Where to Wear It: Functional, Technical, and Social Considerations in On-Body Location for Wearable Technology 20 Years of Designing for Wearability

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ABSTRACT

One of the first questions a researcher or designer of wearable technology has to answer in the design process is where on the body the device should be worn. It has been almost 20 years since Gemperle et al. wrote "Design for Wearability" [17], and although much of her initial guidelines on humans factors surrounding wearability still stand, devices and use cases have changed over time. This paper is a collection of literature and updated guidelines and reasons for on-body location depending on the use of the wearable technology and the affordances provided by different locations on the body.

Author Keywords

Design for Wearability; Wearable Technology; Body Maps; On-Body Location

ACM Classification Keywords

H.5.m.

INTRODUCTION

Francine Gemperle, Chris Kasabach, John Stivoric, and Richard Martin published "Design for Wearability" at the Second International Symposium on Wearable Computers. All of the human factor principles Gemperle et al. laid out in their paper stand the test of time; however, wearable computing and wearable technology have reached out into new application domains over the last 20 (ok 19) years. Devices have become smaller while also being able to sense and measure more. More wearable devices are now used as body sensors, and more devices now take advantage of the human body's ability to sense. Our understanding of how we perceive and interact with wearable devices has also grown. Now is the time to update Gemperle's original set of guidelines.

In this paper, I will address some of Gemperle et al.'s original guidelines such as: proxemics, weight, accessibility (reachability), thermal tolerances, human movement, and sensory interaction (passive haptic feedback and active touch) while adding new and additional information with respect to on-body location choices. I will also discuss further areas of interest–such as bio-sensing, visible feedback, networking, and social acceptability–aspects that have become very important to designers of wearable technology.

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FUNCTIONAL, TECHNICAL, AND SOCIAL CONSIDERATIONS IN ON-BODY LOCATION FOR WEARABLE TECHNOLOGY

A designer might choose to locate a wearable device on one body part rather than another for many reasons. Most choices in on-body location come down to a balance between the desired use of the wearable device and the affordances different parts of the body offer. Each consideration listed has a corresponding body map (see figure 1 as an example) created from synthesizing the affordances found in literature. ***The full collection of body maps can be downloaded for use*** [64].

Proxemics (human perception of size)

Proxemics becomes important for the on-body location of wearable technology when the size of the items being placed on the body exceed the body's natural perceived size. Humans naturally have a slightly enlarged sense of their size to help them navigate the world without bumping into obstacles around them. The distance from our actual skin we still perceive to be our size differs on different parts of the body. A designer might be able to place a larger object on the waist than on the wrist and it still feel natural to the wearer.

A great example of proxemics becoming a design issue is the development process for the Symbol Ring Scanner [55]. Because the device extended beyond the self-perceived size of wrist/lower arm, the keypad housing constantly rubbed against corrugated boxes during trial use in a shipping center. Constant abrasion caused the softer abs plastic to rub away and expose the internal electronics. Because of this, the whole system had to be 'ruggedized' for normal wear and tear. This could have been avoided if the device were smaller and within the user's proxemics (at the time this device was built, technology would have prevented this).

Gemperle talks about proxemics as a consideration for “Design for Wearability” [17], and Edward T. Hall discusses larger aspects of the human relationship to the space around them in “The Hidden Dimension” [20]. Gemperle uses Hall’s definition of intimate space at 0-5 inches to develop an aura around the body of self-perceived size. Henry Dreyfuss Associates’ “The Measure Of Man and Woman” clothing allowances can also act as a proxemics minimum guide as most humans wear clothing [60].

Design Considerations for Proxemics

**Design considerations are a synthesis of guidelines which I compiled from the literature outlined in each section.*

- If a wearable device or garment extends beyond the wearer’s self-perceived body size, then the device or garment will obstruct natural movement within the environment. There will be a period of adjustment (through continued use) before the wearable device is incorporated into a person’s perceived size of self.
- Some parts of the body can accommodate larger wearable devices without the protrusion from the body extending beyond a person’s perceived size of self.

