ARGONAUT: An Inclusive Design Process for Wearable Health Monitoring Systems

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ABSTRACT

Wearable biosignal monitoring systems are becoming increasingly ubiquitous as tools for autonomous health monitoring and other real-world applications. Despite the continual advancements in this field, anthropometric considerations for women's form are often overlooked in the design process, making systems ill fit and less effective. In this paper, we present a full garment assembly, ARGONAUT, with integrated textile electrocardiogram (ECG) electrodes in a 3-lead configuration that is designed specifically for women's form. Through the exploration of materials, anthropometry, and garment assembly, we designed and tested ARGONAUT against the laboratory standard to determine performance through R-peak detection and noise interference. We investigated common issues faced when designing a wearable ECG garment, such as fit, motion artifact mitigation, and social wearability, to develop a dynamic design process that can be used to expand the advancing technology sensor integrated garments to all individuals in order to allow for equal access to potential health benefits.

CCS CONCEPTS

• **Hardware** → **Sensor devices and platforms**; *Sensors and actuators*; • **Human-centered computing** → *Accessibility design and evaluation methods.*

KEYWORDS

Electrocardiogram (ECG), smart textiles, technological integration, motion artifact, iterative design

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1 INTRODUCTION

Real-time biosignal monitoring systems are emerging as a pillar of human-computer interaction (HCI), enhancing the fluency of communication between humans and the computer systems they interact with. While there is constant progress in the discipline of wearable sensor systems, women are often excluded from the design process, creating systems that are designed by men, for men, and ultimately creating a disparity in access to these developing technologies [8, 23, 57]. Fortunately, the technology and engineering communities are beginning to shed light on the gender disparities and increased exploration into this field is emerging to address this gap [13]. In addition, research and design methods to combat the gender bias are also becoming increasingly more prevalent. ARGONAUT is a case study that aims to use design methods that address anthropometric factors which are atypical of current wearable technology development and validation. An ECG monitoring system is used to create a basis for the design process. In this work, a functional ECG garment is developed as well as the design method that allowed for its creation. To achieve this, we conducted a three-step investigation using iterative and innovative design processes:

1) We investigate current and past cardiac monitoring systems and the wearable devices that have been developed to monitor ECG. Through past research, we identify the unique design challenges brought forth by non-idealized models, specifically for women in addressing breast tissue.

2)Following step 1, we identify design concepts and prototype iteration to determine optimized aspects of the garment that achieve the best results for ECG signal detection and minimum noise interference.

3) We present the results of our design validation conducted with four women participants and provide paths forward for future research in this area.

ARGONAUT not only provides an opportunity for increased cardiac monitoring during complex tasks outside of the laboratory environment, but also addresses the gender disparity in the field of HCI. While our study is limited in testing population, the contribution can be utilized to guide future designs of clothing-based health wearable systems and contribute to the state of the art for the overall improvement of all individual experiences regardless of sex or gender.

2 MOTIVATION AND RELATED WORK

Both research and commercial work is emerging at the intersection of biosignals and clothing. Researchers have made strides in the development of sleek, user-friendly systems that allow for real-time monitoring of physiological signals intended to augment HCI through biofeedback. Cardiac monitoring has been used in conjunction with other physiological signals to estimate task difficulty during human-robot interaction (HRI) [17], determine interest in a film [26], detect emotional responses to video stimuli [46], identify emotional state to feed into adaptive software [58], augment

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learning analytics to better understand the interaction between students and educational materials [50], and even monitor astronaut's physical states during spacewalks [32].

Wearable sensor systems that collect high-fidelity ECG data are essential to the continued development of biosignal monitoring as a method of augmenting human-computer and human-robot interaction. The goal of this work is to design, develop, and validate a wearable ECG monitoring system that tackles the challenges of women's form to collect data from the heart. Gender discrepancies have long plagued industries such as technology, science, athletics, and engineering thus excluding an underserved population from the development of novel wearable technology due to their variability of anthropometry [37]. For women specifically, the presence of breast tissue near the heart creates variability which often does not fit the current idealized model. Our work puts these variations at the forefront of our design. Toward this end, we have explored materials, structures, and fit to better understand the design space and develop methods of quantifying performance to guide future garment development. We hope to catalyze the future of wearable sensor systems for interaction augmentation by shifting the focus from a men-centric design perspective to a more inclusive and fluid design method, which embraces the unique differences in the human body.

2.1 Cardiac Monitoring

Cardiac monitoring refers to the continuous inspection of cardiac signals, primarily through an electrocardiogram (ECG), for the assessment of cardiac rhythm or abnormalities. An ECG signal is composed of five main waveforms: P, Q, R, S, and T. Each waveform corresponds to an electrical potential created from the depolarization and repolarization of the heart. Currently, the gold standard for clinical and laboratory ECG monitoring utilizes single-use, adhesive electrodes to collect data. These electrodes often irritate the skin and are not desirable for long-duration use since the conductive gel will dry out over time, affecting signal quality [14]. Standard adhesive electrodes have been integrated into a mobile wearable garment called the Holter system, which allows for real-time cardiac monitoring outside of a clinical setting. The Holter system was designed to enable long duration cardiac monitoring beyond the bounds of a physician's office in order to collect data "in the wild" [10]. It operates similarly to a traditional ECG system with a three-lead configuration and compact data acquisition device, which relays information back to a health care provider. While effective, the Holter monitor has seen minimal improvement in functional and aesthetic design, which results in a bulky and uncomfortable device, missing the mark of "social wearability" [9, 10, 19, 21, 53]. Other monitoring systems currently on the market, while effective, are either invasive, expensive [25, 56], not appropriate for long-duration monitoring, or only provide aggregate metrics opposed to the entire ECG signal, such as smart watches[44].

2.2 Design Considerations for Equity

The lack of consideration for anatomical differences in men and women form has long plagued industries such as athletics and software development, which traditionally have been dominated by men [2, 41]. For the purposes of this paper, we define "women" as referring to individuals that have physical, anthropometric characteristics that correspond to the presence of estrogen and progesterone such as breast tissue. Conversely, the term "men" is defined as individuals that lack the anthropometric characteristics associated with women due to low or reduced estrogen and progesterone. This definition is not limited to the sex or the gender of an individual but strictly to the physical traits. The most significant garment to account for breast tissue during physical activity, the sports bra, was not developed until the late 1970s. It was fabricated out of two jock straps. While there have been many improvements since the 70s, the development of wearables has unfortunately seen a similar trend, with garments being primarily designed for the idealized men's form and retrofitted for women [60]. This research aims to shift that paradigm and proposes to put the unique anthropometric differences of women's anthropometry at the forefront of design.

Women's anthropometry should be celebrated, not just tolerated, in the HCI space, with the uniqueness of an individual at the forefront of all designs. Gender disparities are seen in many facets of HCI such as confidence in software interactions [11], design of gender-specific video games [31], educational materials [38], screen displays [18], and problem solving software [45]. Findings from studies have strongly suggested that men and women process, communicate, and utilize information differently [8, 45]. This becomes applicable not only for the inclusion of all genders in a HCI-related field, but also a design consideration for technology being developed for commercial use. Currently, men are over-represented in the field of HCI, making products designed with a conscious or unconscious bias for men. The same is true in wearable technology. While critical differences that affect garment design for men or women are physical, as opposed to psychological, the bias is still present and the effects can still be seen even with the immense strides toward equality that have been made over the last few decades. As technology continues to be a critical aspect of everyday life, there needs to be a more well-rounded development of software products in order to push society toward equality [33].

