

Contact ECG Recording Using Copper and E-Textile Based Flexible Dry Electrodes

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Abstract—We present experiments of contact electrocardiograms (ECG) recording using copper and e-textile-based flexible dry electrodes. In this work, dry electrodes with different shapes, sizes, and materials were designed and fabricated. In cardiac monitoring using these flexible dry electrodes, three different conditions were considered, which are sitting, standing, and walking. To evaluate the performances of the fabricated dry electrodes, average-to-variation ratios (AVR) of the recorded ECG signals measured using the flexible dry electrodes were calculated and compared with those measured using the commercially-available wet electrodes in all three conditions. The AVR results demonstrate that the dry electrodes have a similar performance to the commercially-available wet electrodes in the sitting and standing conditions and a better performance in the walking condition. These results suggest that it is possible to weave dry e-textile-based electrodes in normal clothing and use them for continuous monitoring of ECG signals in different conditions.

1. INTRODUCTION

Electrocardiographic signals are of utmost importance in medical applications for tracking heart rhythm and diagnosing cardiac diseases. Generally, wet silver/silver chloride (Ag/AgCl) electrodes with conductive liquid electrolyte gels are widely used in hospital electrocardiogram (ECG) recording [1]. However, ECG signal quality will degrade as the gels dehydrate. These adhesive wet electrodes may also cause skin irritation, redness, and allergic dermatitis due to gel ingredients and repetitive applications of the electrodes. Therefore, they are not suitable for long-term use and for use in patients having sensitive skins [2] and [3].

To address these problems, dry electrodes without electrolyte gels were developed using stiff, soft, or flexible materials [4–23]. Stiff materials based dry electrodes are usually made from metal discs or thin metal traces printed on stiff dielectric substrates, which may not conform to human body and suffer from motion artifacts [4–8]. To mitigate the motion artifacts, soft electrodes using conductive foam and flexible electrodes using e-textile or other flexible materials were developed [9–24]. In [9] and [10], conductive-foam-based dry electrodes were designed and used to adapt the skin surface in ECG monitoring. The thickness of such a conductive-foam-based dry electrode is approximately 5 mm. To develop dry electrodes with a 2-D planar flexible structure, e-textiles made by metal wires, metal coated non-conductive fabrics, or conductive nanofibers were used [11–18]. In [11], dry electrodes were sewn as patches on clothes using stainless steel wires with spacing of 3 mm. In [12–16], nickel or silver coated non-conductive fabrics, such as acrylic fiber, nylon, and polyester were proposed to design flexible dry electrodes. Besides using conventional fabrics, conductive nanofibers based dry electrodes

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were developed in [17] and [18]. ECG measurements based on circle-shaped electrodes using different conductive nanofibers and fabrics were compared in [17]. ECG measurements based on square-shaped electrodes with the same size in the sitting and walking conditions were compared in [18]. Flexible conductive materials other than e-textiles were used in designing dry electrodes [19–24]. In [19], circle-shaped electrodes with different thicknesses and diameters were designed using flexible carbon nanotube and polydimethylsiloxane (PDMS) composite for long-term ECG recording. For under water ECG monitoring, carbon black powder and PDMS were used to design circle-shaped electrodes with different sizes in [20]. In [21], a flexible PDMS based circle-shaped electrode with a fixed size was developed. A parylene-based square-shaped dry Ag/AgCl electrode with a fixed size was designed for long-term biopotential recording and reported in [22]. In [23], a self-wetting square-shaped electrode with a fixed size was developed, consisting of ethylcellulose fiber paper and parylene. In [24], circle-shaped electrodes with three different diameters were fabricated by silver flake ink screen printed on a flexible polyethylene terephthalate substrate. The electrodes were attached on a subject’s forearm to record ECG signals in sitting and motion conditions. All the aforementioned dry electrodes were compared with commercially-available wet Ag/AgCl electrodes in the ECG signal quality, showing similar performance. However, most comparisons were based on ECG recording using electrodes with a fixed shape and size and measuring a static subject. A comprehensive study of ECG recording using electrodes with different shapes, sizes, and materials is needed. It is also necessary to compare the performances of these electrodes under different conditions, such as sitting, standing, and walking.

