Using Thin-Film Piezoelectret to Detect Tactile and Slip Signals for Restoring Sensation of Prosthetic Hands

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***Abstract*— Most of the currently available prosthetic hands do not have a proper sensation of touching and slipping. Thus it is not easy for arm amputees to grasp objects properly only with an assistance of visual feedback. In this pilot work, a sensor based on thin-film piezoelectret was used to detect the possible tactile and slip information of a prosthetic hand. The piezoelectret sensor is flexible and is able to be bended, and therefore it could be properly mounted on the surface of prosthetic finger. Our preliminary results demonstrated that both the tactile and slip information could be acquired with the same sensor unit. For a grasp without slippage, the tactile signal was usually a single large peak, whereas the slip signal was a series of vibrations in a small range. Thus these two types of signals could be easily separated based on their different characteristics. This study suggested that by using thin-film piezoelectret sensor, a primary control with involuntary feedback might be achieved for the present prosthetic hands. More studies would be required on the detailed signal processing and control strategy for the restoration of sensation function in prosthetic hands.**

I. Introduction

Prosthetic hand is a very useful tool for arm amputees to partly restore hand functions. The surface electromyographic (EMG) signals recorded from the muscles of residual limbs [1–8] have been widely applied for prosthesis control, and several primary products of myoelectric prosthetic hands are available on the market for a few years. Currently, most of the commercially available myoelectric prosthetic hands are operated only with an assistance of visual feedback. As an example, when a user wants to grasp an object with a prosthetic hand, he/she firstly perform the hand-closing by the EMG signals from residual-muscle contraction. Then he/she would stop the hand-closing when observing with eyes that the prosthetic hand holds the object. In this way, the user would not have any sensation on whether the prosthetic hand has already grasped the object properly or not, and he/she might not make the right judgment every time when performing hand movements only with a visual feedback. In addition, without tactile and slip sensation in prosthetic hands, it would be very difficult to adjust the grasp force to a proper strength. As a result, it is possible to grasp too heavily that the object may be deformed or damaged, or too lightly that the object will fall from the hand. When the user observes that the object is slipping from prosthetic hand, his/her brain may send a motor command signal to further generate EMG signals for more grasp force to stop the slipping. It is obvious that this "visual feedback – brain reaction – EMG generation – motor driving – grasp-force adjustment" procedure, as illustrated in Fig. 1, will take some time and therefore it would be difficult to operate a myoelectric prosthetic hand to fulfill daily activities as a real hand with tactile and slip sensations.

In humans, object touching and slipping are experienced by nervous system through detecting the acting force and micro-vibrations at the contact surface with glabrous skin receptors [9–10]; in prosthetic hands, the possible way to create tactile and slip sensation and to realize an involuntary feedback shown in Fig. 1 is building a sensory system based on various sensory technologies. Tura et al. [11] designed a system based on a force-sensing resistor (FSR) for a upper limb prosthesis, in which the FSR was only used to control the grip strength on objects, and the slipping of the object from the grip was handled with an optical sensor. Kyberd et al. [12] developed a hand prosthesis with hierarchical grip control, where the contact information was gained by a FSR, but the slip signal was detected by means of miniature microphones because the vibration would be caused during the slipping. Another system was suggested by Mingrino et al. [13], which comprised two different sensing elements: a FSR-based force sensor was used to detect both normal and shear forces, and a dynamic sensor was applied to detect vibration based on a piezoelectric polymer film of polyvinylidene fluoride (PVDF). Noda et al. [14] proposed a tactile sensor with standing piezoresistive cantilever array, which could detect the directions and magnitudes of the shear stress applied on its surface. Wisitsoraat et al. [15] reported a thin-film based piezoresistive MEMS tactile sensor with optimized sensitivity for displacement and force sensing. Schmidt et al. [16] also presented a tactile sensor for dexterous grasping, which consisted of a capacitive-sensor array. Besides, based on the