3 ARGONAUT DESIGN

3.1 Overview: Balancing Form and Function

High-quality ECG signals are critical to the identification and measurement of present cardiac waveforms. ECG electrodes must be correctly placed, maintain high contact with the skin, and have low impedance in order to relay high-quality signals from the body to the data acquisition equipment [4]. The challenge for designers is the ability to balance performance with aesthetics in order to make a product with adequate functionality as well as achieving social wearability. Hence, we designed ARGONAUT to address these challenges specifically for women's form.

ARGONAUT is a women-centered design solution for real time monitoring without the social stigma of visible medical instrumentation. As we build on prior work, we aim to improve wearable ECG systems by developing a garment that allows for the seamless transmission of raw ECG signals, opposed to aggregate metrics (such as those measured through wrist-mounted devices). Unobtrusive woven electrodes are placed underneath the collar bone on the right and left side as well as one on the left rib beneath the breast

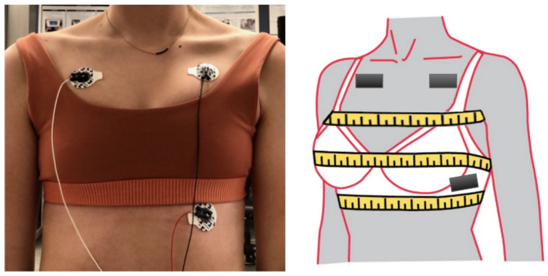

Figure 1: The left figure shows the placements of the traditional 3-lead ECG system. The diagram on the right is of the three circumferential chest measurements utilized in garment fitting as shown by the yellow bands. The black boxes represent each sensor location on the chest in a three-lead configuration for recording electrocardiogram signals.

tissue, as shown in Figure 1, in the standard 3-lead ECG configuration. A key aspect of the ARGONAUT design is the integration of previously-presented woven textile electrodes. The woven electrodes allow for design freedom in size, pattern, and shape and have high potential for comfort and unobtrusiveness since they are integrated into the fabric instead of being added post-production [6]. Their easy integration makes them more desirable in the wearable ECG industry due to their discretion and the satisfaction of the criteria for "social wearability" [24]. The electrodes are seamlessly integrated into the garment by connecting to an on-body data acquisition unit, which relays information from the changes in voltage potentials across the skin. We envision ARGONAUT to be able to continuously relay the ECG signal throughout the duration of wear to inform both the physiological and psychological changes of the wearer over the course of daily life. Unlike other wearable devices developed by industry, real-time monitoring provides raw data, which can allow for the identification of intricate variability within the signal. This area of research is an interdisciplinary field that requires novel design methods to integrate electronics, textiles, and information technology into one product.

3.2 Textile Sensor

Within HCI there has been an expanding interest in using fabric-based electrodes for sensing and measuring of biosignals and other on-body interactions. Producing smart textiles requires novel design methods that fully utilize the specific properties of the yarn and the unique fabrication techniques that fundamentally alter textile properties. For example, traditional screen printing was reenvisioned to apply conductive ink directly onto fabrics to create low profile, highly manufacturable, and inexpensive sensors that can be easily integrated into wearables [59]. Other examples include 3D printing fibers to create felt structures [40], leveraging knit's 3D structures [1, 35], and embroidering intricate patterns for customizable designs [5]. The use of woven structures to create dry electrodes have become an increasingly popular option due to their high contact area, structural stability, and diversity in design possibilities [6, 49].

The sensor design used in ARGONAUT is a 6.75cm x 6.75cm, 1/15 sateen woven electrode created with steel yarn inserted in the weft direction [6]. The sensors were fabricated using A TC2 Digital Jacquard loom (Tronrud Engineering, Norway) and AdaCAD software [27]. This sensor design allows for a large contact surface that can comfortably sit on the skin for extended periods of time without irritation, but mitigates unnecessary motion from the lack of interlacing points. Once the sensor choice was completed, the requirements and user experience for the system were established with a focus on the ease, comfort, and perceived social acceptability of the garment.

3.3 Requirements and User Experience

In designing a wearable system for physiological signal collection, certain requirements for the entire system need to be met in order to achieve a successful design that is both functional and aesthetically pleasing [3]. These requirements are continuous data collection, an unobtrusive design, easy data access and interaction, comfort, electronic durability, and reliability [22, 28, 39]. Challenges that arise from these requirements are intuitive user interfaces, discretion and privacy controls, and fit. In the development of ARGONAUT, our primary focus is on the fit, signal quality, accessible electronic components, and repeatability, which we aim to achieve with novel material integration and iterative designs. Each aspect of the garment was specifically chosen and validated to maximize performance in each of these areas, creating a holistic garment that meets the needs of the wearer. Due to time limitations, the scope of this research does not directly address improvements in the data collection system and interface, or remote accessibility of user data. As a whole, the requirements drove toward a user experience for a system to be worn in an everyday setting and for applications where a clear signal achieved with good skin contact and reduced motion artifact is important. Use cases in mind for system development include health care and fitness applications. Our methods stressed the importance of innovative, iterative design methods to maximize the performance of each aspect. In the development of an effective sport bra we identified five areas of improvement that could be iterated upon. While these design iterations (shown in Figure 3 and Figure 4) address the interface between user and the sensors, we did not include development of user-software interactions into the scope of this study.

3.4 Compression Layer

The compression layer is critical to create constant contact between the user and the sensor, in order to achieve an ECG signal with low noise and voltage variability. A balance must be established between the amount of compression exerted on the body and perceived comfort reported by the user. Too much compression and the users can get skin irritation and more energy or assistance is required to get the garment off and on. Too little compression and the garment becomes susceptible to motion artifact and poor contact on the skin, especially in the chest [54]. Fit plays a critical role in this balance. A well-fitted garment can drastically reduce noise in the signal, increase comfort and increase overall willingness for the user to continue to wear the garment. Due to the sensor location requirements and donning/doffing constraints, four commercially

Table 1: Comparison of compression garments for design requirements including neckline, closure mechanism, length below the breast tissue, integration of all design requirements, and compression. Garments were selected for high neckline, maximum fabric length below the breast tissue, easy integration of addition components, and high compression.

Compression Garment	Neckline	Fabric Layer	Length Below / Breast Tissue	Integration	Compression
 CRZ Yoga-Racerback	High	3	2.7 inches	Easy	Medium
 Outdoor Voices- Venus	High	2	2.9 inches	Easy	High
 Lemedy- Sports Bra	High	3	2.3 inches	Difficult	Medium
 Nine Bull- High Impact Bra	Medium/ High	3	2.4 inches	Difficult	High

available compression garments were selected for prototyping. Base compression garments were required to have a high neckline to allow for sensor attachment approximately below the collarbone. The garment also had to extend 2 to 3 inches below the breast tissue in order for the third sensor to sit at the correct location on the ribs. In addition, garments must allow for the attachment of donning and doffing mechanisms as garments couldn't be pulled over-top of the user due to the durability of the integrated electronics. From the four garments sourced, two were down-selected to create a full garment for testing. The down-selection process was determined through an evaluation of neckline, fabric layers, closure mechanism, length of garment, integration of design components, and compression, as shown in Table 1. The two garments selected achieved sufficient pressure and provided a canvas for the integration of sensors, electronics, and other design aspects, which complete the monitoring system. In future work, a custom garment would be developed to directly address fit and function requirements, but due to time constraints a commercially-available garment was utilized.

