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Characterization of Motion Artifacts from the Interfacial Instability of Textile Electrodes and Skin using a Simulated Method

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Abstract

An objective method to evaluate the motion artifacts of textile electrodes was presented using a self-made apparatus. The apparatus simulates skin-electrode mechanical interaction by controlling electrodes moving on a volume conductor with various speed and contact pressure. Three different types of electrodes was characterized and the motion induced electrical noise (E_{ocp}) of a pair of the same structural electrodes were recorded, peak-to-peak of the noise (ΔE_{ocp}) was calculated for evaluating the amplitude of motion artifacts. The results shown that motion artifacts decreased with increased movement speed and contact pressure. For textile electrodes, woven plain structure exhibits the minimum motion artifacts.

Keywords: Electrocardiogram (ECG); Textile Electrodes; Motion Artifacts; Interfacial Instability; Open Circuit Potential (OCP)

1. Introduction

Wearable systems for ubiquitous health monitoring have received much attention in recent years. The prevailing scenario is to integrate electronic devices or sensors into textiles and garments in easy to use, comfortable to wear, and minimally obtrusive fashion [1]. One of the typical examples in wearable healthcare is for Electrocardiogram (ECG) monitoring using wearable electrodes fabricated from textile structures which also called textile electrode, or textrode. These electrodes are flexible, air and moisture permeable, easy integrated in to clothes, suitable for long-term health monitoring application [2].

The state-of-the-art wearable electrodes can acquire good ECG signal in static state while suffered by interferences in dynamic state. The interference, called motion artifacts, mainly attributes to skin-electrode interfacial instability and skin deformation induced noise [3]. In dynamic state, there is skin electrode relative movement which generates streaming potential at the skin-electrode interface. Considering the clothing pressure, skin deformation or stretching occurs which is another main source of motion artifacts. Moreover, textile structural electrodes are flexible which easily deformed by external force from skin-electrode relative movement and compression, thus affecting skin-electrode interfacial contact and stability. Plenty of work has been done on the motion artifacts of traditional gelled metal plate electrode [3-9] which revealed that the skin-gel-electrode streaming potential is in the order of several micro-Volts(μV) much smaller than that from skin deformation induced noise of several milli-volt (mV)[7]. However, for the dry textile electrodes where no gel presented at the skin-electrode interface, the noise level from skin-electrode interfacial instability and influence of textile structures on motion artifacts yet remain unknown which is the main concern of this paper.

Under dynamic state, textile electrode structural deformation, skin deformation and skin-electrode interfacial contact area variation are concurrently making the evaluation of motion artifacts from different noise sources even more complicated. To characterize skin-electrode interfacial noise, one of the approaches is using simulated method to prevent the influence of skin deformation induced noise. For one thing, this can avoid human factors which may cause variations from subject to subject, or within subject over time [10]. For the other, it has the potential to standardize the characterization of wearable electrodes. Westbrook [11] evaluated the quality of textile electrodes using electrochemical impedance spectroscopy by putting textile electrodes into a plastic tube filled with sodium chloride (NaCl) electrolyte. This method is similar to that described in ANSI/AAMIEC12:2000 standard by measuring the impedance of a pair of gelled disposal electrode putting face to face. Beckmann [12] characterized textile electrodes using standardized measurement setups using a simulated skin dummy, the impedance of a pair of electrode with different structures were measured under varied contact pressures. In these studies, the textile electrodes were in static state and characterized using impedance spectroscopy. Whereas, motion artifacts do not necessarily depends on skin-electrode impedance variation [6]. Actually, motion artifacts is the noise superimposed on the measured bioelectric signal, from the electrochemical point of view, which is the open circuit potential (E_{ocp}) of a pair of electrodes. Therefore, we adopted E_{ocp} for direct characterization of the motion artifacts of wearable electrodes.

