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Development of Noise Resistant Hybrid Capacitive-Resistive Electrodes for Wearable Robotics, Computing and Welfare*

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Abstract—**Myoelectrical signals have many applications in medical, sports, wearable robotics and computing fields. Wet electrodes are widely used to acquire these signals. In contrast, dry contact electrodes and noncontact capacitive coupling electrodes have been developed. However, their use has several limitations. In this research, we developed a hybrid electrode that is capable of both capacitive and resistive recordings by optimizing the sensor input impedance value using a new electrode noise model that contained noise sources. We extend this design so that noise originated during real usage, such as motion artifacts and noise from electric motors is also measured and removed from the sensor output. In experiments, noise analysis and experiments were performed by measuring myoelectrical signals from both upper and lower limbs in realistic situations, including weight lifting, robot arm control, and walking on a treadmill. As the results, we verified that our electrodes were capable of bioelectrical measurements at noise levels comparable to wet electrodes in realistic situations and with high correlation coefficients between both types of sensors.**

I. Introduction

Bioelectrical signals generated by muscle activity, known as myoelectricity, have become an important source of information about movement intention. Myoelectrical signals have been useful for interfacing with physically assistive devices, such as the Robot Suit HAL [1-3], and prosthetic limbs [4-5]. Applications on other areas of human life, such as entertainment industry and virtual reality are also gathering attention [6-7]. However, for such fields, high usability is a requirement alongside high performance.

Traditionally, wet electrodes have been widely used to perform myoelectrical measurements. Because the measurements rely on a passive and resistive electrical contact point, using wet electrodes has major drawbacks such as the requirement for skin preparation and the use of conductive gels [8]. Dry resistive electrodes have been developed to increase sensor performance and usability [9-10]. The dry electrodes rely on active resistive contact with the user's skin surface. Active sensing eliminates the need to use the conductive gels and the problems associated with its use. However, skin preparations such as body hair removal and cleaning may be required because constant electromechanical skin contact is still required for bioelectrical sensing. In order to eliminate this requirement, noncontact electrodes that are capable of achieving capacitive coupling between the electrode lead and the user's skin have been proposed [11-15]. However, ultra-high input impedance is required. Ultra-high impedance input is highly susceptible to any electrostatic noise that originates from the surroundings. Therefore, robust shielding, isolation, and current leakage prevention techniques are mandatory to reduce the noise. Furthermore, complex low noise bootstrapping techniques are necessary to avoid drift due to the bias current from the input. These disadvantages make capacitive electrodes larger, noisier, and more expensive than conventional electrodes.

In order to solve the problems of the previous bioelectrical measurement technologies, we focused in combining the properties of both dry and noncontact electrodes in to a new hybrid resistive-capacitive electrode by optimizing its input impedance so that it is sufficiently high to record bioelectrical signals but low enough to reject external electrostatic noise [16]. However, previous studies consisted of only proof-of-concept basic experiments performed at ideal conditions. Noise from real life situations such as motion artifacts or near high-power devices such as electrical motors are still an issue [13]. In order to solve these problems, the sensor must be designed not only to sensitively measure bioelectrical signals but also to sense and subtract external electrostatic noise from the sensor output.

The aim of this study is to develop a novel hybrid resistive-capacitive electrode using an original sensor based on a circuit model using optimized input impedance for bioelectrical signals while also measuring high frequency noise and removing it from the sensor output. In this study, we focused on a novel extension to our bioelectrical measurement model [16] by actively measuring electrostatic noise and canceling it. This new model allowed us to develop a new electrode design with two inputs, one for electrostatic noise and one for bioelectrical signals, at different input impedance settings which are locally processed using analog circuits. Noise analysis and myoelectricity measurements on lower and upper limbs showed that our electrode maintained a low noise level that was comparable to the noise level maintained by commercially available wet electrodes on both resistive and capacitive modes.