In this paper, we present contact ECG measurements using dry electrodes with different shapes, sizes, and materials. The flexible dry electrodes are made of two different materials copper tapes and e-textiles (conductive silver fabrics), using three different shapes (triangle, circle, and square) and three different areas (3, 12, and 48 cm²). Copper tape electrodes have the same dimensions and shapes as those of the e-textile-based electrodes examined in this work. They are used to investigate the impact of electrode conductivity on the recorded ECG data. All necessary approval permissions on human experimental studies were settled before ECG measurements. These electrodes and commercially-available wet Ag/AgCl electrodes were tightly attached on the chest above the heart of a 29-year-old healthy male human, recording ECG signals in three different conditions: sitting, standing, and walking. In the walking condition, the subject walks on a treadmill with three different speeds of 1, 2, and 3 mph. The ECG heart signals using each type of the electrodes were recorded 10 times. In each measurement, the recording time was 70 seconds. In total, there are 19 different electrodes (3 shapes \times 3 sizes \times 2 materials + 1 commercially-available wet electrode), 5 different conditions (1 sitting + 1 standing + 3 walking), and 950 measurements (19 different electrodes \times 5 different conditions \times 10 times). To demonstrate the performance of the fabricated dry electrodes, average-to-variation ratios (AVR) of the heart signals measured by the fabricated electrodes were calculated and compared with those measured by the commercially-available wet electrodes. AVR is defined by the average of the aligned ECG signals over the variation in each aligned interval of the recorded ECG signals (See details in Section II-B). The AVR values show that the size rather than the shape of the electrodes influences their performance. The fabricated dry electrodes with a larger size provide a higher AVR value. The AVR values also demonstrate that the flexible dry electrodes have a similar performance to the commercially-available wet electrodes in the sitting and standing conditions and a better performance in the walking condition. These results demonstrate that the proposed flexible dry electrodes can be used as an alternate to the conventional wet electrodes and are more suitable for long-term recording.

2. METHODOLOGY

To perform comprehensive ECG heart signal measurements, dry electrodes with different shapes, areas, and materials were fabricated. These electrodes were used to record cardiac signals of a 29-year-old healthy male in three different conditions: sitting, standing, and walking. In the measurement of the walking condition, a treadmill was used to control the walking speed to 1, 2, and 3 mph. Average-to-variation ratios (AVR) of the ECG signals recorded by the fabricated dry electrodes were calculated and compared with those recorded by commercially-available wet electrodes, which are shown in the right bottom side of Fig. 1(b). The ECG signals were segmented into intervals containing a single peak. All intervals were aligned to their salient feature. The averaged signal was obtained by averaging over

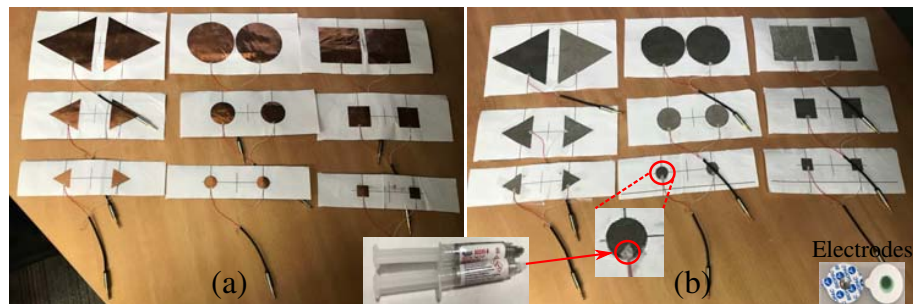


Figure 1. Photographs of (a) fabricated copper-based dry electrodes, (b) fabricated e-textile based dry electrodes and commercially-available wet electrodes. The electrodes with different shapes in the first row have the same area of 48 cm^2 , those in the second row have the same area of 12 cm^2 , and those in the third row have the same area of 3 cm^2 .

all aligned intervals. The variation was calculated based on the subtraction of the ECG signal in each interval from the average. This ratio is also called signal-to-noise ratio (SNR) in [25]. The term AVR is used in this paper, since the recorded signals contain body movement and interferences other than heart rhythms and noise. The commercially-available electrodes are wet Ag/AgCl contact electrodes, incorporating liquid electrolyte gel and moderately-high chloride salt concentration for quick, accurate readings. The surface area of the commercially-available wet electrode is approximately 10 cm^2 . More details can be found in [26].

2.1. Electrode Fabrication and Measurement Setup

Figure 1 shows the fabricated copper and e-textile based dry electrodes. All electrodes are attached on paper to maintain the same center-to-center separation of 8 cm, which is the average width of the human heart. The paper is dry during each measurement of 70 seconds. The copper electrodes are made of copper tapes with different shapes of triangle, circle, and square and different areas of 3, 12, and 48 cm^2 . The surface resistivity of the copper tape is $0.005 \Omega/\text{in}^2$ [27]. The e-textile electrodes are made of Tylson conductive silver fabrics with the same shape and area settings as the copper electrodes. The surface resistivity of the silver fabric is $0.03\text{--}0.05 \Omega/\text{in}^2$ [28]. Soldering paste was used to connect wires to copper electrodes. To connect wires to e-textile electrodes, silver epoxy adhesive (MG Chemicals 8331S) was used and shown in the middle bottom side of Fig. 1. During measurements, an insulating tape was attached on the soldering paste and silver epoxy adhesive to avoid the direct contact of the skin. Fig. 2(a) shows an oven with a thermometer. All the nine e-textile electrodes were baked in the oven at the same time with a temperature of 65°C to achieve a tight connection between the wires and the electrodes through the silver epoxy adhesive. As shown in Fig. 2(b), the temperature was controlled by a variac with an output voltage of 49.9 V. A multimeter was used to read the voltage.