In this paper, a dynamic evaluation apparatus was developed to characterize electrode-skin motion artifacts from their mechanical interaction. The apparatus comprises three main parts: a simulator to mimic skin-electrode contact, a motion controller to control skin-electrode relative movement and a data acquisition unit to record mechanical and electric signals during experiment. The simulator is the core part of this equipment, which is made from Teflon tube with two pieces of membrane fastened at each end to form a container filled with electric conductive gel. A pair of electrodes contacted and moved on the membrane, open circuit potential (E_{ocp}) of the electrode-gel-electrode cell was simultaneously recorded. The E_{ocp} can be assumed to be the motion artifacts solely from skin-electrode interfacial instability as no skin stretch and deformation induced potential arouse like the measurement carried out on living skin [9]. By comparing E_{ocp} variation of different wearable electrodes, we can evaluate the influence of fabric structures on motion artifacts, thus optimizing fabric structures.

2. Experimental

2.1 Measurement setup

To characterize the motion artifacts of wearable electrode, we developed a dynamic measurement setup which comprises a human skin simulator, an electrode motion controller and a data acquisition unit. The skin simulator, as shown in Fig.1, is the core part of this measurement setup made from Teflon tube (height 92mm, inner diameter 60mm). Two filtration membrane (Millipore, USA, pore size 0.22 μm) fastened at each end of the tube to simulate skin. The tube and two membranes formed a container which was filled with electric conductive gel (Lectron II, USA). The motion controller is assembly of two linear stages (New port, USA) placed in perpendicular directions, driving electrodes moving in a plane along a designed trajectory. The linear stage has a travel range of 50mm with a resolution of 0.1 μm and 100mm/sec of maximum speed. The data acquisition unit comprises a computer, an electrochemical Interface 1252A (Solartron, UK) and a frequency Response Analyzer 1287 (Solartron, UK), an auxiliary signal conditioning modules and two force sensors. The accuracy for the E_{ocp} measurement is as high as 1 μV, and for force detection is 0.1 cN. All measurements were done in an ambient condition of 20 and R.H. 65%.

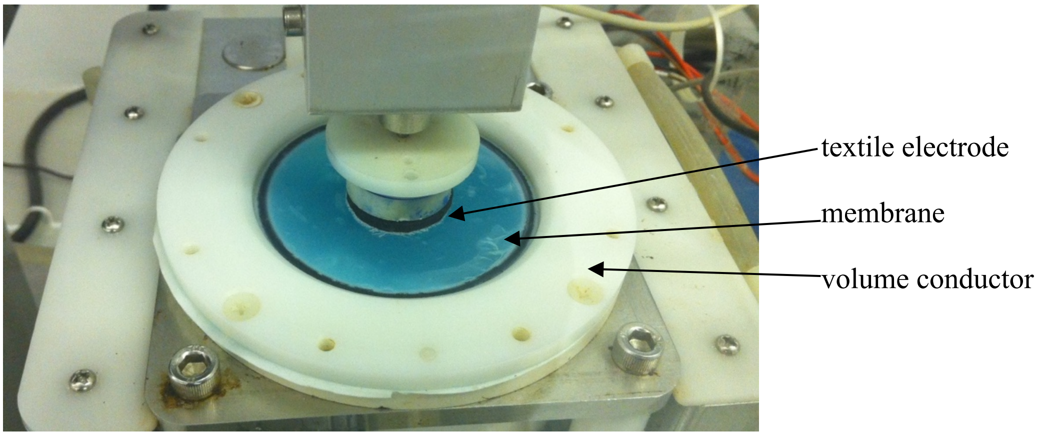

Fig.1. Illustration of electrode testing setup

2.2 Electrode fabrication

As shown in Fig. 2, three kinds of electrodes, two textile electrodes woven and embroidery terry structures, and one commercial metal plate electrode, were prepared in this study. The woven structural electrode were made from commercial silver coated multifilament (140D, 2-ply, 40 filaments) on a sample loom (SL 8900, CCI TECH INC, Taiwan) which has the same weft and warp density of 50 ends per inch. The terry structural electrodes were made on an embroidery machine (TAJIMA, TMCE-61202, TOKAI Industrial sewing machine Co, LTD, Japan) with a terry height of 2mm, ling spacing of 2mm, and stitch width of 0.5mm. The textile electrodes were stuck on a layer of foam substrate (4mm thick) and a snap button was punched through the centre for lead wire connection. For the commercial metal plate electrode, the gel was removed. The diameters of the three electrode types are 30mm, 30mm and 10mm with an effective area of 628 mm^2 , 628 mm^2 , and 78.5 mm^2 , respectively.