3.5 Closure Mechanism

Once compression garments were selected, two closure methods (front zipper and back snaps) were tested for ease, comfort, and unobtrusiveness. A closure mechanism was desired, as opposed to the traditional method of pulling the sports bra over your head, to decrease strain on the electronics. If too much strain is placed on the wires, microtears can form and interfere with signal quality. A front zipper was initially chosen as the closure method, as seen in Figure 3, since it allows for accessible and self-donning and doffing of the garment. It was found that the garment with the zipper as the closure method significantly interfered with the sensors and decreased signal quality, as shown in the right image in Figure 2. It is hypothesized that the zipper, being more rigid than the outer material, did not allow for the material to conform to the body which is imperative to signal quality. Because of this insufficient contact, increased motion artifact prevented the identification of R peaks, which is critical to the determination of heart rate variability. The second iteration, shown in Figure 4, utilized snaps at the back of the bra. The signal measured, which is shown in the left image in Figure 2, from the snaps allows for clear identification of R peaks due to decreased motion artifact noise and increased skin-to-sensor contact. While having a closer mechanism at the back

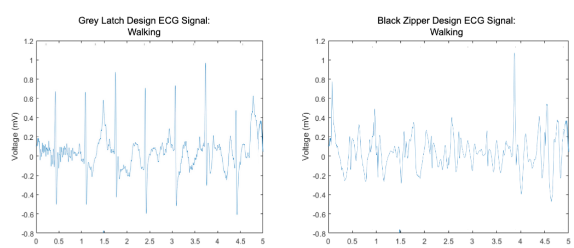

Figure 2: ECG signal from two different closure mechanisms when walking. The signal on the left, which utilizes back snaps on the garment, has less noise than the signal on the right, which uses a front zipper as the closure mechanism. As such, the R peaks are more clearly identifiable.

Table 2: Foam layer thickness, R peak magnitude, standard deviation, and peak detection in assessing the performance of each foam type or combination. Two no foam conditions are presented for comparison, as well as single-foam and layered foam configurations.

Foam Analysis				
Sample	**Thickness**	**R Magnitude (mV)**	**Standard Deviation**	**Peak Detection (of 12)**
No Foam		0.25	0.01	12
Traditional Electrodes		0.58	0.02	12
Memory Foam	25 mm	0.23	0.006	12
Memory Foam	50 mm	0.25	0.06	13
Closed Foam	12 mm	0.22	0.007	11
Double Closed Foam	24 mm	0.28	0.008	12
Open Foam	17 mm	0.21	0.02	12
Double Open Foam	34 mm	0.34	0.007	12
Layered Closed/Open	29 mm	0.17	0.004	12
Layered Closed/Memory	37 mm	0.25	0.007	12
Layered Open/Memory	42 mm	0.32	0.006	12

of the garment slightly increased difficulty in donning/doffing, the encumbrance was minimal and the signal greatly improved, making it an overall better design selection.

3.6 Foam Padding

Due to the curvature of the chest, compressive fabrics bridge the concavity between the breast tissue, rather than conforming to it. This behavior inhibits contact between garment-integrated sensors and the skin, ultimately introducing noise into collected signals. Similarly, concavities for some forms may exist transitioning from the clavicle toward the breast. Given the standard placement of ECG electrodes in this area, the presence of breast tissue can act to decrease skin-electrode contact for wearable ECG monitoring systems, introducing noise. Foam inserts allows for the garment to conform to the curvature of the chest and increase the pressure applied to the body.

To mitigate local shifts in skin contact, a foam backing was applied directly below the textile sensors. Three foams, each with varying densities (high density foam of 12mm thickness, medium density foam of 17mm thickness, and low density foam of 25mm thickness) were tested. Multi-layer foam approaches were also investigated, where two layers of the aforementioned foams were evaluated in all possible combinations. In total, 15 foam combinations were evaluated for comfort and signal strength, refined by the prominence of the R peaks detected, as shown in Table 2. From the results it was found that two 25mm memory foam inserts created the strongest signal while not detracting from the comfort of the garment. It was found that the foam inserts also increased dimensional stability which protected the connection point between the sensor and the wire as well as minimized noise from motion. Thus, 50mm of memory foam was ultimately selected to be inserted behind each sensor in order to address skin contact and electronic integration requirements.

3.7 Electronics Integration

Electronics components, such as microcontrollers, power supplies, and wiring, are essential for the function of wearable sensor systems. Often, these elements are hard components that do not integrate well with soft, flexible fabric components. The challenge of hard electronics is centered around how to integrate them into the garment and manage the interface with soft elements. This further exacerbates issues of social wearablilty and comfort. Minimizing the form factor, thus, becomes important. Another important aspect is on-body placement to minimize wiring (which influences the presence of motion artifacts) and improve interfacing to mount where the garment comfort is not affected. For ARGONAUT, we use flexible silicone-coated wiring to connect a BIONOMADIX data acquisition unit (BIOPAC Systems, Inc., Goleta, CA). It was initially found that the most comfortable and unobtrusive placement of the BIONOMADIX was the center of the back. When the design for the compression material and closure mechanism was changed, housing the device was no longer feasible on the back. The second iteration of ARGONAUT has a built-in pocket placed below the breast tissue over a flatter part of the rib cage, which minimizes wiring length while maintaining full range of motion. This placement was also found to be comfortable, secure, and accessible for removal prior to laundering.

4 DESIGN EVALUATION RESULTS

The final ARGONAUT design is shown in Figure 6. The final design includes a snap closure mechanism on the back of the garment for improved donning and doffing, 5cm layer of memory foam under each sensor lead, and integrated electronics with the data acquisition system mounted below the right breast tissue.

Four women (height 170.2 ± 4.25 cm, and weight 59.5 ± 2.1 kg) participated in a design evaluation study. Each participant's standard sports bra size is between extra small and medium and a traditional bra size between 32A and 34B. Three circumferential anthropometric measurements were taken at the band, breast,

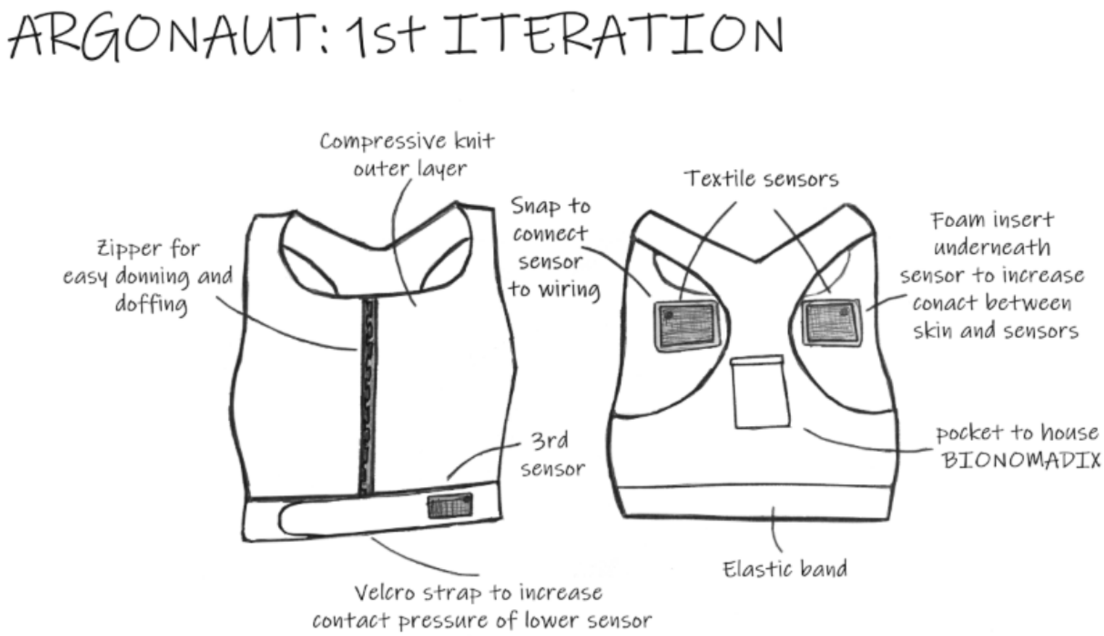

Figure 3: Conceptual sketch of the initial iteration of ARGONAUT. This iteration features a front zipper, optimized sensor locations, Velcro strap for increased pressure production, and a pocket for housing the data acquisition device.

