IRCAM.

Sproles, G. B. (1979). *Fashion: Consumer Behavior Toward Dress*. Minneapolis: Burgess Publishing Co.

Suchman, L. (1999). Working Relations of Technology Production and Use. In D. MacKenzie & J. Wajcman (Eds.), *The Social Shaping of Technology* (2nd ed.). Philidelphia: Open University Press.

Tan, H., Lim, A., & Traylor, R. (2002). *A psychophysical study of sensory saltation with an open response paradigm.* Proceedings of the ASME Dynamic Systems and Control Division.

Tan, H., Ertan, S., Lee, C., Willets, A., & Pentland, A. (1998). *A wearable haptic navagation guidance system.* Proceedings of the 2nd International Symposium on Wearable Computers, Pittsburgh, PA.

Taylor, P. (1990). *Computers in the Fashion Industry*. London: Heinemann Professional Publishing.

Thorp, E. (1966). *Beat the Dealer: A Winning Strategy for the Game of Twenty-One*. New York: Vintage Books.

Twiddler. (2003). *Twiddler One-Handed Chording Keyboard*. Retrieved January 15, 2003, from http://www.handykey.com

Van Langenhove, L., Hertleer, C., Catrysse, M., Puers, R., van Egmond, H., Matthys, D., et al. (1999). *Intelligent Textiles for Children in a Hospital Environment.* Proceedings of the First Conference of the International Centre of Excellence for Wearable Electronics and Smart Products, Cottbus, Germany.

Verrillo, R. T., & Gescheider, G. A. (1992). *Tactile Aids for the Hearing Impaired: Ch. 1: Perception via the Sense of Touch*. London: Whurr Publishers Ltd.

Verrillo, R. T., & Chamberlain, S. C. (1972). The effect of neural density and contactor surround on vibrotactile sensation magnitude. *Perception and Psychophysics, 11*, 117-120.

Verrillo, R. T. (1963). Effect of contactor area on the vibrotactile threshold. *Journal of Acoustic Society of America, 35*, 1962-1966.

ViA, I. (2002). *Industrial and personal wearable computer development and sales*. Retrieved April 13, 2002, from http://www.via-pc.com

Viseu, A. (2003). Shaping Technology/Building Body(nets). In *Sarai Reader 03: Shaping Technologies*. Delhi and Amsterdam: Sarai, Centre for the Study of Developing Societies and Waag Society.

VivoMetrics. (2003). *LifeShirt Continuous Ambulatory Monitoring*. Retrieved January 15, 2003, from http://www.vivometrics.com/site/system.html

Vuorela, T., Kukkonen, K., Rantanen, J., Jarvinen, T., & Vanhala, J. (2003). *Bioimpedance Measurement System for Smart Clothing.* Proceedings of the 7th International Symposium on Wearable Computers, White Plains, NY.

Wall, C. I., Weinberg, M. S., Schmidt, P. B., & Krebs, D. E. (2001). Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt. *IEEE Transactions on Biomedical Engineering, 48*(10), 1153-1161.

Watkins, S. M. (1995). *Clothing: The Portable Environment*. Ames, Iowa: Iowa State University Press.

Weber, R. (1999). Manufacturing Gender in Military Cockpit Design. In D. MacKenzie & J. Wajcman (Eds.), *The Social Shaping of Technology* (2nd ed.). Philidelphia: Open University Press.

Weinstein, S. (1968). Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. Kenshalo (Ed.), *The Skin Senses* (pp. 195-222). Springfield, IL: Thomas.

Wilentz, J. S. (1968). *The Senses of Man*. New York: Thomas Y Crowell Company.

Wong, B., & Starner, T. (2001, August). *Conversational Speech Recognition for Creating Intelligent Agents on Wearables.* Proceedings of the Human Computer Interaction International Conference, New Orleans, LA.

Wong, L. (2003). *Cyborg-Chic Glasses Will Torture Your Eyes and Spin You Into Vertigo*. Retrieved December 4th, 2003, from http://www.techtv.com/freshgear/products/story/0,23008,3572414,00.html

Woolgar, S. (1991). Configuring the User: The Case of Usability Trials. In J. Law (Ed.), *A Sociology of Monsters: Essays on Power, Technology, and Domination*. New York: Routledge.

Xybernaut. (2003). *Xybernaut Wearable Computers*. Retrieved January 15, 2003, from http://www.xybernaut.com