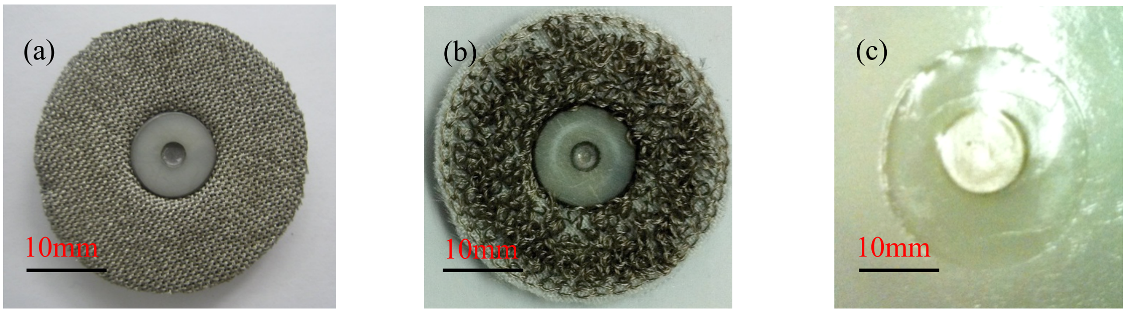

Fig. 2. Comparison of different structural electrodes: (a) woven electrode, (b) embroidery terry electrode and (c) commercial metal plate electrode

2.3 Electrode characterization

The skin-electrode mechanical interaction was defined as horizontal relative movement and vertical compression. To characterize the mechanical interaction induced motion artifacts, textile structures and skin-electrode relative movement speed as well as their contact pressure were the main factors taken into consideration, as listed in Table 1. The electrodes were moved along a circular trajectory (dia. 3mm) passing through the centre of the membrane (Fig.1) under various electrode-membrane contact pressure at various linear velocities according to the experimental parameters in Table 1. Moreover, to study the influence of the skin-electrode compression on motion artifacts, the electrodes were put at the centre of the membrane without cyclic movement while stepwise changing the contact pressure. During these experiments, the open circuit potential E_{ocp} of the upper and lower electrodes was simultaneously measured.

Table 1. Parameters of electrode movement during testing

Sample	Electrode type	Speed(mm/sec)	Pressure(kPa)	Radius(mm)
1-5	woven	1,3,5,7,9	2	3
6-12	woven	1	0.25,0.5,1,2,3,4,5	3
13-17	embroidery	1,3,5,7,9	2	3
18-24	embroidery	1	0.25,0.5,1,2,3,4,5	3
25-29	metal plate	1,3,5,7,9	2	3
30-36	metal plate	1	0.25,0.5,1,2,3,4,5	3

2.3.1 Speed variation

To characterize the motion artifact from in-plane movement, a pair of electrode with a 2KPa preloaded pressure contacting with the membrane to measure the E_{ocp} variation. The lower electrode was stationary while the upper one moved along a circumferential trajectory with a diameter of 3mm at various linear speeds of 1mm/sec, 3mm/sec, 5mm/sec, 7mm/sec and 9mm/sec. During the movement, the electrode-membrane contact pressure and E_{ocp} signals were recorded in the sample rate of 50Hz and 5Hz, respectively, latter of which is limited by the electrochemical instrument.

2.3.2 Pressure variation

Different from the above measurement, the electrode membrane relative movement speed was set to 1mm/sec, while varying their contact pressure under 0.25KPa, 0.5KPa, 1KPa, 2KPa, 3KPa, 4KPa and 5KPa, respectively, for each measurement.

2.3.3 Skin-electrode compression

Apart from the horizontal movement (speed and pressure variation), the electrode contact pressure is another influential factor of the motion artifacts. The lower electrode is stationary with a 2KPa preloaded pressure while the upper one is subjected to stepwise pressure variation in the sequence of 0.25-0.5KPa, 0.5-1KPa, 1-2KPa, 2-3KPa, 3-4KPa, and 4-5KPa, each step held for approximately 20sec.