and chest size with a mean of 80.5 ± 1.3 cm, 88.3 ± 1.7 cm, and 89.0 ± 2.2 cm, respectively. These metrics are used in the fitting of traditional bras [36, 61]. We recruited participants to fit within a narrow range of sizes to have a single garment fit all participants effectively. Each participant performed four motions—sitting, arm flexion and extension, arm abduction and adduction, and walking. Each motion was performed for one minute, and the motion was synchronized to a metronome of 80 beats per minute, with a total of 80 repetitions for each motion [16]. Motions were done with both a traditional, adhesive gel electrode and the final design of ARGONAUT. Flexion and extension were performed at the shoulder and did not exceed 90 degrees. Abduction and adduction were also performed at the shoulder, but the entire range of motion was performed, so it was not restricted at 90 degrees. The four motions were selected in order to test the garment in configurations that would be indicative of everyday motions. It was noted that the textile electrode locations for each subject were slightly different on each participant due to anthropometric differences, but placement within each subject is repeatable. Both technical and user evaluations were conducted in the form of accuracy peak detection metric and a comfort survey, respectively. Technical evaluations focused on the R peak magnitude and variability, noise interference, and the ability for the developed algorithm to detect true peaks. A comfort survey was conducted after testing of each sensor type in order to provide a user evaluation for each system. The survey consisted of 15 different adjectives describing possible garment characteristics [29]. Each adjective was to be rated from 1 to 4, 1 being that the garment completely fit within that descriptor and 4 being the garment partially fit within that descriptor. In addition to the survey, a visual inspection of the skin to determine if there was any skin irritation during the duration of wear was performed [29].

4.1 Signal Processing

Data was collected with the BIOPAC MP160 module (BIOPAC Systems, Inc., Goleta, CA) and processed in MATLAB. From the one minute of data that was collected, a 30-second segment was extracted for analysis. The raw ECG signal was processed using multiple filters to clean the signal while preserving the waveforms. A 0.5 Hz- 20 Hz band pass IIR filter was used to remove noise from the electronics, respiration, metronome frequency, and other high frequency noise [30, 34, 42, 55]. In addition, a wavelet filter was applied to remove noise while preserving small, but critical features [7].

Peaks from the R, Q, S, T, and P waveforms were identified by their prominence and distance with respect to the R peak, which is the most prominent and easiest to identify [15, 47, 48, 52]. Visual and automated detection methods were implemented to validate the detection algorithm used to analyze the data. The R peak is the most dominant feature in an ECG signal and is most often used to calculate valuable metrics such as heart rate and heart rate variability [12]. The detection of small waveform features was also evaluated as an indicator of signal quality. The algorithm employed used the expected prominence and distance, with respect to the R peak, in order to identify the location of the desired aspect of the ECG signal. Figure 7 shows an ECG waveform sensed using ARGONAUT with the algorithmic detection of each peak. Visual inspection remains

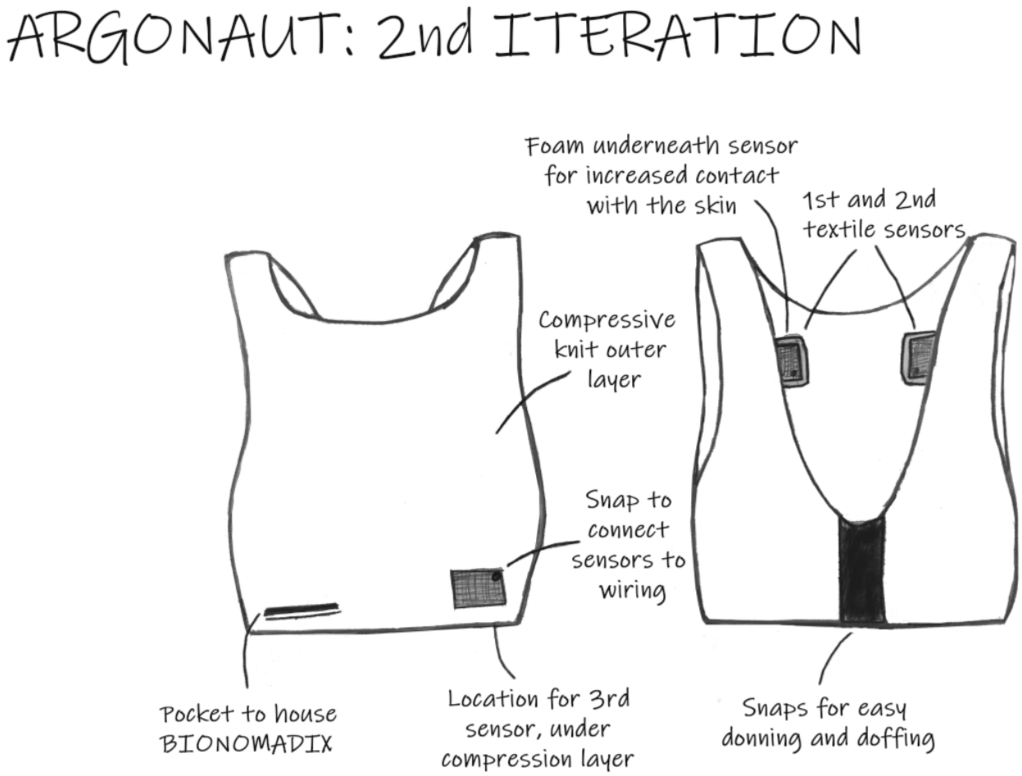

Figure 4: Conceptual sketch of the current iteration of ARGONAUT. This iteration features snaps in the back for putting on and removing the garment, optimized sensor locations, unobtrusive housing for the data acquisition device, and memory foam inserts for increased compression at sensor locations.

the standard method of peak detection for medical professionals and therefore was utilized as the control to compare against the output of the algorithm.

4.2 Performance

To evaluate the technical performance of the system, three metrics were calculated: precision, recall, and a noise score [20]. Precision and recall evaluate the number of false positives and false negatives respectively. Precision, also known as positive predictive values, is the fraction of relevant peaks among the ones identified, which tell you how many identified peaks are relevant. Recall, also known as sensitivity, is the fraction of relevant peaks that were successfully identified by the algorithm. This metric provides information about the relevance of the retrieved peaks. The noise score is the ratio of false assessments to true assessments [16], which gives information about the number of errors per heart beat. False positives and false negatives were identified by visual inspection. Each measure was calculated using the following formulas:

$$precision = t_p/(t_p + f_p) \quad (1)$$

$$recall = t_p/(t_p + f_n) \quad (2)$$

$$noisescore = (f_n + f_p)/(t_p + f_n) \quad (3)$$

Where t_p is the number of true positives, f_p is the number of false positives, and f_n is the number of false negatives. A value of 1 for precision and recall or a value of 0 for the noise score means that every peak was correctly identified.