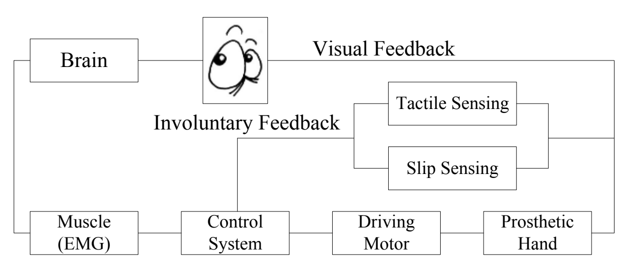

Figure 1. Control of a myoelectric prosthetic hand by visual feedback and involuntary feedback with sensory technologies.

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photoelectric technology, Shang et al. [17] studied a slip sensor to detect micro-vibrations. Yamada et al. [18] illustrated an artificial elastic finger skin which had ridges at the surface to divide the stick/slip area, and the slippage of the ridge could be detected. Hashimoto et al. [19] built a tactile sensor with a silicone rubber cap that had a cavity full of incompressible fluid, where the contract force was transferred by the fluid to a semiconductor pressure gage. Curcie et al. [20] used myo-pneumatic sensors to measure three-dimensional mechanical dynamics, and also developed a linear filter to decode the finger commands. Wang et al. [21] applied a linkage to connect the thumb and finger of a prosthetic hand, and the grasp force was achieved by measuring the force acting upon the linkage with strain gauges.

As reviewed, possible tactile and/or slip sensation of prosthetic hands may be realized by means of different sensory technologies. However, most of the sensory systems were usually complicated in structure and/or had relatively high cost. In addition, some methods used two different technologies for tactile and slip sensation respectively, e.g. FSR for touching and optical sensor for slipping, which further increased the complexity of the system. As a result, almost all the currently available prosthetic hands are still lack of tactile and slip sensation functions.

Recently, the piezoelectret, a new kind of piezoelectric material, was introduced based on thin-film polymer foams [22–25]. It is morphologically a polymer film with gas-filled voids inside, as depicted in Fig. 2, where bipolar charges are stored separately in the voids to form a permanent dipole moment, and compensating charges are subsequently generated on the outer electrodes. Once a piezoelectret is compressed by an applied force, its dipole moment density is varied, resulting in a change of the compensating charge. Therefore, the mechanical signal would be converted into electric signal as voltage or charges. It should be noted that the piezoelectrets only generate charges upon the force variation, and a static force will not result in any charge generation since no structure deformation occurs [22–23]. Most of the current piezoelectrets are based on thin polypropylene films with a thickness from a few dozen to hundred micrometers. They have strong piezoelectric response with d_{33} up to 600 pC/N, which is more than ten times larger than that of PVDF. In addition, piezoelectrets are flexible, light-weight, and low-cost. The polymer-based characteristics make the piezoelectret sensors very suitable for embedding on artificial skins. In this pilot study, a piezoelectret-based sensor unit was mounted on the surface of a myoelectric prosthetic hand to detect tactile and slip information. The relevant sensing performance was evaluated by experiments. In addition, possible improvement in future work was also suggested.

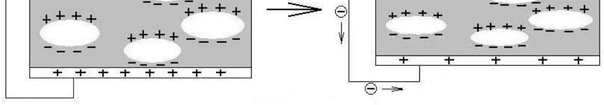

Figure 2. Crosssection and working principle of the piezoelectret.

II. Experiments

A thin-film piezoelectret sensor based on polypropylene (*eTouch, Shanghai China*) was used to measure the tactile and slip signals for a myoelectric prosthetic hand (*Kesheng MH32, Shanghai China*) in the experiments. The sensor unit was in rectangular shape with a size of 2.4 mm×1.3 mm, and its total thickness was 0.24 mm, including the piezoelectret film and protection layers. It was flexible and could be bended, as shown in Fig. 3. The sensor unit was mounted on the thumb area of the prosthetic hand with adhesive tapes, as schematically illustrated in Fig. 4.