Weight Distribution (where to carry weight and amount)
As a general rule, we can start with Gemperle’s advice:

“The weight of a wearable should not hinder the body’s movement or balance. The human body bears its own extra weight on the stomach, waist and hip area. Placing the bulk of the load there, close to the center of gravity, and minimizing as it spreads to the extremities is the rule of thumb.” [17]

When designing the original beta Google Glass (a head mounted display and wearable computer), designers and engineers focused first on what types of features would make the device useful [68]. Early rapid prototypes were somewhat heavy and hard to wear all day [58]. As the team worked, and because of the importance of weight and comfort, a separate but parallel prototype called ‘Lennon’ developed. The Lennon prototype started with a set maximum weight the team believed a user would wear comfortably all day (45 grams), and only added features up to that weight. Lennon was the first Google Glass prototype that could be worn on the head all day without undue fatigue. Mark Spitzer a HUD expert who worked on the design team states that "nose-borne weight should never exceed 75 grams”.

The body carries heavier items better in some locations than others. Watkins details how Scribano, Burns, and Baron were tasked with developing a system in the 1970s for finding load thresholds for discomfort in aiding the design of body armor for the U.S. Army [51, 62]. In doing so, they also described the weight thresholds for discomfort for the torso of a male. This knowledge aids in developing wearable systems where weight might be distributed and should be minimalized across the body.

Design Considerations for Weight Distribution

- Weight, load, or the pressure of weight should be placed on the fleshy but non-sensitive parts of the body, avoiding boney areas.
- The lower waist is a good area for heavy loads.
- Weight should be balanced across the body evenly and aligned to the center of gravity if possible.
- Heavy items should not be placed on the body’s extremities for long periods of time.
- Batteries for wearable devices tend to be the source of most of the weight. If a device needs a large battery (to last a long time or because it needs large amounts of power to function), place the large battery on the waist. If the wearable needs to be located on a different part of the body for use, then consider distributing the power from the area of use. Finally, consider distributing battery cells instead of using one large battery.

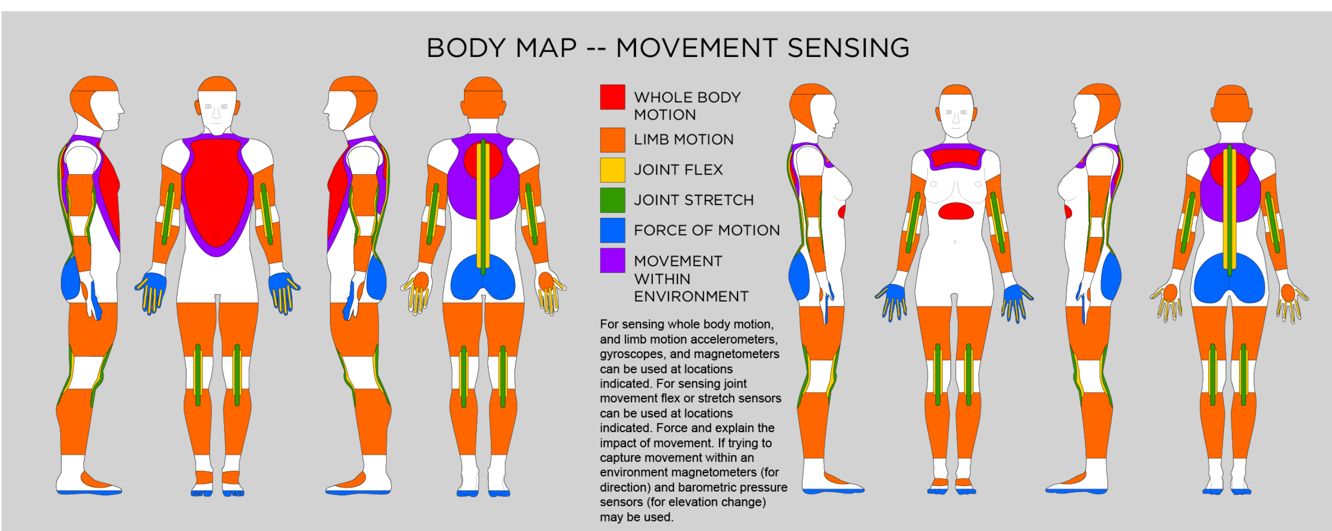

Figure 1 - ©Clint Zeagler - Movement Sensor Placement Body Map [64].