Figure 5 displays each motion and the corresponding ECG signal for a participant while wearing the traditional, adhesive electrodes and ARGONAUT. The R peaks have been identified for each of the signals and visually it can be seen that the quality of both signals are similar, which is reflected in the noise scores. Table 3 shows the noise score for both traditional adhesive electrodes and the ARGONAUT system across each motion and each waveform. Precision and recall were calculated, and for both metrics, the performance was consistent with the noise score. Thus, we report the noise score in Table 3 as it encompasses both the information from recall and precision as well as more relevant for critical ECG metrics such as heart rate and heart rate variability. As expected, the adhesive electrode perfectly detected the R peak (precision= 1; recall=1, noise score = 0), indicating the automated algorithm was appropriate. For the seated, abduction/adduction, and walking conditions, the Q and S waves were also perfectly detected. During flexion/extension, a slight decrease in the signal quality for the Q and S waveforms was exhibited. The P and T waveforms were the most challenging peak to identify. These results derived from the traditional electrode

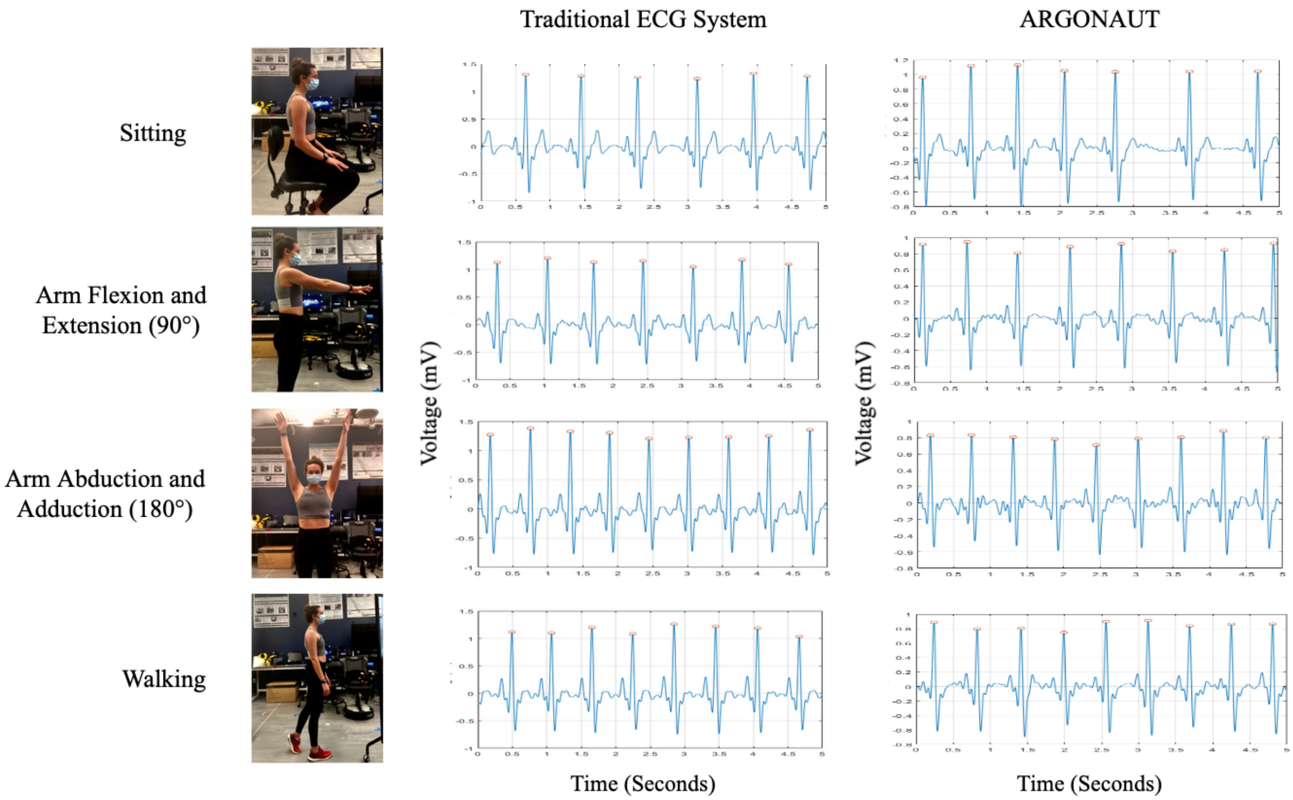

Figure 5: The four motions conducted in the study, sitting, flexion/extension, abduction and adduction, and walking, are depicted with the corresponding ECG signals for the traditional and garment ECG system. R peaks are identified in each signal.

represent the highest anticipated performance against which the ARGONAUT is compared.

When assessing the textile electrodes, the R peaks were perfectly detected for all four subjects in each activity (precision= 1; recall=1, noise score = 0). Figure 7 is an example of how the algorithm detected each of the peaks in the ECG signal for the textile electrode. As can be seen in the figure, the signal quality for ARGONAUT was high. The S waveform was perfectly detected in each motion condition. The Q waveform was perfectly identified in the seated condition, but exhibited slightly deteriorated performance in all other motion conditions. The P and T waveform were the most difficult to detect, as expected, and were only able to be calculated for the seated and flexion/extension conditions. Overall, the signal quality associated with the textile electrodes is equivalent to that of the adhesive electrodes for the larger waveforms, and shows promise for smaller waveforms. The identification of these features can have significant implications on the development of psychophyisological research, which aims to use metrics derived from variability in small features of the waveform.

4.3 Comfort

From the comfort survey [29], participants ranked 15 traits on an intensity scale of 1 to 4, where 1 corresponds to 'totally', 2 to definitely', 3 to 'mildly' and 4 to 'partially'. Traditional sensors were given low scores of less than 2 for the descriptor cold, clammy, and sticky, while ARGONAUT was given low scores for rough, scratchy, and tight. Note that the traditional electrodes were not integrated into a garment, as shown in the left image of Figure 1, so they were not anticipated to yield low scores for tight or snug. It was noted in subjective comments that the rough and scratchy areas were primarily concentrated at the locations of the woven sensors and not throughout the entirety of the garment. Additionally, ARGONAUT was given higher ratings of greater than 3 or had no noticeable intensities in cold, clammy, stiff or prickly. It was also noted that ARGONAUT was lightweight and unobtrusive to the conducted motions, while subjects commented that the leads and strap that secures the data acquisition hardware to the subject were the primary sources of discomfort for the traditional ECG monitoring system, as well as interfered with the arm abduction/adduction and flexion/extension motions. Importantly, for some subjects, redness was documented after the removal of the traditional sensors, but not for the textile sensors. These results suggest that while areas of ARGONAUT did cause discomfort, overall the comfort scores and participant comments indicated that ARGONAUT is more conducive to daily wear with reduced skin irritation and unobtrusive to movements often executed in daily life.

Table 3: Noise scores for the traditional ECG system and ARGONAUT in the identification of each waveform. Low scores indicate improved accuracy and ability for the algorithm to identify each individual waveform.

	Traditional ECG System				Textile ECG System			
	Sit	**Flexion/Extension**	**Abduction/Adduction**	**Walking**	**Sit**	**Flexion/Extension**	**Abduction/Adduction**	**Walking**
P	0	0.04	0.019	0.04	0.022	0.056	N/A	0.022
Q	0	0.042	0	0	0	0.024	0.16	0.06
R	0	0	0	0	0	0	0	0
S	0	0.042	0	0	0	0	0	0
T	0.1	0.357	0.24	0.14	0.157	0.356	N/A	N/A

5 DISCUSSION

In this study, we focused on the design process for a population that differs from the typical population used to validate wearable systems. The system exhibited comparable performance to detect large ECG waveforms compared to traditional adhesive electrodes, and showed promise for smaller waveform detection. Fit is a critical component to make a system of this nature functional, so we limited the subject population tested to a certain range of sizes in order to optimize signal quality. While the similarity of participants' anthropometric form may limit the generalizability of these results to other populations, the particular body of the user provides a case study and design process that expands the development of wearable technology and questions what is considered a design constraint in a novel and innovative way. While signal detection was successful for all participants, differences in signal-to-noise ratio highlight how unique differences in individuals interact with ARGONAUT. This research is a case study that can potentially be the basis for future work in wearable development. This poses future HCI design questions for wearable ECG garments, such as how do we go about designing clothing-based monitors that can merge what we know about anthropometry and e-textiles to design for all individuals? How do we create an inclusive space for the development and design of complex electronic systems? What if instead of hiding the ECG sensors, we develop a beautiful functional sensor for health promotion? Reflecting on the findings of our study, we suggest a shift in thinking about wearable technology and a push to include a more diverse population in order to expand future research of clothing-based ECG monitoring for everyday life that is not just health-driven but also a wearable art piece.