Figure 3 shows the experiment setup. In Fig. 3(a), two electrodes are placed on the left chest of a 29-year-old healthy male subject. The skin for placing electrodes was cleaned from sweat and hair before each measurement. To attach the electrodes to the skin above the heart tightly, an adjustable belt was used around the body after placing the electrodes. As shown in Fig. 3(b), the belt consists of a Nylon strap with adjustable length (black curve) and an elastic strap (gray curve). To ensure the same pressure is applied to the electrodes and the tension of the belt is consistent for the different measurements. The length of the elastic strap was fixed at 21.5 cm. The corresponding tension is 1.49 kg, measured by a scale (shown in Fig. 3(c)). Fig. 3(d) shows the ECG front-end and software for recording the heart signals (Heart and Brain Spiker, Backyard Brains [29]). This heart signal recording system uses a driven-right-leg active ground to reduce common-mode noise [30], where the reference electrode position is shown in a blue circle in Fig. 3(d). In heart signal recording, the frequency was chosen from 0.5 Hz to 100 Hz with a sampling frequency of 10 kHz. There is a built-in notch filter in Heart and Brain Spiker, which was used to remove the 60 Hz interferences from power line.

To perform a comprehensive study of the fabricated dry electrodes, three different conditions were

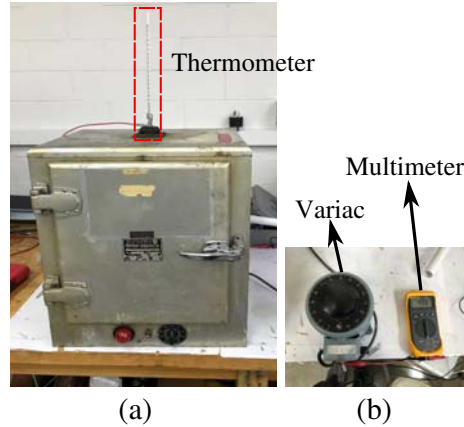


Figure 2. (a) The wires were attached to the e-textile electrodes using silver paste and the entire assembly was baked in the oven shown in part. (b) The temperature was maintained at 65° using the variac shown in part.

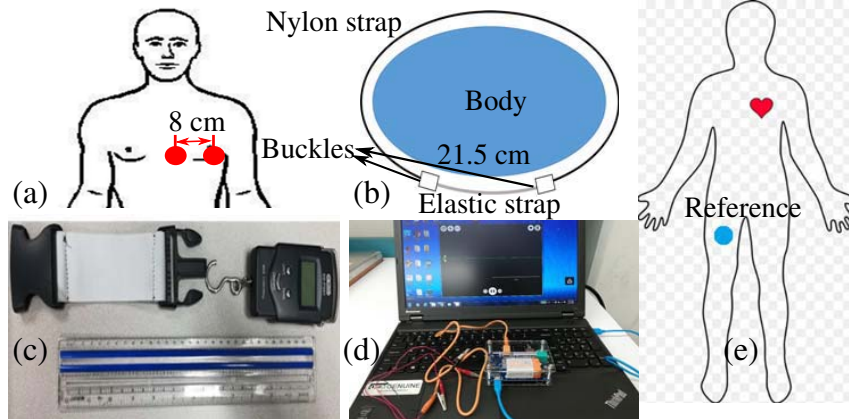


Figure 3. Pictures of (a) electrodes attached on the chest above the heart, (b) cross sectional view demonstrating how the adjustable belt was used to hold the electrodes in place, (c) the elastic strap used to control the tension of the adjustable belt, (d) ECG front-end and software for recording heart signals, and (e) the reference electrode location.

considered, which are sitting, standing, and walking with different speeds of 1, 2, and 3 mph. We repeated the measurement of each condition for 10 times using all the fabricated and commercially-available electrodes on different days. In each measurement, the heart signal recording time was 70 seconds. To remove unwanted transition effects and obtain accurate results, the first and last five seconds of each recorded data were excluded. In all measurements, the adhesive commercially-available wet electrode was used as the reference electrode and attached on the right leg with the position shown in Fig. 3(d).