3. Results and Discussion

Motion artifacts induced by the skin-electrode mechanical interaction was studied using simulated method from horizontal relative movement and perpendicular pressure variation aspects. As the diameter of woven and terry electrodes are different from that of metal plate electrode, to compare the noise level of these electrodes, the noise level of should be normalized to the same electrode area. According to Huigen's investigation [7], the noise level (n) is proportion to reciprocal of square root of the electrode contact area (A) as shown in Eq.1.

$$n \propto \frac{1}{\sqrt{A}} \tag{1}$$

3.1 Influence of electrode pressure

The motion artifacts of different electrode types under different preloaded pressures were shown in Fig.3 (a-c). It is obvious that the motion artifacts decreased with the increased contact pressure because of the stable electrode membrane interfacial contact under higher pressure. As shown in Fig. 3(d), woven structural electrodes have the minimum motion artifacts, while terry structure and commercial metal plate are much higher. The overall trend of motion artifacts decreased with pressure, which may attributed to the enhanced contact stability of electrode and membrane.

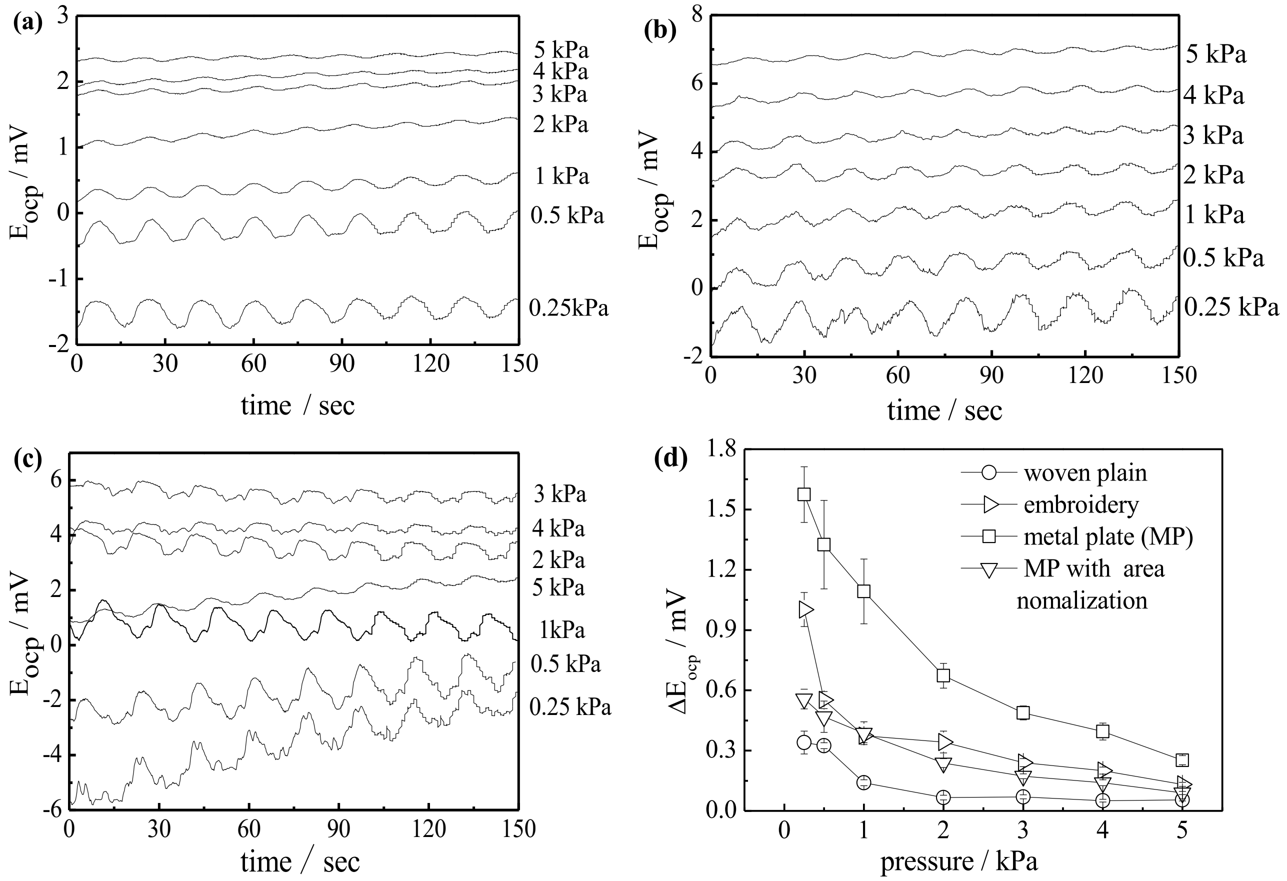

Fig. 3. Motion artifacts of different structural electrodes moving at constant speed under various preload pressures: (a) woven plain, (b) embroidery terry, (c) metal plate (d) comparison of three type electrodes.

3.2 Influence of moving speed

As shown in Fig. 4, E_{ocp} variation of embroidery terry structural electrodes have the maximum variation while woven textile electrode is the minimum, and commercial metal plate electrodes are the intermediate. Motion artifacts of woven electrode are smaller than that of embroidery terry one due to its simple and stable structure, and small contact surface variation during movement. Moreover, E_{ocp} variation of three types of electrode has the same trendy, which is decreased with the increasing movement speed. This can be explained as the interface moisture effect, the quicker speed, the shorter duration of electrodes moved to a specific position, thus the minimum equilibrium potential differences. Ödman S. [6] assumed the electrode movement as a newly applied electrode that needs time for stabilization.