Body Mechanics and Movement

Gemperle et al. [17] propose that wearable technology should be placed at areas on the body that do not actually move that much relative to the rest of the body. These areas will not likely obstruct body movement. The outer upper arm, for instance, is a better location to place a wearable device than inside the elbow. A wearable designed for inside the elbow with any bulk or rigidity would greatly hinder the arm's ability to bend.

Roebuck ran into the problem of hindering body movement when helping develop the EVA suit for NASA in the 1960s [48]. To aid in his endeavor, he created a system for annotating body movement built on what he called "linkages," or joints or combinations of joints that allow the body to bend or move at a point. This simplified and codified way of finding movement points can help a designer today know where to avoid placing wearable technology objects which might hinder motion.

Henry Dreyfuss and Associates also created charts with the standard range of motion of most humans. These charts also help describe in visual detail areas where larger, bulky, or rigid objects might get in the way of human motion [60].

Movement Sensing Consideration

Capturing the movement of the body through space, and the movement of specific body parts relative to the rest of the body, is the driving motivation behind many wearable technology devices [1]. The general public's interest in fitness tracking by means of body movement and step counting launched companies like Fitbit into household names. While complex algorithms have made it possible to capture some body movement information without respect to the location of the sensor on the body, more precise readings can come from planning on-body sensor location, placement, and attachment (see figure 1).

Body Placement

In their "Review of accelerometry-based wearable motion detectors," Yang and Hsu also discuss placement of devices [65].

"Wearable activity sensors can be placed on different parts of a human body whose movements are being studied. In many cases, it is necessary to measure the whole-body movement. Therefore, the sensors are commonly placed on the sternum [41]*, lower back* [37]*, and waist* [28]*. Most studies adopted waist-placement for motion sensors because of the fact that the waist is close to the center of mass of a whole human body, and the torso occupies the most mass of a human body. This implies that the accelerations measured by a single sensor at this location can better represent the major human motion."* [65]

This approach to sensor placement to capture movement seems logical. Sensors placed near the center of mass will be able to tell whole-body acceleration, walking/steps/running, and even posture [14, 28], while sensors placed on the arms and legs will be able to tell movement of the limbs. Accelerometers and gyroscopes placed on the head might be able to tell balance, head tilt, or head turning. Magnetometers placed at the chest can tell the direction a person is moving relative to the earth North/South/East/West.

Legs

When interested in acquiring gate or foot position using accelerometers or gyroscopes, placing the sensor on the thigh or just above ankle would be appropriate [2]. If using sensors other than accelerometer or gyroscopes to detect leg movement, a different placement might be needed: pressure sensors under the foot can be very informative of body movement [19], as can stretch resistance sensors placed over knee joints [7].

Arms

Arm movement and positioning can be very important for a number of reasons. Athletes like American baseball pitchers might use sensors to record the position of their arm as it moves through a pitch [61] (to get a complete picture, a sensor should be placed on the upper arm, lower arm, and on the hand). This method of using accelerometers to determine form of motion can also be use in Archery, and many other sports applications where form is important [69]. To sense whether the elbow is bending and by how much, bend sensors or even knitted resistance sensors can be placed over the outside of the joint. This can be seen in Jonny's Sensor Jacket [14, 68].

Hands

The hand is an obvious location for sensors. Accelerometers and gyroscopes placed on the back of the hand can capture grand gestures and sweeping motions of the arm. Bend sensors placed along the knuckles and joints can give insight into the location and movement of the individual fingers. Pressure sensors placed on the pads of the fingers can detect touch. Gloves dominate the sensor platforms for recognizing hand movement [57]. The Nintendo Power Glove is an early example of the use of bend sensors to detect finger movement [68]. A great example of later combining these two types of sensing are the MI.MU gloves designed by Hannah Perner-Wilson in collaboration with (and for) Imogen Heap [39].

Head

Accelerometers and gyroscopes placed on the head can be helpful in determining head movement, turning, nodding, and even falling [32]. Google Glass uses accelerometers to capture head gestures for interface interactions [23, 26]. Head-mounted motion sensors are also helpful in monitoring falling in high-risk individuals [38].

Design Considerations for Movement Sensor Placement

- If trying to capture whole body motion, accelerometers, gyroscopes, and magnetometers should be placed close to the center of gravity on the chest.