2.2. Average-to-Variation Ratio Calculation

Figure 4 shows three examples of the recorded heart ECG signals in the sitting condition, using fabricated circle-shaped copper and e-textile electrodes with the same area of 12 cm^2 and commercially-available electrodes. The recorded ECG signals have a length of 60 seconds with removing the initial and last five seconds. Observe that the heart rhythms can be captured by all the three types of electrodes. To compare the performances of the different fabricated electrodes in a quantitative fashion, average-to-variation ratios (AVR) of all the recorded heart signals are calculated. Fig. 5 shows the flowchart used to

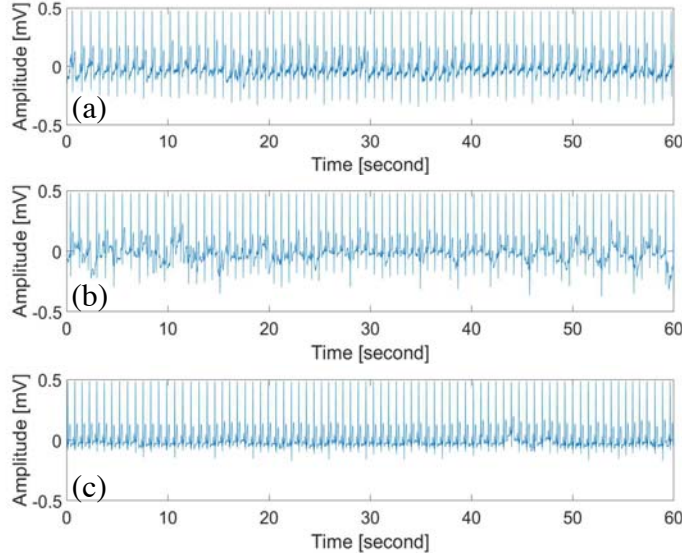


Figure 4. The recorded ECG heart signals in the sitting condition using, (a) circle-shaped copper electrodes with an area of 12 cm^2 , (b) circle-shaped e-textile electrodes with an area of 12 cm^2 , (c) commercially-available electrodes.

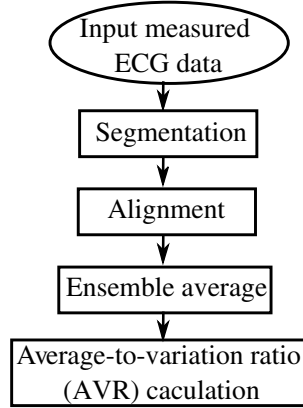


Figure 5. Flowchart demonstrating the procedure used to calculate the average-to-variation ratio (AVR) for the recorded ECG signals.

perform the AVR calculation, where segmentation, alignment, and ensemble averaging of the recorded ECG data were performed. First, the recorded ECG data were segmented into intervals containing a single peak. Second, these intervals were aligned to their peaks and adjusted to have the same length. To make sure the same length of each interval, the peak is centered at 0.4s and a time window of 0.8s centered at the peak is used to extract each interval. Third, the ensemble average of all the aligned intervals S_{avg} was obtained and defined as,

$$S_{avg} = \frac{1}{N} \sum_{i=1}^N S_i \quad (1)$$

where S_i is the ECG signal in each aligned interval; i is the interval number with $1 \leq i \leq N$; and N is the total number of the intervals. The AVR value in each interval AVR_i is defined by the root-mean-square error (RMSE) of the ensemble average S_{avg} over that of the difference between S_{avg} and S_i [25],

$$AVR_i = \frac{\text{RMSE}[S_{avg}]}{\text{RMSE}[S_{avg} - S_i]} \quad (2)$$

To quantify the performance of the fabricated electrodes, the average AVR value AVR_{avg} over all intervals of the recorded ECG signal in decibel is calculated,

$$AVR_{avg} = 20 \log \left(\frac{1}{N} \sum_{i=1}^N AVR_i \right) \quad (3)$$

The AVR values of the recorded heart signals are calculated using Eqs. (1)–(3) after the segmentation and alignment in Matlab and shown in the following section.

3. EXPERIMENTAL RESULTS

Figures 6 and 7 show some examples of the segmented and aligned ECG heart signals in different conditions using fabricated and commercially-available electrodes. Note that the non-bold plots in different colors are the segmented and aligned ECG signals S_i and the plots in bold red are the ensemble average S_{avg} of all the aligned ECG signals using Eq. (1). Fig. 6 presents the segmented and aligned ECG heart signals from one of the ten measurements using circle-shaped electrodes with the same area of 12 cm^2 but different material and conditions. Comparing Figs. 6(a), 6(f), and 6(k) in the sitting condition, a similar performance of the fabricated and commercially-available electrodes is observed. Comparing Figs. 6(e), 6(j), and 6(o) in walking condition with the speed of 3 mph, the performance of the fabricated electrodes is better than that of the commercially-available electrodes. Comparing Figs. 6(a)–6(e) in different conditions, the aligned ECG signals in the walking condition is not as clean as those in the sitting and standing conditions, due to the body movement. As the walking speed increases from 1 to 3 mph, the variation of the aligned ECG signals becomes higher. However, the ensemble average of all the aligned ECG signals in bold red shows clear PQRST waves in different conditions except the result using commercially-available electrodes in the walking condition with the speed of 3 mph shown in Fig. 6(o). Fig. 7 shows the segmented and aligned ECG heart signals from one of the ten measurements using copper electrodes in the sitting condition with different shapes and areas. The segmented and aligned ECG heart signals using copper electrodes with the shape of circle and the area of 12 cm^2 in the sitting condition are shown in Fig. 6(a). Comparing Figs. 7(a), 6(a), and 7(b)

