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Electrode Integration in a Wearable Undershirt for Stress Detection

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This study focusses on the implementation of electrodes on a smart shirt for heart rate detection in individuals with limited verbal communication abilities. The objective is to determine the optimal location while ensuring optimal skin-electrode contact. The methodology includes exploring solution to enhance conformal contact, the development of prototypes, and conducting tests using two electronics modules called MoveSense and SentiECG. Findings reveal that placing the electrodes horizontally underneath the breast on the front of the shirt gives optimal performance with minimal motion artifacts and noise. The proposed final design incorporates a shirt composed of 87% nylon and 13% elastane, along with the recommended electrode placement. Future research should focus on different shirt sizes, expanding the participant population, extending measurement duration, and addressing motion artifacts during active sessions. Overall, the smart shirt holds promise for accurate heart rate monitoring in individuals with limited verbal communication abilities.

Monitoring Heart Rate; Skin-Electrode contact; Fabric composition; Electrode Design; Electrode Placement

1. Introduction

Mentech Innovation has developed the HUME, a stress recognition platform, to predict stress in individuals with limited verbal communication abilities. This platform uses wearable devices, including a sock and strap, to monitor increases in heart rate and electrodermal activity (EDA), respectively [1]. However, not all clients can wear the sock either due to the need of compression socks or personal preference. Consequently, only heart rate can be measured through the strap, which is a third-party product. Mentech aims to achieve independence from external companies and reduce reliance on them by introducing a smart shirt capable of detecting heart rate. This innovation provides greater flexibility in choosing a wearable that suits the clients' preferences and needs.

Heart rate can be derived from two consecutive R-peaks of an electrocardiogram (ECG) wave. An ECG wave is obtained by the implementation of two dry flat film electrodes onto a shirt [2], [3]. Dry electrodes are reusable as they lack a gel layer, making them suitable for wearable applications. However, the absence of a gel layer creates air gaps between the electrode and the skin [4]. This gap weakens the security of the skin-electrode contact and increases vulnerability to motion artifacts [5]–[7], which negatively affects the quality of the ECG signal. Insecure skin-electrode contact can be further exacerbated by the interference of chest hair in males. To ensure better skin-electrode contact, the *electrodes' placement* and sufficient *pressure application* are crucial.

The positioning of electrodes determines the observed view and wave pattern. While traditional electrode placement follows Einthoven's model, advancements in wearable devices have led to adjustment in electrode location to minimize noise and motion artifacts [8]. Placing the electrodes at the lower lateral part of the pectoralis major muscle in the front (underneath the breast) *or* the lower, lateral part of the latissimus dorsi at the back, reduces motion artifacts caused by muscle interference [9]. This location also tends to have the lowest hair distribution for men on the anterior side [10], [11], making it suitable for electrode placement in men. However, positioning the electrodes at the correct height of this location can be challenging for women due to varying breast sizes. Research [8] suggests that placing the electrodes on the back may be promising for the shirt design, as it reduces interference from breast in women, chest hair in man, and minimizes motion artifacts.

However, since the aforementioned studies were conducted in clinical settings under "perfect" conditions, the practical outcomes may differ. Therefore, the primary focus of this study is to implement electrodes on a shirt for heart rate detection, emphasizing the need for optimal skin-electrode contact achieved through adequate pressure on the electrodes and optimal electrode location.

2. Methodology

The implementation of electrodes onto a shirt while maintaining proper conformal contact starts with exploring the solutions and creating conceptual designs (2.1). These designs are translated into manufacturable formats to create prototypes (2.2). The test protocol is discussed to provide clarity on the testing process (2.3).

2.1 Designs

To establish proper *skin-electrode contact,* it is necessary to apply sufficient pressure to the electrodes on the skin and to determine the optimal electrode placement. The application of *pressure* can be achieved through the use of fabric with high stretchability and elasticity, which ensures a constant electrode pressure against the skin. Incorporating a high percentage of elastane in the fabric composition helps to achieve these properties. Nylon is used alongside elastane due to its stretchability, strength, and durability [12], which are important qualities for wearables.

Two electrode *designs* (Design A and Design B) are created, which can be laminated at different *locations* to identify the most optimal placement and design (**figure 1**). Design A offers flexibility in electrode placement, including underneath the breast, above the breast and at the back. The selected locations underneath the breast and at the back are based on clinical studies [8]–[11]. The placement on the chest is chosen to assess whether it would be more suitable for women by reducing interference from their various breast sizes. On the other hand, Design B is based on Einthoven's triangle and serves to compare the effectiveness of Design A and the location of the electrodes.