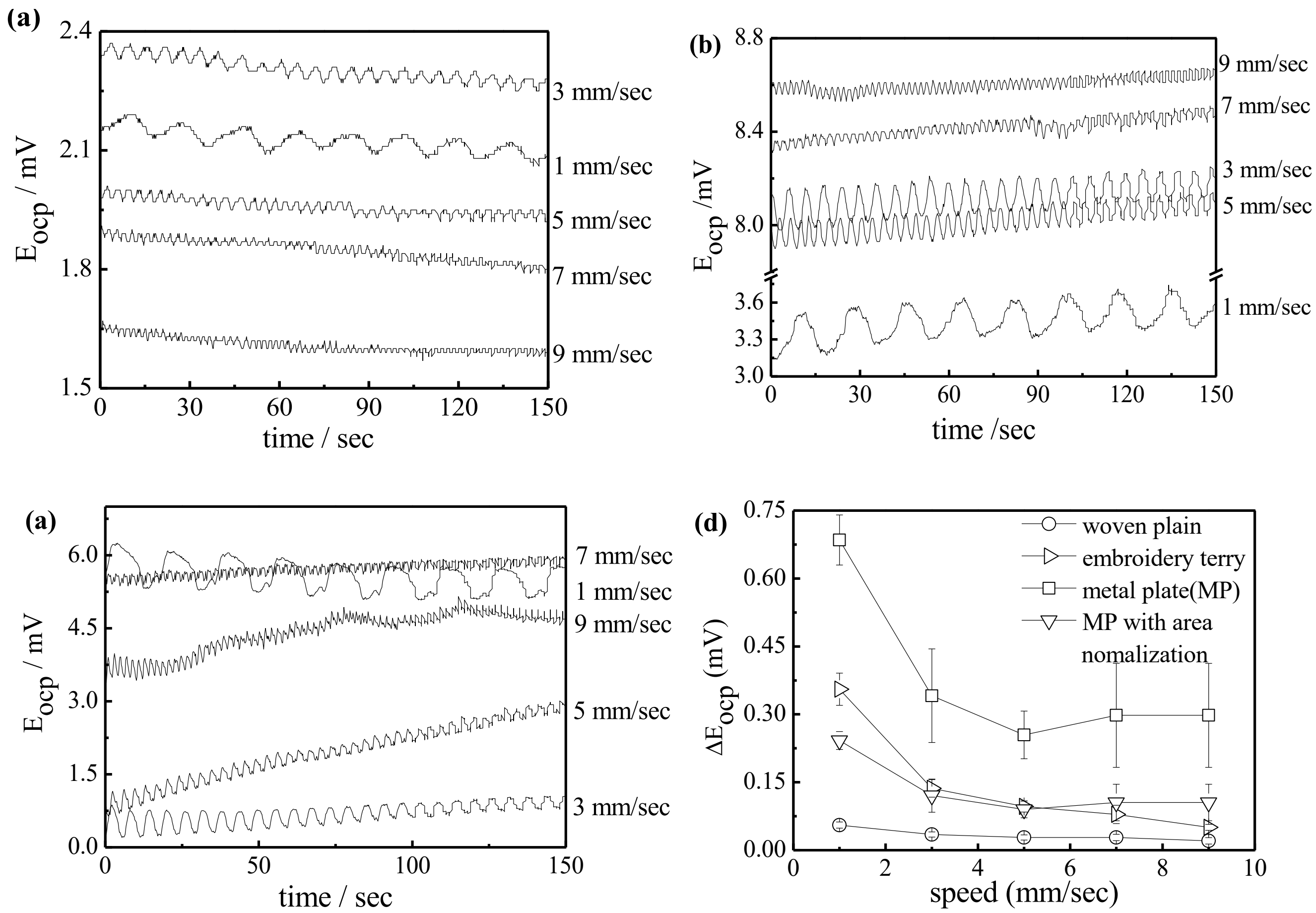

Fig. 4. Motion artifacts of different structural electrodes moving at constant speed under various preload pressures: (a) woven plain, (b) embroidery terry, (c) metal plate (d) comparison of three type electrodes.

3.3 Influence of vertical compression

The instant change of electrode-membrane contact pressure also causes considerable motion artifacts. As shown in Fig. 5, the abrupt shift of E_{ocp} gradually decreased as increased electrode-membrane contact pressure. Terry structural electrodes have the highest E_{ocp} shift while the commercial metal plate has the lowest which could be attributed to the compressive Young's modulus of electrode, the higher modulus, the less influence of pressure on the interfacial contact area. The metal plate electrode has the highest modulus exhibiting no obvious E_{ocp} shift. For the woven electrode, when the electrode contact pressure is higher than 2kPa, the E_{ocp} decreased to a minimum which can be assumed that the interfacial contact came to stable state. Therefore, a pressure higher than 2kPa is recommended for wearable electrodes in practical application.