- If trying to capture motion of limbs, accelerometers and gyroscopes can be placed on the limbs. Combinations of sensors in lower and upper limb configurations can aid in more defined movement capture (such as bending of joints and gate).
- If trying to capture motion with respect to the environment, magnetometers (for direction) and barometric pressure sensors (for elevation change) may be used.
- Bend / Flex sensors can be used to determine joint bends and degree of bending. These sensors should be placed across the joint so that the movement of the joint causes the sensor to bend. Bend / Flex sensors are often used in gloves to detect finger movement, and in sleeves to detect elbow movement.
- Stretch sensors can be used in the same way as bend sensors. When sewn into form fitting garments properly, stretch sensors can give most of the same information bend sensors can and without the added rigidity from the sensor housing.
- Force sensors are often used in shoe applications to detect steps. They can also detect a number of other movements by the force placed on different parts of the foot. Force sensors placed in glove fingertips can tell tapping and pressing. This information combined with other sensing information can give a very complete picture of body movement.

Thermal Tolerances

In his 2001 IEEE Micro article "The Challenges of Wearable Computing," Thad Starner clearly laid out *heat* as one of the challenges designers and technologists will have to overcome [53, 54]. In "Design for Wearability," Gemperle simply states: "There are three thermal aspects of designing objects for the body - functional, biological, and perceptual. The body needs to breathe and is very sensitive to products that create, focus, or trap heat." [17]

Where the blood vessels are closer to the skin, more heat transfer can take place [8]. When designing a wearable, it would be best to avoid insulating these areas of thermal regulation, and especially refrain from locating sources of heat (such as battery packs) at these locations. A person who is uncomfortably warm due to extra heat and insulation caused by a piece of wearable technology will certainly discontinue wearing the device. If they do not take off the device, overheating and physical harm could follow.

Biometric Sensing

Another huge motivating factor for the design of wearable devices is the sensing of biometric data. Watkins and Dunne suggest, "For most people, the term body sensor evokes an image of measuring vital signs. The most common vital signs are heart rate, blood pressure, body temperature, and respiration." [63]

Heart Rate

An electrocardiogram monitor will usually have to be located on the chest or arms, depending on the preciseness of measurement needed [56, 63]. Whereas heart rate can be determined by a pulse oximeter or photoplethysmography (PPG) placed where blood vessels are close to the surface of the skin [3, 45, 52, 59].

Blood Pressure

PPG sensors can also capture blood pressure when placed correctly on the body [36]. Makikawa et al. lay out a number of solutions for collecting indirect blood pressure measurements, including palpatory, flash (skin color change), auscultatory (change in tone), oscillometric (detects vibration), ultrasound, volume-oscillometric (volume pulse wave), arterial tonometry (pressure through the artery wall), and volume-compensation [33]

Blood Glucose

Many people today have body-worn continuous blood glucose monitors [40, 47]. Most blood glucose monitors are worn at the waist [35], but advances might soon see contact lens glucose monitors [5, 66].

Respiration

Most respiration monitors actually measure chest cavity expansion through a piezoelectric / piezoresistive sensor, or through electrical resistance change across a knitted conductive textile [10, 43, 49]. Makikawa also describes a thermistor, which is placed inside the nostril to detect breathing patterns [33].

Temperature

Constant temperature monitoring may be necessary in some medical situations. It could also be helpful in environments where a person might overheat. Thermistors can also be used to measure temperature (can be worn in the nostril or in the rectum). A thermophile made of many thermocouples can be worn in the ear to collect temperature data [33]. Thermocouples can also be used in smart watches and fitness bands to estimate body temperature.

Stimulation/Perspiration/Hydration

Galvanic Skin Response (GSR) data can give quite a number of insights including stress, and of course perspiration. These measurements can be taken from anywhere on the skin once calibrated to a location. Body media used armbands and patches to measure GSR [11, 68], but other consumer items like Jawbone measure GSR at the wrist. Researchers at Georgia Tech have used wrist mounted GSR/accelerometer sensors to recognize the stress of social interactions of children with autism [24]. A number of electrochemical and hydration sensors are also being developed. These can also be calibrated for anywhere on the body, but many are being located on the wrist, arm, and forehead [16, 25].