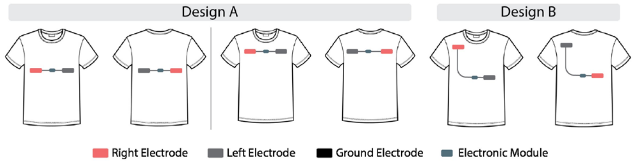

Figure 1.; Abstract Design and Location electrodes.

2.3. Prototypes

The designs of **figure 1** are detailed to enable the manufacturing of functional prototypes. This involves defining the dimensions and layer structure necessary for the screen-printing process. The electrodes are then laminated onto shirts with specified material properties. **Figure 2** illustrates the detailed electrode designs, with an electrode size of 70 x 25 mm, which is based on the strap electrode size. The horizontal design ensures a width of 300 mm between the electrodes, which falls within the range of the anthropometric under bust width of men and women at the 50th percentile [13], [14]. This ensures proper positioning of the electrodes at the lateral side.

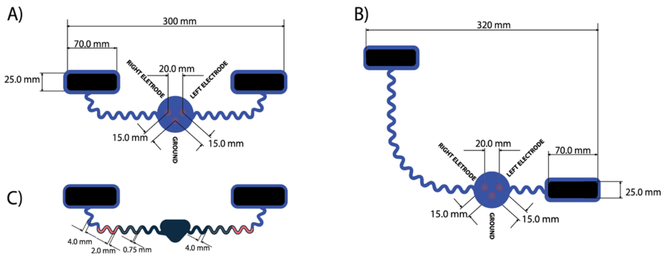

Figure 2.; Detailed Electrode Design.

The layer-structure, depicted in **figure 3**, is screen-printed onto each other and applied on both designs. The substrate TPU layer acts as a barrier between the silver layer and the garment, providing stretchability during wear. The silver conductive sensing layer collects and transmit data from the electrode to the electronics module. The isolation layer prevents signal interference during transmission. The carbon layer on top of the silver layer ensures good conformal contact with the skin while preventing direct contact between the silver and the skin. The PU top layer provides stretchability during wear. The signal is transferred to the electronics module through snap fasteners, and the top PU circle acts as a barrier to prevent the snap fasteners from directly contacting the skin, thereby reducing false readings.

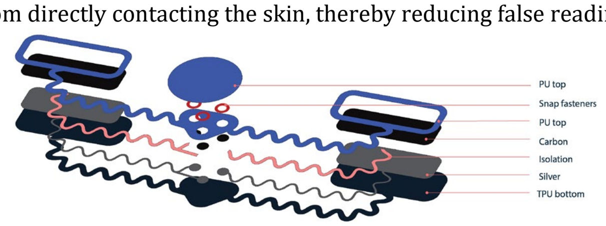

Figure 3.; Electrode layers

The screen-printed electrodes are laminated at the predefined locations discussed in section 2.1 **Figure 4** illustrates the prototypes, with electrodes located at the front and back, along with their corresponding shirt numbers. Shirts 1 and 3 have sleeves to allow electrode placement at the chest, while shirt 2, sleeveless, has both electrodes positioned under the breast. Each shirt has a different elastane-nylon ratio **(table 1**) to evaluate the composition that best facilitates good electrode-skin contact without the electrodes breaking.

Figure 4.; Prototyped shirts.

Shirt no.	*Material composition*
1	25 % elastane / 75% nylon
2	11 % elastane / 50% nylon / 39% Cotton
3	13 % elastane / 87 % nylon

Table 1.; Material composition fabric shirts

2.3. Test protocol

The electrodes on the three prototypes are tested to determine the optimal electrode design, location, and fabric composition. 6 participants, consisting of 3 males and 3 females, participate in the functionality test. Shirt 1 is specifically designed to accommodate varying breast sizes of female and is tested exclusively by female participants. Shirts 2 and 3 are tested by both male and female participants.

The shirt is worn over a reference strap, with each electrode pair equipped with an electronics module. Two types of electronics modules, MoveSense and SentiECG, are used for data comparison and evaluation. MoveSense, which displays heart rate, is used to compare the electrode data of the shirt with the reference strap data, providing insights into the correlation between the electrode pair and an existing product. MoveSense, however, is not able to show raw ECG signal, and will eventually be substituted with Mentech's own electronics module. Therefore, SentiECG is used to evaluate the raw ECG data of each electrode pair.

The measurements involve resting and active sessions to assess electrode performance in different practical situations. This is done with 2-minute periods of resting and 2-minute periods of walking. Each session is repeated twice, resulting in 2 resting and 2 active sessions for each shirt per participant.