II. Materials and Methods

A. Measurement Principles

Biolectrical recordings are performed throughout active resistive contact with the skin when the electrodes are capable

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of electromechanical contact(resistive mode). In the case of poor electromechanical contact conditions, the electrodes measure bioelectrical signals by capacitive coupling with the skin(capacitive mode). The model for our hybrid electrodes contains two built in sensing leads, one for the bioelectrical signals and one for electrostatic noise. The sensor output is given as the difference of potential of both sensing leads as

$$V_{out} = V_{in} - V_{in\_N} \tag{1}$$

where V_{out} is the sensor output, V_{in} is the bioelectrical signal with noise and V_{in_N} is noise originated from motion artifacts or pulses from nearby electrical devices. Figure 1 shows the equivalent circuit when the electrodes are in use. This model also includes noise from capacitive sources as

$$V_{IN} = \frac{R_c}{Z_{nc}} V_{nc} + \frac{R_c}{Z_{nsei}} V_{nsei} + \frac{R_c}{Z_{sei}} V_{BES} \tag{2}$$

where V_{BES} is the bioelectrical signal voltage, V_{nsei} is the total noise source voltage at the skin-electrode surface, V_{nc} is the total noise source voltage on the electrode board, Z_{sei} is the skin-electrode interface impedance, R_c is the electrode input impedance, i.e., the input impedance of the bioelectrical sensing lead, Z_{nsei} is the noise input impedance at the skin-electrode interface, and Z_{nc} is the noise input impedance on the electrode board. This noise can be significant if the electrodes are in capacitive mode. However it can be minimized when the sensor input impedance is optimal. Based on our previous studies [16], we define the input impedance optimal when it is just large enough to allow the sensor electrode to capacitively sense bioelectrical signals. With these settings the sensor input impedance is low enough to reject low frequency capacitive noise signals from the environment. Optimal input impedance is calculated using

$$R_c = \frac{V_{IN}}{V_{BES}} \cdot \frac{d}{\varepsilon_r \varepsilon_0 A 2\pi f} \tag{3}$$

where ε_0 is the dielectric constant in vacuum, ε_r is the relative dielectric constant to the material, A is the electrode lead sensing area nearest to the skin, f is the frequency of the target signal and d is the distance between the skin and the electrode lead.

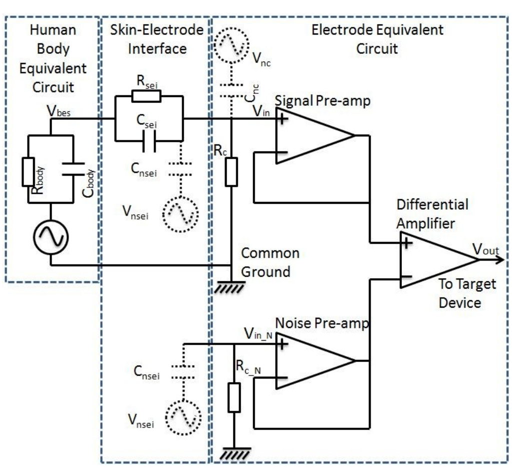

Figure 1. Electrode equivalent circuit

Similar equations are used when calculating the input impedance R_{c_N} of the electrostatic noise electrode lead, but in this case, designing the lead so it can sense only high frequency noise signals over bioelectrical and low frequency noise signals.

B. Developed Hardware and Noise Evaluation

Based on the proposed electrode model and assuming a maximum 3 mm distance between the electrode and the skin, a circular electrode lead with 38mm diameter and signal input impedance of 1 TΩ was developed. Furthermore, in similar fashion the noise electrode lead is designed. Under these conditions a 1 mm thick ring shaped electrode lead with outer radius of 40 mm is designed. Noise input impedance R_{c_N} is also set to 1 MΩ, so that only noise signals with frequency above the myoelectrical frequency spectrum are measured. In resistive contact mode the area of the leads has little effect on the input impedance and low input impedance contact are enough to measure bioelectrical signal. Because of that the noise sensing lead is electrically isolated using a thin layer of plastic coating. Without the coating, in resistive contact mode, very similar bioelectrical signals would be collected by both the bioelectrical and noise sensing leads, canceling each other during the differential preamplifier stage at the electrode. A High Pass Filter circuit is also implemented by using traditional circuits in order to eliminate undesirable offset voltages that can appear due to the difference in potential between both electrode sensing leads. Furthermore, back-to-back diodes are also attached to the leads in order to reduce the effects from input bias current.

In order to further increase sensor robustness, shielding was implemented as shown in Figure 2 by making using of inner layers of the sensor printed circuit board, in which the electronic components as well as most of the circuit pattern is located in the component layer and the sensing leads in the solder layer. The assembled electrode is shown in Figure 3.