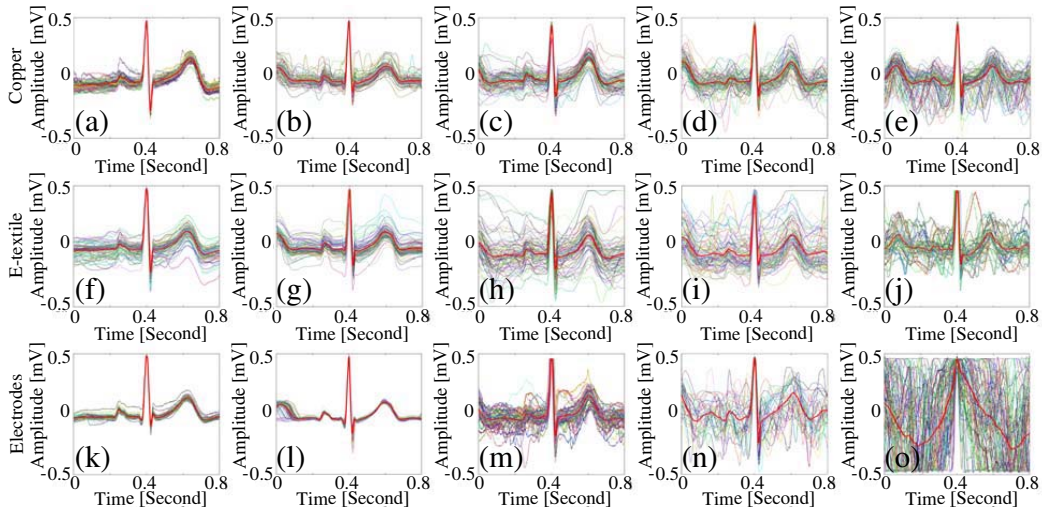


Figure 6. The segmented and aligned ECG heart signals using circle-shaped electrodes with the same area of 12 cm^2 but different material and conditions. (a)–(e) Copper tape. (f)–(j) E-textile. (k)–(o) Commercially-available electrodes. The first column shows the results in the sitting condition. The second column shows the results in the standing condition. The third column shows the results in the walking condition with a speed of 1 mph. The fourth column shows the results in walking condition with a speed of 2 mph. The fifth column shows the results in the walking condition with a speed of 3 mph. The plots in bold red show the ensemble average of the ECG signal.

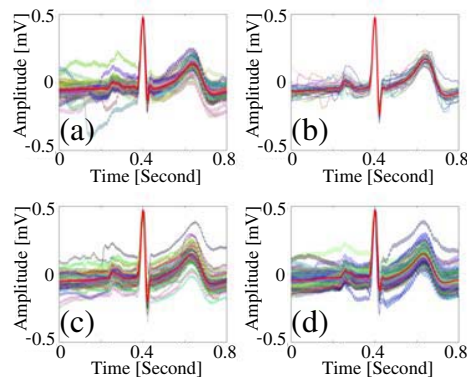


Figure 7. The segmented and aligned ECG heart signals using copper electrodes in the sitting condition with, (a) the shape of circle and the area of 3 cm^2 , (b) the shape of circle and the area of 48 cm^2 , (c) the shape of triangle and the area of 12 cm^2 , (d) the shape of square and the area of 12 cm^2 . The plots in bold red show the ensemble average of the ECG signal.

using the electrodes with different areas, the electrodes with a larger area can provide a cleaner ECG signal. Comparing Figs. 7(c), 6(a), and 7(d) using the electrodes with different shapes, similar results are observed, which is verified by calculating AVR values shown in the following.