The data collected from the sensors is processed for analysis. MoveSense data is processed by plotting the strap data alongside the data form one electrode and calculating the Pearson Correlation Coefficient. SentiECG data can only be visualised as an ECG wave, making direct comparison between the strap and electrode more challenging due to timing variations. Therefore, the evaluation of raw ECG data focusses on the ECG pattern, particularly the visibility of R-peaks.

3. Results

The results are obtained from the data collected through MoveSense and SentiECG are analysed and presented in this section. MoveSense data, enabling the calculation of the Pearson Correlation Coefficient, helps to determine which electrode design, location, and fabric composition performs most optimal in comparison to existing products. Additionally, the presence of motion artifacts caused by poor skin-electrode contact can be assessed by comparing data from active and passive sessions.

Since, Mentech intends to replace MoveSense with their own sensor, SentiECG, it is crucial that the data obtained from SentiECG is not predominantly affected by motion artifacts and noise. This would hinder the derivation of heart rate from the RR-intervals. By examining the plots obtained from SentiECG, the level of noise per electrode can be determined, which will help in assessing which electrode *location* has the least impact on the noise level.

3.1 Heart Rate measurements obtained by MoveSense.

Table 2 summarizes the average Pearson Correlation Coefficient of the sessions conducted with MoveSense in passive and active sessions, and total average. During the rest sessions, the front electrodes of shirts 2 and 3 show a strong correlation with the strap electrodes. However, while walking, only shirt 2 demonstrates high correlation with the strap, even though weaker than during the rest session.

	Shirt 1		Shirt 2		Shirt 3	
Electrode location	**Low**	**High**	**Front**	**Back**	**Front**	**Back**
Average Rest	0,66	0,00	0,84	0,00	0,73	0,00
Average Walking	0,00	0,00	0,70	0,00	0,16	0,00
Average Total	**0,33**	**0,00**	**0,77**	**0,00**	**0,49**	**0,00**

Table 2.; Average Pearson Correlation Coefficient per electrode.

3.2 Raw ECG signal obtained by SentiECG.

The data obtained from SentiECG is visualised through ECG waveforms, allowing for the examination of motion artifacts, noise levels, and signal strength. **Figure 5** provides an example of the measurement of heart electrical activity from the front and back electrodes on shirt 2 on participant 3 during the first sitting session. The plot for the back electrodes **(figure 5A)** shows more motion artifacts and a higher noise level compared to the front electrodes (**figure 5B**). The strength of the signal is evaluated based on the amplitude range. The amplitude of the R-peaks from the back electrodes falls within a range of 11k, whereas the front electrode reveals a range of 25k. Therefore, the strength of the back electrodes is approximately 56% weaker than that of the front electrodes.

Overall, the electrodes on the front of shirt 2 demonstrate clearer ECG waveforms, fewer motion artifacts, and lower noise levels compared to those on the back and other shirts.

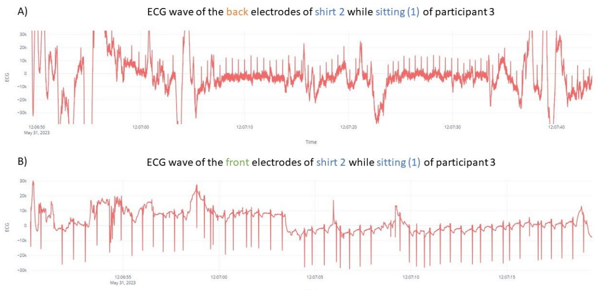

Figure 5.; Example ECG

4. Discussion

This study focused on achieving proper electrode-skin contact by considering two aspects: the application of pressure and the design and location of the electrodes. The results revealed some important insights and limitations.

4.1. Interpretation of results

Based on the obtained results, several interpretations can be made. The absence of data from the high electrodes of shirt 1 suggests potential issues with the electrode contact caused by a poorer fit above the breast. To properly position the electrode at this location is challenging due to the proper fit in most shirts and the space limitation at the strap in a tank top.

The absence of data and therefore the poor correlation of the electrodes on the back could be caused by a weaker electrical signal compared to the front electrodes. Since MoveSense is a third-party product with its programming unknown, it is possible that the signal strength of the R-peak falls below its detection threshold. The hypothesis of a weaker signal on the back electrodes is confirmed by the measurements obtained from SentiECG, which indicates that the amplitude of the R-peaks from the back electrode is approximately 56% smaller than that of the front electrode. This weaker signal could be caused by additional tissue or bones that the electric activity of the heart needs to pass through.