The tactile and slip information was monitored as an acting force applied on the sensor-unit surface. The charges were generated by the piezoelectret film upon the acting force, and then amplified by a *Piezo Film Lab Amplifier* (*Measurement Specialties P/N 1007214, USA*) with a bandpass of 0.1–10 Hz. The output of the amplifier was voltage and it was captured by an oscilloscope (*Agilent DSO-X3024A 200M/4Gsa/s, USA*) with a sampling rate of 400 Hz. The sensor unit was firstly calibrated with forces in the normal direction by the use of a set of weights, in order to verify the sensor's linearity and to get a voltage-force relation. Then the prosthetic hand was controlled to grasp an object (a plastic cup was used), as shown in Fig. 4. The corresponding acting force of grasp (hand-closing) and release (hand-opening) was determined according to the voltage signal and the calibration results. Thereafter, slip signals were measured for the slippage between the sensor-unit surface and different objects of glass, plastic, hand, and cloth.

Figure 3. The piezoelectret-based sensor unit used in this work.

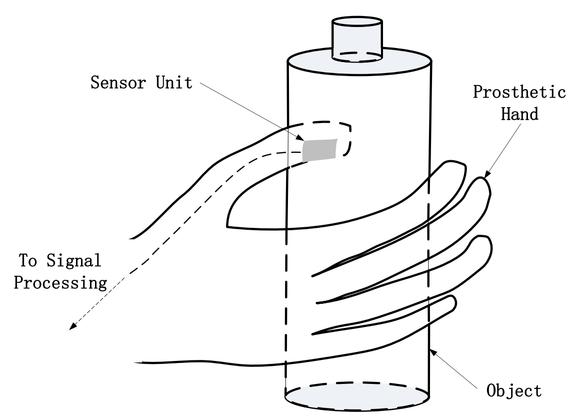

Figure 4. The sensor unit was fixed on a myoelectric prosthetic hand to detect the tactile and slip signals.

III. Results

A. Sensor Calibration

Fig. 5 shows the output voltage upon the applied force (expressed in gram) for the calibration of the sensor unit (left vertical axis). By acting a force on the sensor, a sudden voltage peak occurs and then it decreases gradually to zero with the time. This is because the piezoelectret generates charges only upon the force variation, and no more charge is accumulated once the piezoelectret's structure deformation stops (the *zero point* in the figure). The corresponding charge signal is calculated and shown in Fig. 5 (right vertical axis). Since $Q = \int I \cdot t dt = \int (V/R) \cdot t dt$ and R is a fixed value, there is $Q \cdot R = \int V \cdot t dt$, where Q, I, V, R, and t is the charge, current, voltage, resistance, and time, respectively. Here we use $Q \cdot R$ instead of Q, because only the relationship but not the real value is needed. The linearity of the sensor unit, as an inserted figure in Fig. 5, shows that both the voltage and charge are in direct proportion to the applied force in the testing range of this experiment.

B. Tactile and Slip Signal Detection

The mean absolute values of the acquired tactile and slip signals were calculated with a time window of 0.1 s, as illustrated in Fig. 6. The single and relatively large peaks represent the grasp and release of the plastic cup by prosthetic-hand closing and opening. The grasp and release peaks were similar in shape, and the peak values of 1.305 and 1.325 V yield an acting force of 697 and 708 g (about 6.8 and 6.9 N), respectively, as calculated according to the calibration curve in Fig. 5 (inset). For slip signals, only vibrations with small peaks in the range from -0.5 to 0.5 V are achieved, corresponding to an acting force of 267 g (about 2.6 N). Similar curves are achieved for the slippage between the sensor-unit surface and different objects of glass, plastic, hand, and cloth.