Figure 6: Final ARGONAUT garments with sensor, electronic, and closure mechanism integration.

5.1 Jumping into Additional Explorations

In addition to the original four motions, data was taken with a fifth motion: jumping. For three of the participants, data taken from jumping resulted in data that had an overwhelming amount of noise, such that R peaks were not detectable with the algorithm or visual inspection with any certainty. The garment produced clear data during jumping with one participant. We speculate that there

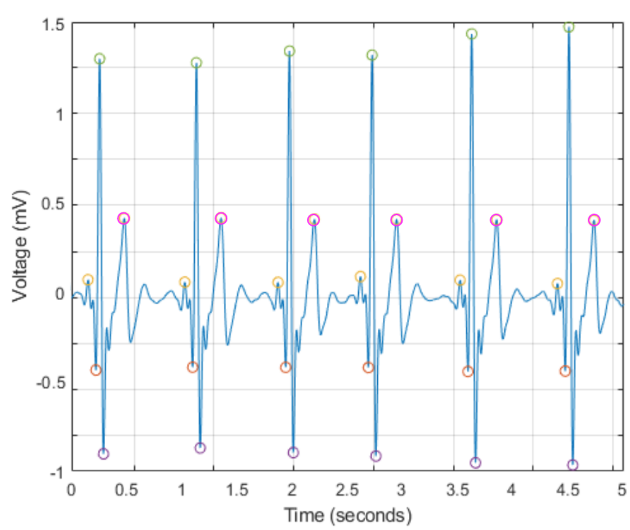

Figure 7: ECG signal with all five major waveforms identified via an algorithm. Signal shown is for the ARGONAUT system.

are a couple potential explanations why clearer data was collected on a single subject but not the others. The first hypothesis is the quality of the wiring in the garment at the time of testing. The electrical aspect of a wearable is one of the most challenging design requirements, especially with considerations such as washability and multi-use functions. We designed our garment with removable wires to address some of the electrical concerns, but with that the number of connection points increase, allowing for more areas of failure. In addition, since we used very fine, flexible wire, minimal strain can cause microtears which affect the signal. Another factor that could have affected signal quality is the anthropometry of the participants. This subject with clean jumping data was also the only subject where the circumferential measurement at the chest was greater than at the breasts. This could indicate that the concavity between the breast and the chest was smaller than the other subjects, allowing for higher skin-electrode contact and less motion when jumping. Even with these potential differences, the signal quality for this subject was not different from the other subjects for the other motions evaluated. Further testing is needed to determine whether either factor played a role in the change in signal quality.

5.2 Reflections

As a subtle, clothing-based monitoring system, ARGONAUT could provide ever-present monitoring throughout varied contexts of daily life. The population that was utilized for this study was small and fairly homogeneous, but the methods presented allow for an expansion far beyond these four participants. A shift in mindset is required to utilize the talents and invaluable information stored in the majority of the population that are not represented in the process of technology creation and validation [43, 51]. Throughout the study, feelings of genuine excitement, interest, and empowerment were expressed by participants. In this way, ARGONAUT is not merely a sports bra for ECG monitoring, but also a spark for the engagement of populations that are underserved by or underrepresented in the HCI community. A hunger and drive for technological advancements in any manner is an advancement for the entirety of the community and can continue to combat the biases that still affect our industry.

6 APPLICATIONS AND IMPLICATIONS

This study demonstrates a systematic design method that focuses not only on the materials and electronics that provide the function of the system but also the anthropometry which allows for complex design solutions. These design solutions have significant impacts on signal quality and HCI. From previous research and feedback from participants, ARGONAUT was a more comfortable and long term solution to autonomous cardiac health monitoring. Inter-individual variability is a critical factor to consider and while we were able to detect and accurately identify all waveforms in each participant's ECG signal, noise and magnitude of the signal had a large span that has the potential to affect results in the future. Systematic testing with multiple participants across research groups will augment the quality of our understanding of wearable electrode performance.

From astronauts to everyday citizens, ARGONAUT has the potential to change the lives of many and add to a growing database of biosignal information that can increase our understanding of the heart and conditions that affect it. As research continues to progress in fields such as psychophysiology, alternative electrodes, and predictive health monitoring, autonomous health monitoring becomes increasingly imperative to facilitating the success of these areas. As women make up around half of this population, their needs must be met to provide equal opportunities and effective care just as any other population.

7 FUTURE WORK

This garment is a proof of concept for every garment that can record real-time ECG data with limited motion artifacts. The humans body is composed of many individual complexities that are unique to the individual. Significant advances need to be made in order to fit all individuals and be utilized for day-to-day monitoring. An expansion to other sizes and increased variability in breast size need to be tested in order to determine feasibility for the general population. Through this study we hope to provide more resources to push the development of wearable technology for the traditionally underserved populations with the future goal to create a garment that is comfortable, socially acceptable, and provides real-time ECG signal collection.

8 CONCLUSION

Our study demonstrates that clothing-based ECG monitors can and should function within the complex and unique anthropometry of all individuals, regardless of sex. By embracing instead of tolerating differences between individuals we will be able to provide accessible care to all and progress the technological development of wearable textiles for individuals that do not fit the mold of the traditional body form. The innovations presented here stand to improve the comfort and wearability of garment-integrated electrodes for a variety of monitoring purposes. Utilizing the known features of woven textiles in new ways creates space for technology to be integrated seamlessly. This opens doors for communication and increased understanding between physicians and patients with physical health problems, psychiatrists and mental health patients, and humans and their increasingly robotic partners. Collaboration between engineers and designers is key to the success of this technology and blurs the line between strict requirements and creative solutions. With this work, we have illustrated the benefits of this collaboration and hope to encourage more like it in the future.

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REFERENCES

[1] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300414

[2] Celia Fernández Aller and Sara Román Navarro. 2018. Gender in Software Engineering Degrees. In *Proceedings of the 12th European Conference on Software Architecture: Companion Proceedings* (Madrid, Spain) *(ECSA '18)*. Association for Computing Machinery, New York, NY, USA, Article 15, 4 pages. https://doi.org/10.1145/3241403.3241420

[3] Teresa Almeida, Rob Comber, and Madeline Balaam. 2016. HCI and Intimate Care as an Agenda for Change in Women's Health. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA)

(CHI '16). Association for Computing Machinery, New York, NY, USA, 2599–2611. https://doi.org/10.1145/2858036.2858187

[4] Katya Arquilla, Sarah Leary, Andrea K Webb, and Allie P Anderson. 2020. Wearable 3-Lead Electrocardiogram Placement Model for Fleet Sizing of Medical Devices. *Aerospace Medicine and Human Performance* 91, 11 (2020), 868–875.

[5] Katya Arquilla, Andrea K Webb, and Allison P Anderson. 2020. Textile electrocardiogram (ECG) electrodes for wearable health monitoring. *Sensors* 20, 4 (2020), 1013.