The developed electrode data recording and evaluation system is shown in Figure 2, and it includes three stages. In the first stage, a second instrumentation amplifier receives analog

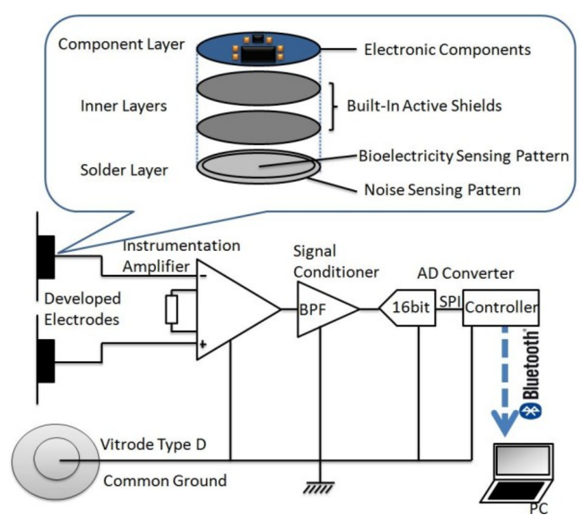

Figure 2. Measurement system diagram

signals from two electrodes and outputs the amplified difference between them. The second stage is responsible for conditioning the signal for the AD converter. The final stage involved a 16-bit AD converter connected via an SPI channel to a microcontroller. Signal sampling was performed at 1 kHz. Data was transferred from the controller to a laptop computer via a Bluetooth connection. This system is compatible with the hybrid electrodes and the commercially available Vitrode(Nihonkohden, Japan) wet electrodes for simultaneous comparative recordings. The common ground was connected to a clean exposed body area of the user via a stainless steel plate. Each sensor was connected to the system using a 1 meter long cable. Noise frequency spectrum measurement experiments were performed for both resistive and capacitive modes using this system by placing two electrodes face to face on differential input.

C. Upper Limb Myoelectrical Measurement

Lifting objects and moving the arms are important actions when using wearable robotic devices [1-2]. In this study we evaluate the performance of our enhanced hybrid electrodes through a two-part experiment. First part is defined by measuring myoelectrical signals when lifting up and letting down various weights and second part is defined by performing robot arm control using myoelectrical signals.

For the first part of the experiment, myoelectrical signal measurements are performed under various loads. The participant leaves his arm at rest for 5 seconds, slowly starts lifting the load for 5 seconds and then slowly let the load down for another 5 seconds until the arm returns to rest position for the final 5 seconds. Loads of 2.5 kg, 5.0 kg, 7.5 kg and 10 kg were used in this part of the experiment. Simultaneous measurements on both resistive and capacitive mode as well as using standard Vitrode wet electrodes were performed. For both experiments the hybrid electrodes were attached to the biceps of the participant as shown in Figure 4. Methods for attaching the Vitrode wet electrodes and the developed hybrid electrode in both resistive and capacitive modes are shown in Figure 5. The ground electrode was attached to the abdomen of the participant. Electrodes in capacitive mode were separated from the skin through a 1mm cotton shirt. Correlation coefficients between data collected from wet electrodes and hybrid electrodes in resistive and capacitive modes are calculated using Pearson's calculation method.

The second part of the experiment verifies the operation of the hybrid electrodes near electrical appliances by performing simple robot arm control experiment. While leaving the arm at rest, the robotic arm(Jaco by Kinova, Canada) also stayed at a resting position. By lifting the arm in to a 45-degree position, the myoelectrical signals from the biceps switch on the robotic arm, also rotating it 45-degree. Each movement was repeated two times for 10 seconds. The participant's arm was in contact with the robotic arm through the entire experiment. Electrodes were placed in capacitive mode over the arm similarly to the previous weight lifting experiment. Only capacitive mode was measured as it was the weakest to noise and the high correlation coefficient with wet electrodes was confirmed using the results from the first part of the experiment.