Figures 8 and 9 show the calculated AVR values and their averages of the heart ECG signals using Eq. (3) for all ten measurements of the heart ECG signals in different conditions. The commercially-available electrodes and fabricated electrodes with different materials, areas, and shapes are used. The average and variance of the AVR values from all ten measurements in dB are calculated and summarized in Tables 1 and 2 as well. In Fig. 8, it is observed that the AVR values of the heart ECG signals obtained from copper electrodes are similar to those obtained using the commercially-available electrodes. For example, Fig. 8(a) shows that the AVR values are 13.89 dB and 14.91 dB in the sitting condition using the square-shaped copper electrodes with an area of 48 cm^2 and commercially-available electrodes respectively. Comparing the average AVR values using the electrode with the same shape but different areas, the electrode with a larger area provides a higher average AVR value. This shows that the received signal strength is proportional to the electrode area in the sitting and standing conditions. Comparing the average AVR values using the electrode with the same area of 48 cm^2 but different shapes in the standing condition in Fig. 8(b), similar AVR values are obtained, which are 12.49, 12.89, and 12.30 dB using the electrodes with the shape of triangle, circle, and square respectively. This shows that the shape of the electrode has less influence on the received signal strength than does the area of the electrode. Comparing the average AVR values in the sitting and standing conditions with the same electrode area of 3 cm^2 , the standing condition provides a lower AVR value than does the sitting condition. This results from the unwanted movements in the standing condition. In the walking condition, observe that the average AVR values obtained from the copper electrodes are much smaller than those in the sitting and standing conditions. For example, for the copper electrodes with the shape of circle and the area of 48 cm^2 , the average AVR values are 12.20 dB in sitting condition and 12.89 dB in the standing condition, but these values are 2.72, -1.11 , and -4.82 dB in the walking condition with the speed of 1, 2, and 3 mph respectively. The average AVR values obtained from the commercially-available electrodes in the walking condition are even worse, which are -0.54 , -3.32 , and -6.72 dB in Figs. 8(c)–8(e) respectively. This might be caused by the motion artifact between the Ag/AgCl part in the middle of the Ag/AgCl electrode and the skin in the walking condition. The adhesive backing of the Ag/AgCl electrode cannot guarantee the tight contact between the Ag/AgCl part and the skin during walking. In Fig. 8(c), although the copper electrode with the area of 48 cm^2 and triangular shape provides the highest AVR value at the eighth measurement. Comparing the average AVR values using the electrodes with the same shape but different areas, the electrode with the area of 12 cm^2 provides the highest average AVR value. This is different from the sitting and standing conditions, where the electrodes with the area of 48 cm^2 provides the highest average AVR value. This might be caused by the strongest motion artifact when using the electrodes with the largest area in the walking condition.

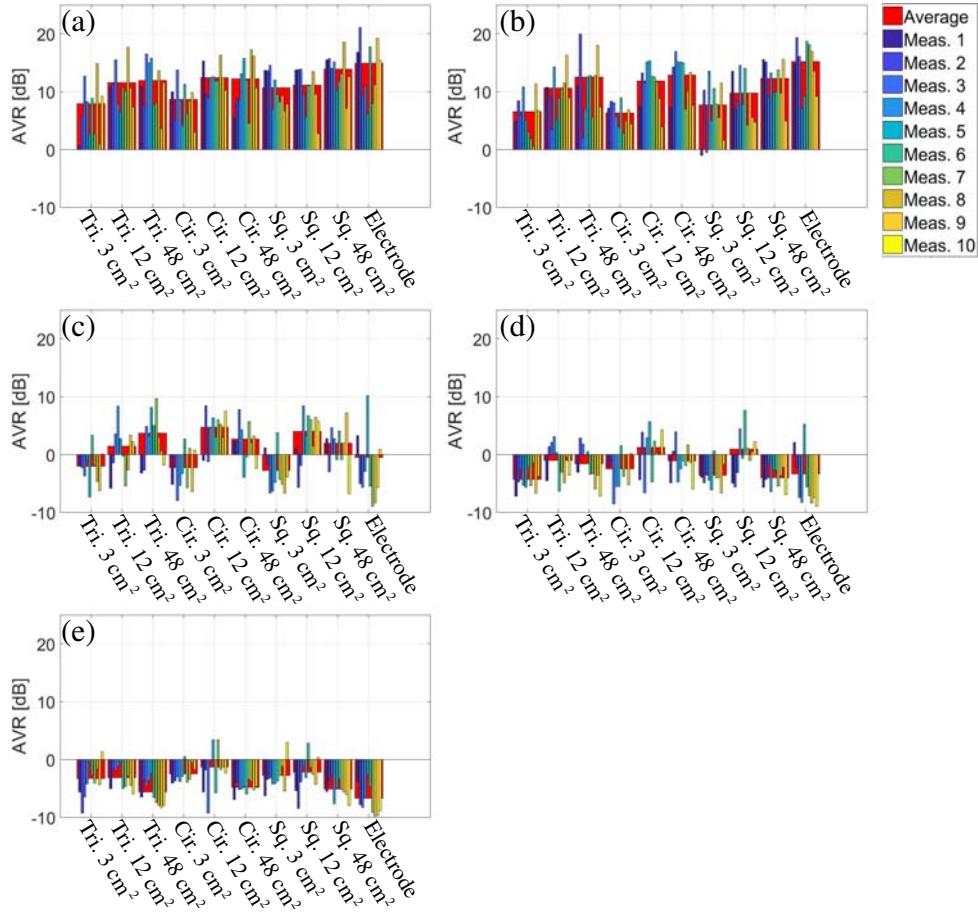


Figure 8. Average-to-variation ratios of the aligned ECG heart signals using copper and commercially-available electrodes in different conditions. The copper electrodes have different shapes and areas. (a) In the sitting condition. (b) In the standing condition. (c) In the walking condition with a speed of 1 mph. (d) In the walking condition with a speed of 2 mph. (e) In the walking condition with a speed of 3 mph.