[6] Katya Arquilla, Andrea K Webb, and Allison P Anderson. 2020. Woven electrocardiogram (ECG) electrodes for health monitoring in operational environments. In *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, Piscataway, NJ, USA, 4498–4501.

[7] Athira Balachandran, M Ganesan, and EP Sumesh. 2014. Daubechies algorithm for highly accurate ECG feature extraction. In *2014 International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE)*. IEEE, Piscataway, NJ, USA, 1–5.

[8] Shaowen Bardzell. 2010. Feminist HCI: Taking Stock and Outlining an Agenda for Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1301–1310. https://doi.org/10.1145/1753326.1753521

[9] Paddy M Barrett, Ravi Komatireddy, Sharon Haaser, Sarah Topol, Judith Sheard, Jackie Encinas, Angela J Fought, and Eric J Topol. 2014. Comparison of 24-hour Holter monitoring with 14-day novel adhesive patch electrocardiographic monitoring. *The American journal of medicine* 127, 1 (2014), 95–e11.

[10] Eric B Bass, Edward I Curtiss, Vincent C Arena, Barbara H Hanusa, Alfred Cecchetti, Micheal Karpf, and Wishwa M Kapoor. 1990. The duration of Holter monitoring in patients with syncope: is 24 hours enough? *Archives of Internal Medicine* 150, 5 (1990), 1073–1078.

[11] Laura Beckwith, Margaret Burnett, Susan Wiedenbeck, Curtis Cook, Shraddha Sorte, and Michelle Hastings. 2005. Effectiveness of End-User Debugging Software Features: Are There Gender Issues?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 869–878. https://doi.org/10.1145/1054972.1055094

[12] Gary G Berntson, J Thomas Bigger Jr, Dwain L Eckberg, Paul Grossman, Peter G Kaufmann, Marek Malik, Haikady N Nagaraja, Stephen W Porges, J Philip Saul, Peter H Stone, et al. 1997. Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology* 34, 6 (1997), 623–648.

[13] Margaret Burnett. 2017. Gendermag: Getting Gender Biases out of Software. *J. Comput. Sci. Coll.* 33, 1 (Oct. 2017), 100–101.

[14] Yu Mike Chi, Tzyy-Ping Jung, and Gert Cauwenberghs. 2010. Dry-contact and noncontact biopotential electrodes: Methodological review. *IEEE reviews in biomedical engineering* 3 (2010), 106–119.

[15] VS Chouhan and SS Mehta. 2008. Detection of QRS complexes in 12-lead ECG using adaptive quantized threshold. *International Journal of Computer Science and Network Security* 8, 1 (2008), 155–163.

[16] Alper Cömert, Markku Honkala, and Jari Hyttinen. 2013. Effect of pressure and padding on motion artifact of textile electrodes. *Biomedical engineering online* 12, 1 (2013), 1–18.

[17] Abe Crystal and Beth Ellington. 2004. Task analysis and human-computer interaction: approaches, techniques, and levels of analysis. *AMCIS 2004 Proceedings* 391 (2004), 1–9.

[18] Mary Czerwinski, Desney S. Tan, and George G. Robertson. 2002. Women Take a Wider View. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Minneapolis, Minnesota, USA) *(CHI '02)*. Association for Computing Machinery, New York, NY, USA, 195–202. https://doi.org/10.1145/503376.503412

[19] Bruce Del Mar. 2005. The history of clinical Holter monitoring. *Annals of noninvasive electrocardiology: the official journal of the International Society for Holter and Noninvasive Electrocardiology, Inc* 10, 2 (2005), 226.

[20] B Aldecoa Sanchez Del Rio, T Lopetegi, and I Romero. 2011. Assessment of different methods to estimate electrocardiogram signal quality. In *2011 Computing in Cardiology*. IEEE, Piscataway, NJ, USA, 609–612.

[21] John P DiMarco and John T Philbrick. 1990. Use of ambulatory electrocardiographic (Holter) monitoring. *Annals of internal medicine* 113, 1 (1990), 53–68.

[22] Genevieve Dion. 2013. Garment Device: Challenges to Fabrication of Wearable Technology. In *Proceedings of the 8th International Conference on Body Area Networks* (Boston, Massachusetts) *(BodyNets '13)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), Brussels, BEL, 97–102. https://doi.org/10.4108/icst.bodynets.2013.253707

[23] Susan M. Dray, Daniela K. Busse, Anke Marei Brock, Anicia N. Peters, Shaowen Bardzell, Allison Druin, Margaret M. Burnett, Elizabeth F. Churchill, Gayna Williams, Karen Holtzblatt, and Diane Murray. 2014. Perspectives on Gender and Product Design. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI EA '14)*. Association for Computing Machinery, New York, NY, USA, 53–56. https://doi.org/10.1145/2559206.2559218

[24] Lucy E Dunne, Halley Profita, Clint Zeagler, James Clawson, Scott Gilliland, Ellen Yi-Luen Do, and Jim Budd. 2014. The social comfort of wearable technology and gestural interaction. In *2014 36th annual international conference of the IEEE engineering in medicine and biology society*. IEEE, Piscataway, NJ, USA, 4159–4162.

[25] Catherine A Elliot, Michael J Hamlin, and Catherine A Lizamore. 2019. Validity and reliability of the hexoskin wearable biometric vest during maximal aerobic power testing in elite cyclists. *The Journal of Strength & Conditioning Research* 33, 5 (2019), 1437–1444.

[26] Stephen H. Fairclough, Alexander J. Karran, and Kiel Gilleade. 2015. Classification Accuracy from the Perspective of the User: Real-Time Interaction with Physiological Computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 3029–3038. https://doi.org/10.1145/2702123.2702454

[27] Mikhaila Friske, Shanel Wu, and Laura Devendorf. 2019. AdaCAD: Crafting Software For Smart Textiles Design. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300575

[28] Vivian Genaro Motti and Kelly Caine. 2015. An Overview of Wearable Applications for Healthcare: Requirements and Challenges. In *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers* (Osaka, Japan) *(UbiComp/ISWC'15 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 635–641. https://doi.org/10.1145/2800835.2809436

[29] Norman RS Hollies, Anna G Custer, Catherine J Morin, and Marilyn E Howard. 1979. A human perception analysis approach to clothing comfort. *Textile Research Journal* 49, 10 (1979), 557–564.

[30] AD Jeyarani and T Jaya Singh. 2010. Analysis of noise reduction techniques on QRS ECG waveform-by applying different filters. In *Recent Advances in Space Technology Services and Climate Change 2010 (RSTS & CC-2010)*. IEEE, Piscataway, NJ, USA, 149–152.

[31] Yasmin V. Kafai. 1998. *Video Game Designs by Girls and Boys: Variability and Consistency of Gender Differences.* MIT Press, Cambridge, MA, USA, 90–114.

[32] Arun Kumar, Edwin Levin, Patricia Cowings, and William B Toscano. 2015. Evaluation of the Accuracy of Astroskin as a Behavioral Health Self-Monitoring System for Spaceflight. In *Annual Summer STEM Internship Symposium*. NASA, Washington DC, USA, 1.

[33] Susan Leavy. 2018. Gender Bias in Artificial Intelligence: The Need for Diversity and Gender Theory in Machine Learning. In *Proceedings of the 1st International Workshop on Gender Equality in Software Engineering* (Gothenburg, Sweden) *(GE '18)*. Association for Computing Machinery, New York, NY, USA, 14–16. https://doi.org/10.1145/3195570.3195580

[34] Yangdong Liao, Ru-Xin Na, and Derek Rayside. 2014. Accurate ECG R-peak detection for telemedicine. In *2014 IEEE Canada International Humanitarian Technology Conference-(IHTC)*. IEEE, Piscataway, NJ, USA, 1–5.