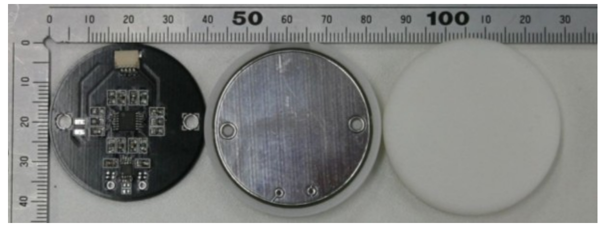

Figure 3. Developed electrodes - Circuit board, sensing lead and case

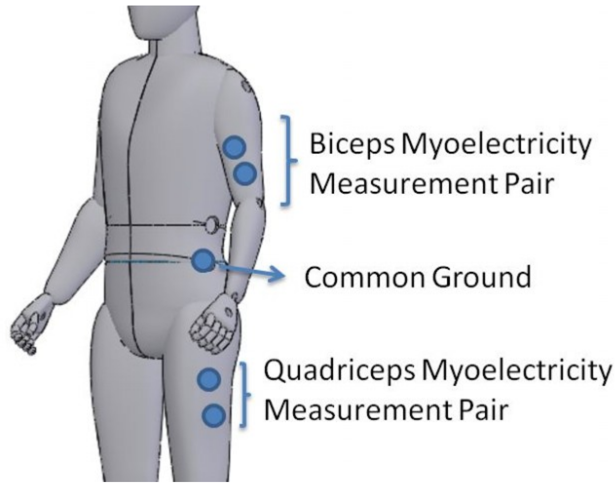

Figure 4. Myoelectrical signal measurement areas used in this study

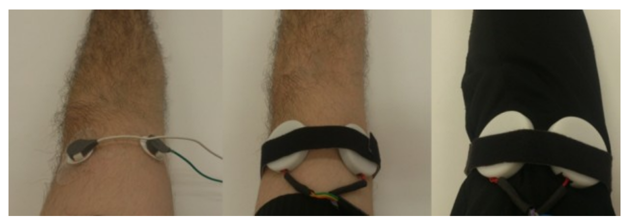

Figure 5. Electrode placement methods: standard vitrode, hybrid electrode resistive mode, hybrid electrode capacitive mode

D. Lower Limb Myoelectrical Measurement

Measurement of myoelectrical signals while walking is a fundamental procedure in lower limb to evaluate walking ability accurately in rehabilitation treatments [3]. In this study we evaluate the performance of our enhanced hybrid electrodes during walking by measuring myoelectrical signals from the quadriceps when the participant walks on a treadmill. The participant walks at a constant speed of 1.2 m/s on a treadmill for a period of 20 seconds. The hybrid electrodes were attached to the quadriceps of the participant as shown in Figure 4. The ground electrode was attached to the abdomen of the participant. Simultaneous measurements on both resistive and capacitive mode were performed. Electrodes in capacitive mode were separated from the skin through a 2.2 mm jeans pants. The correlation coefficient between data sets acquired from both resistive and capacitive modes was calculated.

III. RESULTS

A. Noise Evaluation Results

The noise spectrum in the 1-500 Hz band is shown in Figure 6. The results show that the maximum noise is of 11

$\mu V/Hz^{1/2}$, which happens in capacitive modes at lower frequencies. As myoelectrical signals are in the order of 100-1000 μV and commonly used signals oscillate in the 30-500 Hz band [17], the results show that our enhanced hybrid electrodes are reliable enough for myoelectrical measurements.

B. Upper Lim Myoelectrical Measurement

The recorded experiment data for the bioelectrical signal measurement under variable load part of the experiment is shown in Figure 7. From the results the correlation coefficient between resistive mode and conventional wet electrode mode was of 0.98. The correlation coefficient between capacitive mode and wet electrode was of 0.92. It is important to notice that even though there was constant movement during the period 5-15 s, no motion artifacts were observed in any of the trials with any load. The relatively high myoelectrical signal output observed during the seconds 5 to 7 in all the data sets is the due to the extra power required to surpass the inertia of lifting the load from complete rest.