Although the electrodes with the smallest area of 3 cm^2 have the weakest motion artifact, they cannot capture enough ECG signals, resulting in a lower average AVR value than do the electrodes with the area of 12 cm^2 . Comparing the average AVR values using the electrodes with the same shape and area but different speeds, the higher the speed is, the worse the AVR value is. This results from the higher level of body movement and noise when increasing the walking speed. Comparing the average AVR values in the sitting, standing, and walking conditions, these values might be used to estimate whether the subject is stationary. If the AVR value is smaller than 5 dB, there is a high possibility that the subject is moving. Otherwise, there is a high possibility that the subject is stationary. Comparing AVR variance values of the ten measurements in Table 1, the generally small AVR variance values of the recorded ECG signals measured by the fabricated copper electrodes show that the fabricated copper electrodes have a more stable performance than do the commercially-available electrodes. For example, the AVR variance is 6.74 dB using the copper electrodes with the shape of triangle and area of 3 cm^2 in the sitting condition, which is smaller than 19.94 dB using the commercially-available electrodes.

Table 2 shows that the average AVR values obtained from the e-textile electrodes are generally smaller than those obtained from the copper and commercially-available electrodes. For example, the average AVR values are 10.92, 13.89, and 14.91 dB using the e-textile and copper electrodes with the same shape of square and the same area of 48 cm^2 and commercially-available electrodes in the sitting condition respectively. This might be caused by the lower conductivity in the e-textile electrodes than

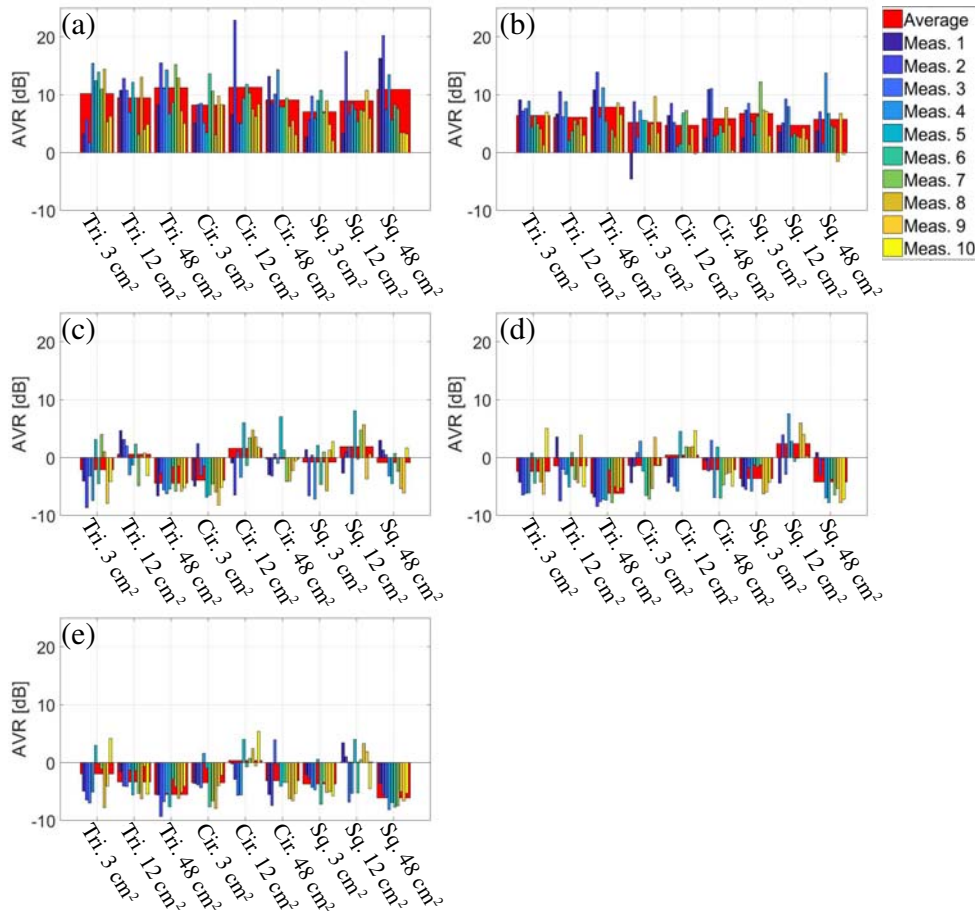


Figure 9. Average-to-variation ratios of the aligned ECG heart signals using e-textile electrodes in different conditions. The copper electrodes have different shapes and areas. (a) In the sitting condition. (b) In the standing condition. (c) In the walking condition with a speed of 1 mph. (d) In the walking condition with a speed of 2 mph. (e) In the walking condition with a speed of 3 mph.