Brain Activity

Some dry wireless wearable (Bluetooth connected) electroencephalogram EEG sensor systems have been developed over the past couple of years [9, 67]. These systems may not give as detailed information as the wired and wet/gel systems, but they can be useful for determining general brain activity. These systems can be used to develop wearable devices called emotive-wearables [4], and also somewhat determine alertness for activities such as driving [31].

Tangible / Tactile / Haptic Feedback (passive touch)

Many wearable devices use tangible, or haptic, feedback through the use of vibration motors and sometimes other means, such as electrical stimulation [15, 30]. "Active touch refers to the exploratory action of touching, whereas *passive touch* describes a stimulation of the skin brought about by some outside agent [18]."[44] This vibration can be better felt on some locations of the body than others. If more than one tactor (or haptic stimulator) is used to create a pattern, it is also helpful to understand the body's sensitivity to the "just noticeable difference," or how close stimuli can be to each other and still be detected as separate stimuli. A popular test to determine each individual's level of skin sensitivity to passive touch is the "two-point discrimination test" [42]. Knowing the level of sensitivity local to each area of the body can help designers develop meaningful haptic stimulations. Mancini et al. [34] have a great overview of whole body two-point discrimination data. Understanding the body's level of sensation can have major impact on the choice of body-location for wearable devices using haptic feedback or haptic displays. Schiffman's text book "Sensation and Perception" also does a great job of explaining skin sensations [50].

Aside from sensitivity with regards to on-body location, there are other factors to consider when designing wearable devices with haptic feedback. Vibration stimuli have "extra parameters," including rhythm, roughness, intensity, and frequency, that can all be altered to aid in correct vibrotactile display designs [6]. Pasquero outlines some of these factors in his "Survey on Communication Through Touch" [44].

Touch (Active Touch)

"*Active touch* represents the exploratory action of touching, which is generally involved with kinesthetic movement of the body" [18, 30].

Designing interfaces made to be "easy to find" through active touch is a tenant of human factors. The shapes of buttons and levers offer affordances for hands to discover a way to use them through active touch. A cylinder with a grip on the side affords turning the cylinder, just as a textile design with raised embroidery affords active touch investigation [29].

Active touch happens almost exclusively with the hands. It is where the human body is the most sensitive, and the part of the body that humans use the most to investigate their surroundings through touch. The feet and the mouth might also be used for active touch but much less than the hands.

Reach-ability

In terms of reach-ability, it is important to know which parts of the body, and therefore wearable devices placed on those parts of the body, are reachable by a person's hands. One way to start to qualify reachability is by looking to - clothing, specifically the location of garment closures for self donning and doffing [63]. Buttons are placed on the front of a shirt because they can be reached for use, whereas dresses with back zips need long pulls or a helping hand to aid in closure.

Visible Feedback

When designing a wearable device with a visual display, it is important to consider where a person can see visual feedback emitting from the body most effectively. Chris Harrison developed such a study to find out where to locate wearable displays [22]. Participants wore devices with LED lights and were asked to press the button on the device when the LED blinked. The devices were placed in seven different body locations to see if reaction time would change depending on where the light was signaled.

Networking on the body

Thad Starner also listed networking as one of the major challenges for Wearable Computing. For wearable computers, networking involves communication off body to the fixed network, on body among devices, and near body with objects close to the user. Each of these three network types requires different design decisions. Designers must also consider possible interference between the networks [54]. When considering on-body location, designers also need to consider the location of the antenna that communicates with the off-body fixed network. The mass (water/muscle/tissue) of the body can block many of the lower powered high frequency wireless network signals we use for communication [21].

Manufacturing for Garments

Understanding just a little bit about how garments are designed and constructed can aid tremendously in designing wearable technology, especially if it is to be integrated into clothing. This knowledge can help in making decisions about sensor location and the location of wired connections to components placed across the body. Conversely, if a sensor needs to be placed on a specific body part, the clothing pattern can be designed to accommodate for that [27, 62, 63]. While most wired connections do not stretch, most fabric does stretch. Designers should avoid horizontal wires connecting components and instead opt for vertical or diagonal traces.

Design Considerations for Garment Manufacturing

- Wires and leads should be incorporated into seams when possible.
- Wires and leads should almost always run vertical (up and down) the body and not horizontal (around) the body.