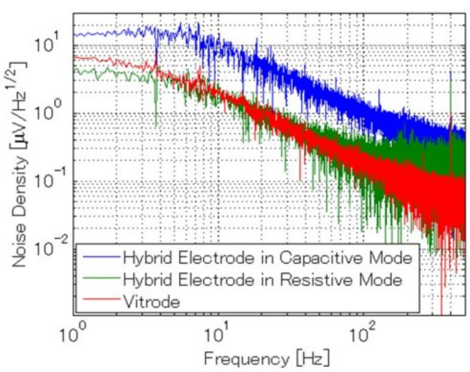

Figure 6. Electrode noise frequency spectrum

The high correlation coefficient between the hybrid electrode in capacitive mode and wet electrodes suggested that we could use the hybrid electrode for the robot control. Therefore the second part of the experiment was performed using only the hybrid electrode in capacitive mode. The recorded experiment data for the robot arm control experiment is shown in Figure 8. The arm weight was enough to stimulate the biceps and create a signal strong enough to be used as in a simple trigger algorithm. Moreover, the presence of an electrical motor near the electrodes did not interfere with its functionality and no noise was observed.

C. Lower Limb Myoelectrical Measurement

The recorded experiment data for the treadmill walking experiment is shown in Figure 9. The results showed constant myoelectrical activity in the quadriceps suggesting continuous load. In particular, during the walking process, the load is the biggest when there is contact of the leg with the floor. From the results we also can observe that the myoelectrical data collected by the enhanced hybrid electrode in both resistive and capacitive mode is mostly overlapping, with a calculated correlation coefficient of 0.76. No visible motion artifacts from leg movements nor electrostatic noise from the treadmill were observed.

IV. DISCUSSION

One of the key aspects and the breakthrough point of this paper is the implementation of the novel dual signal lead system with a differential preamplifier unit built in the electrode. Comparing to previous studies from other groups [12-15] as well as our own [16], this breakthrough point is better design choice than applying an analog or digital Low Pass Filter during signal conditioning because it removes a

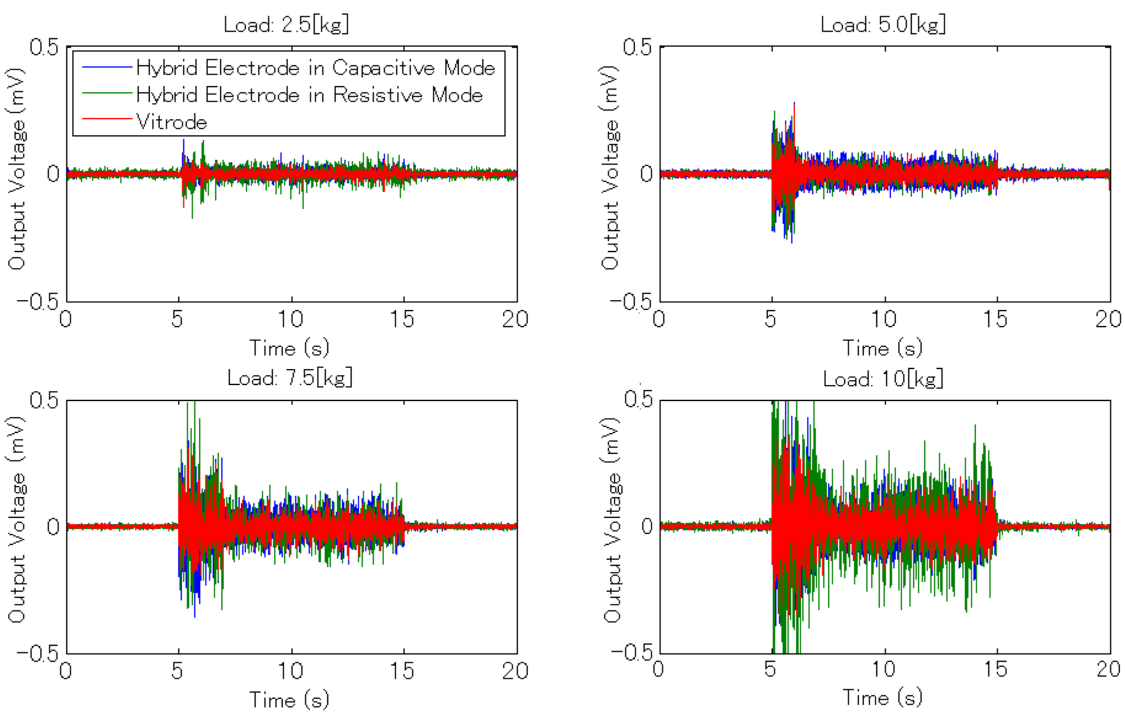

Figure 7. Myoelectrical signals from biceps while lifting up(5s<t<10s) and letting down(10s<t<15s) different loads and at rest