Table 1. AVR average and variance of the aligned ECG heart signals using copper and commercially-available electrodes in different conditions. The copper electrodes have different shapes and areas. The unit is dB.

Condition	Shape	Triangle			Circle			Square			Electrode
	Area [cm ²]	3	12	48	3	12	48	3	12	48	
Sitting	Average	7.95	11.54	11.91	8.66	12.45	12.2	10.7	11.12	13.89	14.91
	Variance	6.74	9.47	10.17	0.94	2.74	11.75	3.22	4.42	9.57	19.94
Standing	Average	6.56	10.62	12.49	6.35	11.83	12.89	7.73	9.76	12.3	15.22
	Variance	-1.91	7.01	17.64	-12.48	5.48	9.58	4.78	6.24	7.21	16.08
Walking, 1 mph	Average	-2.06	1.48	3.71	-2.25	4.73	2.72	-2.74	4.03	2.00	-0.54
	Variance	-21.01	-8.13	-4.17	-18.9	-9.27	-10.6	-18.07	-6.73	-10.77	-2.28
Walking, 2 mph	Average	-4.3	-1.01	-1.57	-2.46	1.24	-1.11	-3.57	0.97	-3.97	-3.32
	Variance	-34.25	-19.18	-19.91	-22.9	-12.17	-19.32	-29.94	-9.71	-34.78	-12.33
Walking, 3 mph	Average	-3.26	-3.12	-5.63	-2.49	-1.32	-4.82	-2.75	-2.18	-5.09	-6.72
	Variance	-24.6	-32.35	-34.89	-33.2	-16.76	-46.77	-23.3	-21.81	-38.27	-33.17

Table 2. AVR average and variance of the aligned ECG heart signals using e-textile electrodes in different conditions. The e-textile electrodes have different shapes and areas. The unit is dB.

Condition	Shape	Triangle			Circle			Square		
	Area [cm ²]	3	12	48	3	12	48	3	12	48
Sitting	Average	10.2	9.48	11.23	8.2	11.3	9.09	7.09	8.96	10.92
	Variance	9.69	2.6	7.83	0.54	22.45	3.37	-5.09	9.53	18.32
Standing	Average	6.38	6.09	7.86	5.23	4.7	5.88	6.75	4.72	5.74
	Variance	-10.69	-7.88	3.39	-5.26	-9.2	-1.65	-3.51	-10.5	2.48
Walking, 1 mph	Average	-2.09	0.57	-4.45	-3.89	1.58	-0.23	-0.76	1.92	-0.9
	Variance	-14.42	-17.51	-33.42	-22.59	-12.56	-12.57	-17.34	-7.8	-19.58
Walking, 2 mph	Average	-2.38	-1.43	-6.15	-1.41	0.41	-2.09	-3.63	2.41	-4.23
	Variance	-15.22	-15.65	-37.04	-17.15	-13.94	-19.72	-31.29	-9.62	-24.32
Walking, 3 mph	Average	-1.98	-3.34	-5.52	-3.46	0.38	-3.14	-3.7	0.09	-6.14
	Variance	-14.99	-30.92	-38.35	-24.53	-14.38	-18.5	-29.81	-14.27	-43.33

that in the copper ones. Similar to the observations from the average AVR values obtained from the copper electrodes, the average AVR values obtained from the e-textile probes increases as the electrode’s area increases and the sitting condition provides better average AVR values than does the standing condition. In the walking condition, similar to the observations from the AVR values obtained from the copper electrodes, the e-textile electrodes with the area of 12 cm² provides the highest average AVR value, which is better than that provided by the commercially-available electrodes. Comparing AVR variance values of the ten measurements, the fabricated e-textile electrodes also generally have a more stable performance than the commercially-available electrodes.

4. CONCLUSIONS

In this paper, we presented experiments of contact ECG heart signal recording using flexible dry electrodes with different materials, shapes, and sizes. Copper and e-textile based dry electrodes were fabricated and used, which were tightly attached on the chest above the heart of a healthy 29-year-old male in each measurement. To achieve a comprehensive performance comparison with commercially-available wet electrodes, ten independent measurements were performed in each condition, such as sitting, standing, and walking. To quantify the performance of the fabricated dry and commercially-available wet electrodes, AVR values of the recorded heart signals were calculated after the segmentation and alignment. The AVR results demonstrated that the size rather than shape of the electrodes impacts their performance. In the sitting and standing conditions, the dry electrodes with a larger size can provide a higher AVR value. In the walking condition, the dry electrodes with an area of 12 cm² provides the highest AVR value. The AVR results also demonstrated that the dry electrodes with an area of 12 cm² had a similar performance to the commercially-available wet electrodes in the sitting and standing conditions and a better performance in the walking condition. These results validated that the proposed flexible dry electrodes can be used as an alternate to the conventional wet electrodes and are more suitable for long-term recording. To further integrate the dry electrodes into underwear, e-textile could be a good candidate due to the washability.

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