[35] Ching-Wen Lou, Chih-Hung He, and Jia-Horng Lin. 2019. Manufacturing techniques and property evaluations of conductive elastic knits. *Journal of Industrial Textiles* 49, 4 (2019), 503–533.

[36] N Luk and W Yu. 2016. Bra fitting assessment and alteration. In *Advances in Women's Intimate Apparel Technology*. Elsevier, Amsterdam, The Netherlands, 109–133.

[37] Deirdre E McGhee and Julie R Steele. 2020. Biomechanics of breast support for active women. *Exercise and sport sciences reviews* 48, 3 (2020), 99–109.

[38] Paola Medel and Vahab Pournaghshband. 2017. Eliminating Gender Bias in Computer Science Education Materials. In *Proceedings of the 2017 ACM SIGCSE Technical Symposium on Computer Science Education* (Seattle, Washington, USA) *(SIGCSE '17)*. Association for Computing Machinery, New York, NY, USA, 411–416. https://doi.org/10.1145/3017680.3017794

[39] Yao Meng, Heung-Kook Choi, and Hee-Cheol Kim. 2011. Exploring the user requirements for wearable healthcare systems. In *2011 IEEE 13th International Conference on e-Health Networking, Applications and Services*. IEEE, Piscataway, NJ, USA, 74–77.

[40] Carey R. Merritt, H. Troy Nagle, and Edward Grant. 2009. Fabric-Based Active Electrode Design and Fabrication for Health Monitoring Clothing. *IEEE Transactions on Information Technology in Biomedicine* 13, 2 (2009), 274–280. https://doi.org/10.1109/TITB.2009.2012408

[41] Michael A Messner. 1988. Sports and male domination: The female athlete as contested ideological terrain. *Sociology of sport journal* 5, 3 (1988), 197–211.

[42] Suneet Mittal, John Rogers, Shantanu Sarkar, Jodi Koehler, Eduardo N Warman, Todd T Tomson, and Rod S Passman. 2016. Real-world performance of an enhanced atrial fibrillation detection algorithm in an insertable cardiac monitor. *Heart Rhythm* 13, 8 (2016), 1624–1630.

[43] Manasee Narvilkar, Josiah Mangiameli, Adriana Alvarado Garcia, Azra Ismail, Daniel Schiff, Danielle Schechter, Jordan Chen, Karthik Bhat, Marisol Wong-Villacres, Anusha Vasudeva, Aparna Ramesh, Michaelanne Dye, Naveena Karusala, Pragati Singh, Savanthi Murthy, Shubhangi Gupta, Udaya Lakshmi, and Neha Kumar. 2019. Bringing Shades of Feminism To Human-Centered Computing. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290607.3310419

[44] Pravin Pawar, Val Jones, Bert-Jan F Van Beijnum, and Hermie Hermens. 2012. A framework for the comparison of mobile patient monitoring systems. *Journal of biomedical informatics* 45, 3 (2012), 544–556.

[45] Marek N. Posard. 2014. Status processes in human-computer interactions: Does gender matter? *Computers in Human Behavior* 37 (2014), 189–195. https://doi.org/10.1016/j.chb.2014.04.025

[46] Raj Rakshit, V Ramu Reddy, and Parijat Deshpande. 2016. Emotion Detection and Recognition Using HRV Features Derived from Photoplethysmogram Signals. In *Proceedings of the 2nd Workshop on Emotion Representations and Modelling for Companion Systems* (Tokyo, Japan) *(ERM4CT '16)*. Association for Computing Machinery, New York, NY, USA, Article 2, 6 pages. https://doi.org/10.1145/3009960.3009962

[47] Pentti M Rautaharju, Lawrence Park, Farida S Rautaharju, and Richard Crow. 1998. A standardized procedure for locating and documenting ECG chest electrode positions: consideration of the effect of breast tissue on ECG amplitudes in women. *Journal of electrocardiology* 31, 1 (1998), 17–29.

[48] Tanushree Sharma and Kamalesh Kumar Sharma. 2017. QRS complex detection in ECG signals using locally adaptive weighted total variation denoising. *Computers in biology and medicine* 87 (2017), 187–199.

[49] H-Y Song, J-H Lee, D Kang, H Cho, H-S Cho, J-W Lee, and Y-J Lee. 2010. Textile electrodes of jacquard woven fabrics for biosignal measurement. *The Journal of the Textile Institute* 101, 8 (2010), 758–770.

[50] Catherine A. Spann, James Schaeffer, and George Siemens. 2017. Expanding the Scope of Learning Analytics Data: Preliminary Findings on Attention and Self-Regulation Using Wearable Technology. In *Proceedings of the Seventh International Learning Analytics ; Knowledge Conference* (Vancouver, British Columbia, Canada) *(LAK '17)*. Association for Computing Machinery, New York, NY, USA, 203–207. https://doi.org/10.1145/3027385.3027427

[51] Katta Spiel, Os Keyes, and Pınar Barlas. 2019. Patching Gender: Non-Binary Utopias in HCI. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3290607.3310425

[52] Yan Sun, Kap Luk Chan, and Shankar Muthu Krishnan. 2005. Characteristic wave detection in ECG signal using morphological transform. *BMC cardiovascular disorders* 5, 1 (2005), 1–7.

[53] Tadashi Suzuki, Tsugiyasu Kanda, Sachio Kubota, Susumu Imai, and Kazuhiko Murata. 1994. Holter monitoring as a noninvasive indicator of cardiac involvement in sarcoidosis. *Chest* 106, 4 (1994), 1021–1024.

[54] Hakw Tam and John G Webster. 1977. Minimizing electrode motion artifact by skin abrasion. *IEEE Transactions on Biomedical Engineering* BME-24, 2 (1977), 134–139.

[55] DA Tong, KA Bartels, and KS Honeyager. 2002. Adaptive reduction of motion artifact in the electrocardiogram. In *Proceedings of the Second Joint 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society][Engineering in Medicine and Biology*, Vol. 2. IEEE, Piscataway, NJ, USA, 1403–1404.

[56] Rodrigo Villar, Thomas Beltrame, and Richard L Hughson. 2015. Validation of the Hexoskin wearable vest during lying, sitting, standing, and walking activities. *Applied Physiology, Nutrition, and Metabolism* 40, 10 (2015), 1019–1024.

[57] Mihaela Vorvoreanu, Lingyi Zhang, Yun-Han Huang, Claudia Hilderbrand, Zoe Steine-Hanson, and Margaret Burnett. 2019. From Gender Biases to Gender-Inclusive Design: An Empirical Investigation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300283

[58] Ya Xu, Guangyuan Liu, Min Hao, Wanhui Wen, and Xiting Huang. 2010. Analysis of affective ECG signals toward emotion recognition. *Journal of Electronics (China)* 27, 1 (2010), 8–14.

[59] Murat A Yokus and Jesse S Jur. 2015. Fabric-based wearable dry electrodes for body surface biopotential recording. *IEEE Transactions on Biomedical Engineering* 63, 2 (2015), 423–430.

[60] W Yu and J Zhou. 2016. Sports bras and breast kinetics. In *Advances in women's intimate apparel technology*. Elsevier, Amsterdam, The Netherlands, 135–146.

[61] Rong Zheng, Winnie Yu, and Jintu Fan. 2007. Development of a new Chinese bra sizing system based on breast anthropometric measurements. *International Journal of Industrial Ergonomics* 37, 8 (2007), 697–705.