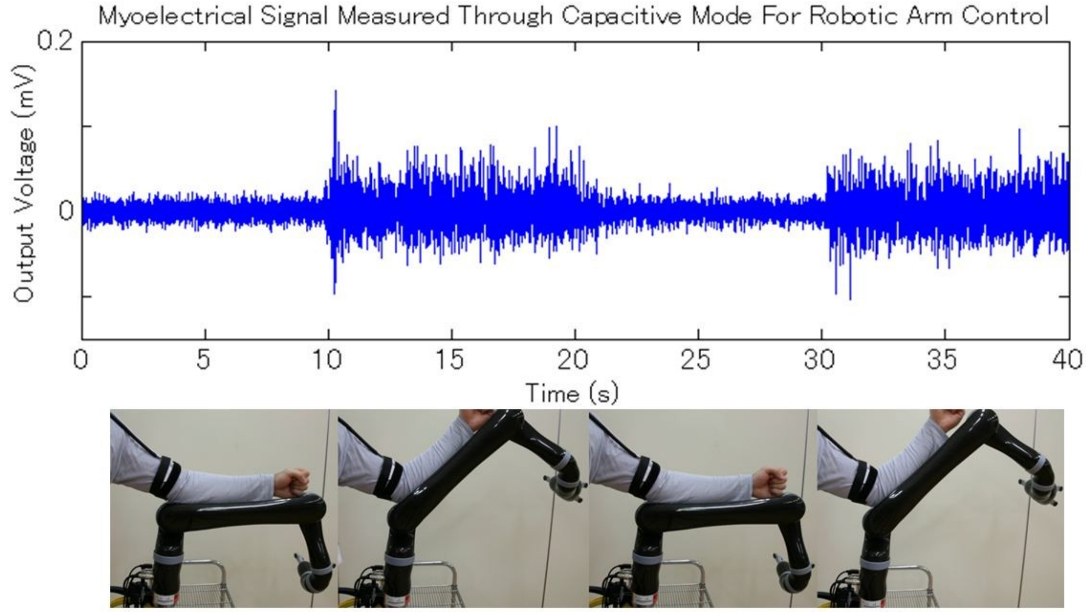

Figure 8. Robot arm movement control experiment using biceps myoelectrical signal measurement