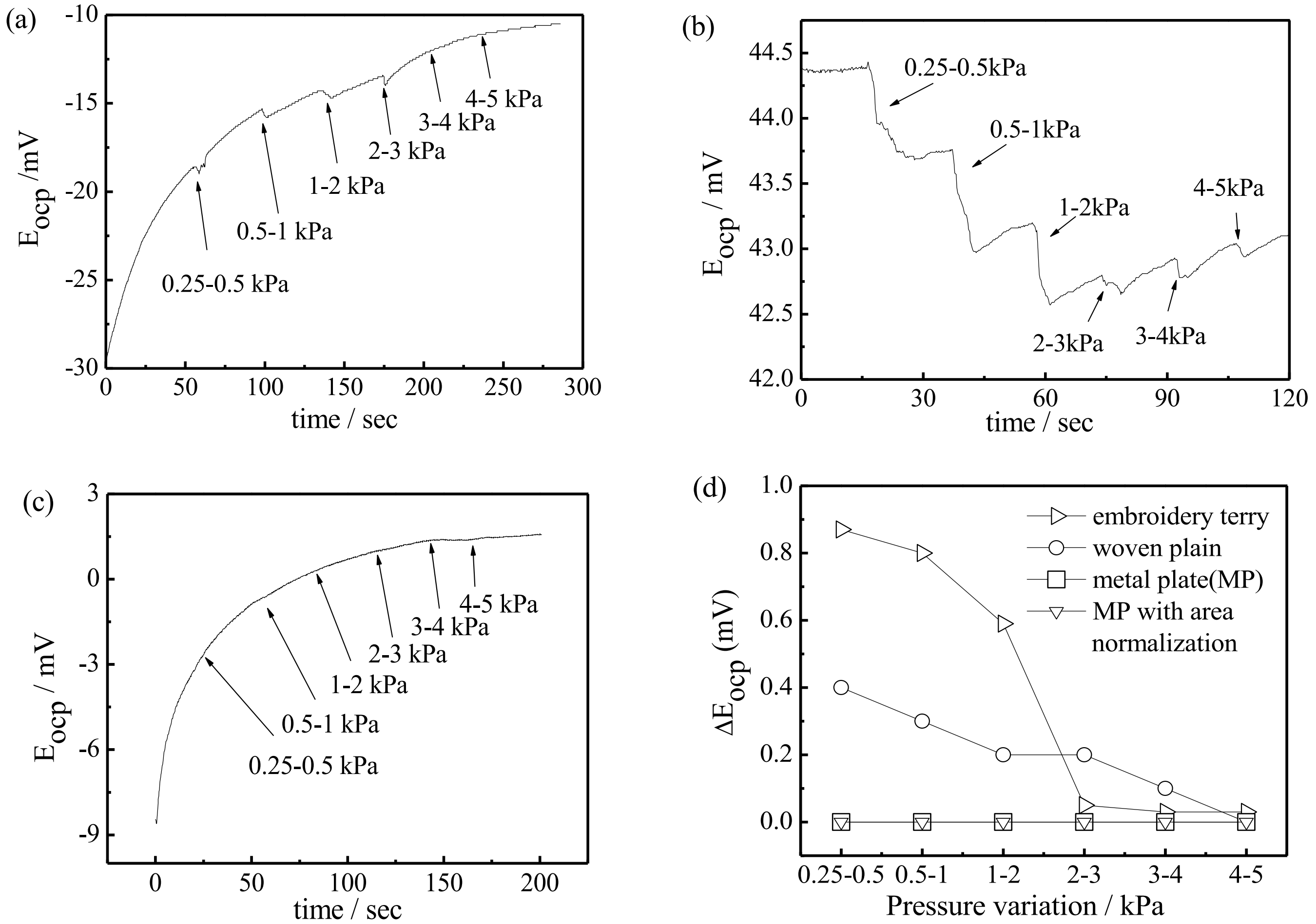

Fig. 5. Motion artifacts of different structural electrodes moving at constant speed under various preload pressures: (a) woven plain, (b) embroidery terry, (c) metal plate (d) comparison of three type electrodes.

3.4 Influence of electrode structures

Textile structures have a significant influence on the motion artifacts. In Fig. 3 and 4, the electrodes moved in the horizontal plane parallel with the membrane under varied contact pressures and moving speeds. The results demonstrated that the woven structural electrodes exhibited the smallest motion artifacts, while the terry structural electrodes were the highest, and the metal plate electrodes were in between. In Fig. 5, the electrode-membrane contact pressure was stepwise increased, inducing obvious motion artifacts for the woven and terry structures. From these results, we can infer that textile electrodes made from simpler and stiffer textile structures may result in a better dynamic performance in terms of motion artifacts.

4. Conclusion

In this paper, the motion artifacts of textile electrodes induced by skin electrode mechanical interaction were evaluated using simulated method. The mechanical interaction was defined as a horizontal relative movement and a vertical compression of the electrode versus skin. The motion artifacts, indicated by the open circuit potential (E_{ocp}) of a pair of electrode, which decreased with the increased electrode-skin contact pressure and movement speed. Abrupt variation of electrode-skin contact pressure also caused significant motion artifacts which decreased as the pressure increased and came to a stable state when pressure higher than 2kPa. Textile structures were also an important contributor to the motion artifacts suggesting that the simpler and stiffer textile structural electrodes have a stable electrode-skin contact, thus introducing less motion artifacts in the dynamic state. To lower the motion artifacts of wearable electrodes, the interfacial stability of electrode and skin should be enhance by carefully designing of electrode structure and properly setting the electrode-skin contact pressure. However, there are properties differences between membrane and real human skin, a comparison study will be carried out to verify the effectiveness of using simulated method.

5. Acknowledgement

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