The electrodes intended to be positioned underneath the breast showed for women a deviation in practise, as they were located at the inferior part of the breast. This wrongful location in electrode placement did not affect the correlation while sitting compared with the male measurements (**table 3**), indicating that the breast did not interfere with the electrode performance. However, during walking, the Pearson Correlation of female participants showed a significantly lower correlation compared to men for both shirts 2 and 3. This finding confirms that the breast causes some motion artifacts, even when the electrodes are tightly pressed to the skin. Despite the motion artifacts caused by the breast, shirt 2 still exhibited a relatively high correlation, indicating that this design may be more suitable and robust.

The performance of the electrodes on the front of shirt 3 was overall poorer than that of shirt 2 for men. This could be attributed to less pressure applied by the chest electrode on the skin, similar to the high electrodes of shirt 1.

	Shirt 2		Shirt 3	
	Men	**Women**	**Men**	**Women**
Average Rest	0,85	0,84	0,57	0,90
Average walking	0,91	0,66	0,16	0,00
Average Total	0,88	0,75	0,36	0,45

Table 3.; Comparison of the average Pearson Correlation Coefficient between men and women

4.2 Final design

Based on the results, a final design is created to ensure proper skin-electrode contact. Shirt 2, with electrodes on the front, performed most optimal and demonstrated a very high correlation to the strap. The material composition of shirt 2, which includes 50% nylon, 39% cotton, and 11% elastane, allows for good *electrode pressure* on the skin due to its stretchability and elasticity. However, the use of cotton resulted in some delamination issues. An alternative version of the tank top, consisting of 87% nylon and 13% elastane is utilized, which has a higher percentage of elastane than the original for increased pressure on the electrodes.

The final horizontal electrode design underwent slight alterations, with the distance between the electrodes based on the anthropometric under-breast width of men and women [13], [14] (**figure 6**).

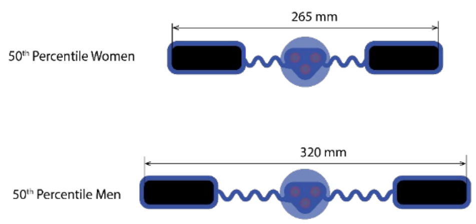

Figure 6.; Final design electrodes

The most optimal location for the horizontal design was found to be underneath the breast for both men and women. **Figure 7** illustrates this location with the new electrode design. Due to the varying breast sizes in women, it is important to laminate the electrodes at varying heights to accommodate different sizes. Establishing a precise reference point for electrode placement can help achieve this.

Figure 7.; Final Location electrodes

4.3 Limitations

Several limitations should be acknowledged in this study related to participant recruitment, duration of measurement, and data processing.

The experiment was conducted on a small sample size of 6 participants who were internally recruited within Mentech. This sample size is not representative of the eventual target group. Therefore, it is advised to include a larger and more diverse participant population, especially individuals in the target group. Additionally, the requirement for participants to fit size M shirts resulted in the exclusion of participants who did not fit this size. It would be beneficial to develop electrode designs that accommodate various sizes, ensuring inclusivity in future studies.

The duration of each measurement was 2 minutes. However, clients within the target group would need to wear the garment throughout the entire day (approximately 12 hours). Extending the measurement duration to a longer period would provide an understanding of the garment's performance during prolonged use.

Another limitation is regarding the data processing. The results obtained from SentiECG were based on visual evaluation rather than a quantitative method. This was due to the unavailability of a quantitative analysis tool within Mentech at the time of the study, and conducting such an analysis would have exceeded the assignment's scope and time constraints.

4.4 Future research

In terms of future research, it is important to continue the development and evaluation of the proposed final design. First, the dimensions of the proposed electrode design should be translated into different shirt sizes, ensuring that each size has a corresponding electrode designed to fit based on the anthropometric width underneath the breast. By doing so, a wider range of participants can be included in the evaluation of the shirt.

Moreover, future experiments should focus on a larger population consisting of participants who belong to the target group of individuals with limited verbal communication abilities. It is advisable to extend the duration of the session, ideally combining both active and passive sessions, to gather data over a 12-hour timespan. This will provide a more complete understanding of the garment's performance under prolonged use.

Another aspect to address is the occurrence of motion artifacts during active sessions. The current design does not completely resolve this issue, as proper electrode-skin contact is not achieved by applying sufficient pressure and positioning the electrodes at specific locations. It is recommended to explore methods that enhance electrode adhesiveness. This could involve considering a conductive silicone surface layer or modifying the electrode surface using biostructures.

5. Conclusion

In conclusion, the implementation of electrodes onto a shirt with horizontal electrodes positioned underneath the breast, combined with a garment composition of 87% nylon and 13% elastane, enables optimal electrode-skin contact and shows potential for accurate heart rate monitoring in individuals with limited verbal communication abilities.

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