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

Social Acceptability

Use of wearable technology and body placement has a great deal to do with the social acceptability of a wearable system. Google Glass had an issue with its beta release because of public misunderstanding about the forward facing camera [68]. This lead to a difficult release, even though designers had factored in privacy by design, and there are a number of features on the device which alert the user to active filming. Other devices on the market can video and film with much more discretion, but the location of the camera on the face of the wearer (visible and noticeable during face to face social interactions) made the camera of Google Glass a touch point for discussions related to privacy [12].

Uncomfortable social situations can also arise from the gestures and touches users make with wearable technology to interact and control devices. The placement of interactive textiles, interfaces, and the types of gestures used to control interfaces sensed through motion detection can make a wearer/user and bystanders feel quite awkward. “For wearable devices, the social perception and comfort of worn artifacts often extends beyond the ‘static’ aesthetic variables of the artifact (worn on the body, but not interacted with) into the social aesthetics of interacting with a body- worn device.” [13] Profita et al. look specifically at body placement of interactive electronic textiles and how third party viewers deem interactions socially acceptable when placed on different parts of the body [46]. Given the information collected in these studies, I have developed a body map with regions of socially acceptable locations for wearable technology interaction.

Design Considerations for Social Acceptability

- Body placement of wearable technology can drastically affect the social acceptability of the wearable device. In general, avoid touch-based interactions and displays within regions of the body associated with sexual activity or elimination of body waste. An exception would be if the wearable device were specifically designed to aid in sexual stimulation.
- In general, it is also advisable to avoid the breast as an interaction location for wearable technology (except for wearable devices specific to cis-gender males, but there are still more socially acceptable places on the body which could work better). An exception would be products designed to work with the breast (e.g. a breast milk pump).

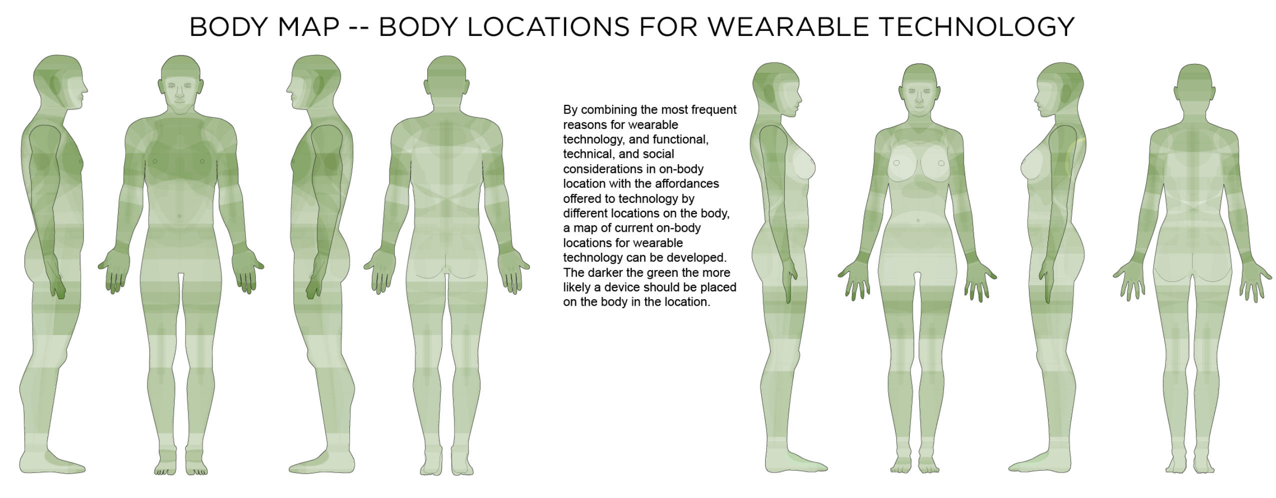

Figure 2 – ©Clint Zeagler - Most likely on-body locations for wearable technology if all considerations are weighted equally [64].