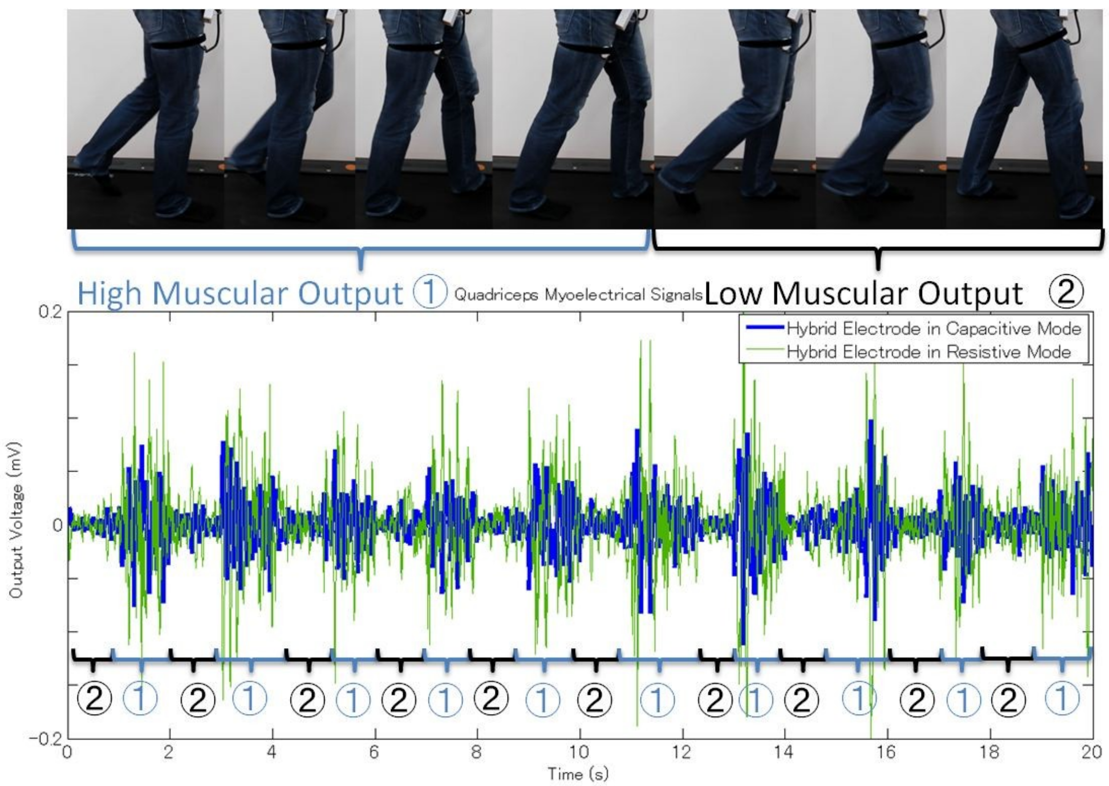

Figure 9. Quadriceps myoelectrical signal measurement results when walking

significant amount of noise before the electrical signal enters our system, avoiding problems caused by the limits on operational amplifiers power supply as well as signal distortion and delays from the filters.

The comparative experiments between our electrodes in both resistive and capacitive mode and standard wet electrodes have shown that our electrodes were capable of measuring myoelectrical signals under conditions simulating real world environments. Measurements performed under the presence of movement and active electromechanical devices nearby matched expected clear recordings that match known phenomena. Our noise frequency analysis shows that our hybrid electrodes have a noise level below 11 $\mu V/Hz^{1/2}$, performing at comparable levels to commercially available electrodes as well as other studies [15]. Furthermore the comparison experiment with commercial electrodes results from Figure 7 and the high correlation coefficient validate the effectiveness of our electrodes.

The single board design which integrates the circuitry, shielding and sensing leads in a single printed circuit board allowed us to make a sensor with 4 mm thickness, which is less than half systems developed in other studies [12-16]. With further miniaturization of electronic components and the use of flexible printed circuit boards, more user friendly sensors can be developed for wearable computing and robotic applications.

In this paper, we used a single conventional electrode made of stainless steel in order to create a robust ground between the user and the electronic system. In order to maximize the usability of the system, we suggest that while designing a wearable robotics or computing system, ground connection should be guaranteed by developing a mechanism in which the user is always in contact with a conductive grounded area of the system.

Myoelectrical signals are used extensively on rehabilitation both as a diagnosis, evaluation tool and as a method for interfacing with assistive devices. Rehabilitation in particular is a medical treatment where user enthusiasm is important, and one of the key factors in maintain enthusiasm is keeping the treatment as accessible as possible, including having an intuitive user interface. The hybrid electrodes developed in this paper using the extended electrode and noise model from Figure 2 are prototype sensors that are capable of measuring bioelectrical signals, regardless of skin contact conditions from both upper and lower limbs while performing movements near electromechanical equipments. This breakthrough is a step towards the prolonged monitoring of bioelectrical signals in a clinical and home environments necessary in rehabilitation treatments. Features such as being able to register myoelectrical signals over clothing, quick sensor placement and being able to using sensors for very long periods of time without signal degradation from sweat and conductive substrate degradation greatly contribute to the increase of usability. Evaluation of the effects that the increased usability have on the total treatment through clinical trials is necessary. Furthermore evaluation of reliability and wearability over long periods of time, such as an entire day or week, is also critical for future medical use as well as for sports and entertainment applications.

V. CONCLUSION

In this study, we developed a novel hybrid resistive-capacitive electrode using an original sensor based on an model using optimized input impedance for bioelectrical signals while also measuring high frequency noise and removing it from the sensor output. Noise analysis and myoelectricity measurements on lower and upper limbs showed that our electrode maintained a low noise characteristic and bioelectrical sensing performance that was comparable to commercially available wet electrodes.

In future studies, we intend to further increase the accuracy of our electrode model and expand the design to specific applications such as exoskeleton control and virtual reality in the fields of rehabilitation, sports and entertainment. Our sensors help increase the usability and reliability of bioelectrical interfaces and promote the popularization of medical and wearable devices in daily life.

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