CONCLUSION AND FUTURE WORK

Each consideration listed has a corresponding body map (see figure 1 as an example) created from synthesizing the affordances found in literature. ***The full collection of body maps with references and design considerations can be downloaded for use*** [64]. Overlaying all of the individual body maps illuminates the areas on the body where a designer should most likely place a wearable device (figure 2). Figure 2 only shows where a device should be located if all design considerations are given equal weight. The body map shows that the most likely locations for wearable technology to be successful are the hand, wrist, forearm, upper arm, upper chest above the breast, forehead, ear, and mid thigh. Of course specific use cases and designs will place more weight on some considerations than others. The next step in this research is to create a web tool allowing designers to throttle the importance of specific considerations. There should also be an option to throttle needs from body location affordances. As adjustments and selections are made, a corresponding body map will be produced, creating an image of where the specific wearable device should be located. The full collection of body maps [64] also contain valuable accessibility design considerations to aid in designing for people of all abilities, and extrapolating this information to be used in the design process is another future goal.

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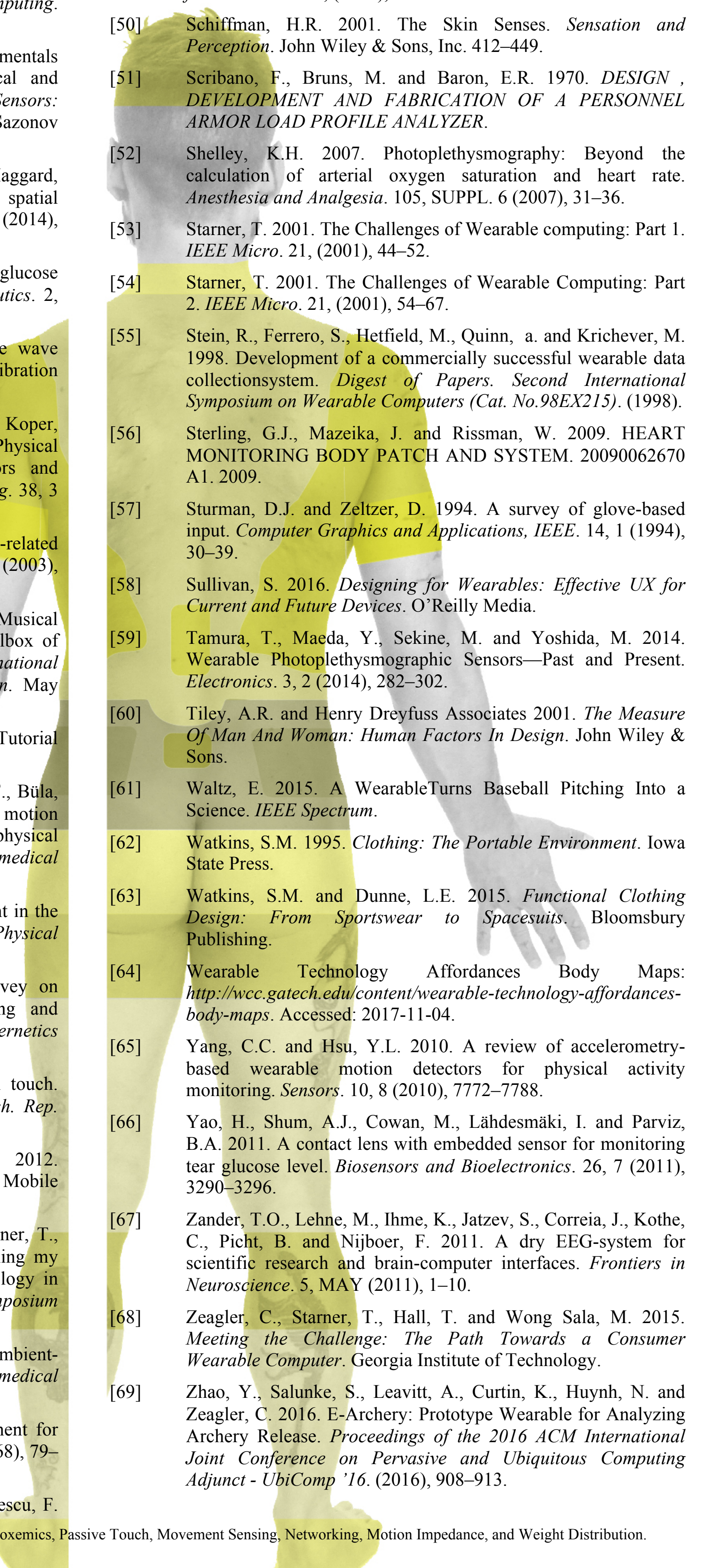

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