IV. Discussion

The experimental results of this pilot study suggested that it would be possible to detect the tactile and slip signals by the use of a piezoelectret-based sensor unit. The polymer-based

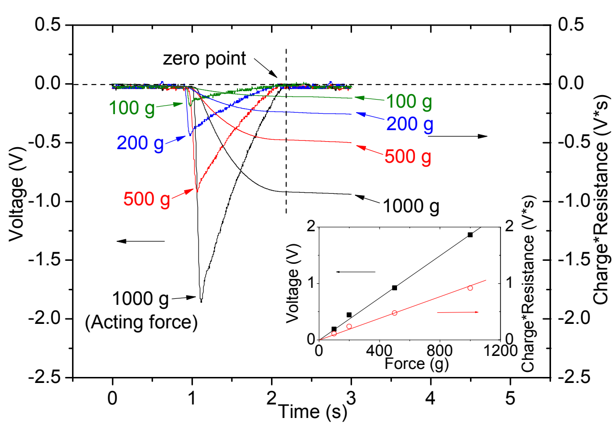

Figure 5. Voltage signals of the sensor unit upon the acting force (left vertical axis) and calculated charge signals by integrating the voltage and time (right vertical axis). The inset figure shows the linearity of the sensor. The negative values only represent the force direction.

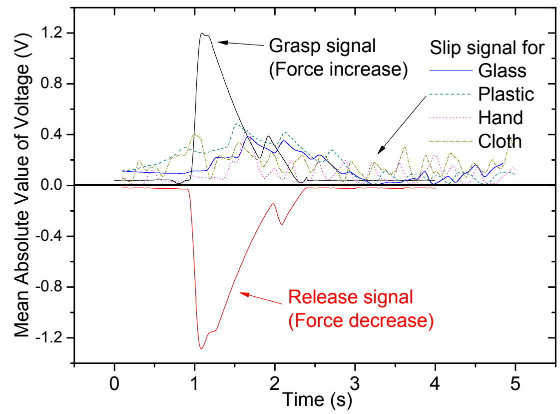

Figure 6. Mean absolute values of the voltage signals for the prosthetic-hand closing/opening to grasp/release an object and for the slippage between the sensor-unit surface and objects made of different materials. The negative values only represent the force direction.

characteristics make piezoelectrets suitable for the application on prosthetic hands, e.g. they are flexible and therefore can be bended along the finger surface. The sensor unit shows a good linear electromechanical response in the testing range of this experiment. In addition, the signal upon force increase (the grasp signal, 1.305 V) is in a good agreement with that upon force decrease (the release signal, 1.325 V), which is only 1.5% in difference. The sensor unit is sensitive, and the tiny peaks on the grasp and release curves are possibly due to the shake of prosthetic hand during operation. It is worthy to note that both the tactile and slip information could be acquired with the same sensor unit. Compared to the previously proposed systems where two different sensory technologies were often used for touching and slipping detection respectively, the piezoelectret sensor is much simple in structure and therefore more stable. For a "safe" grasp without slippage, the tactile signal is usually a single large peak, whereas the slip signal is a series of vibrations in small range. It is possible to recognize a "safe" grasp by calculating and comparing the mean absolute values of the voltage signals.

Based on the results of this work, a preliminary control strategy of prosthetic hand with involuntary feedback might be suggested. A low threshold should be preset in advance. When a prosthetic hand is grasping an object, the acting force is monitored simultaneously. Once the signal is larger than the low threshold, the driving motor stops the further grasping automatically, which means that a "safe" grasp is achieved. In the case of a voluntary control by prosthesis user, a high threshold can be set to prevent possible object damage if the grasp force is too large.

Note that only a single sensor unit was applied for the sensation information detection in this study. It might be necessary that a sensor array would be distributed on different fingers of a prosthetic hand to achieve more exact signal acquisition. In the experiment it was found that the slip signals for different kinds of objects were very similar, and it was impossible to recognize the roughness of the material. In addition, a narrow bandpass was used in this work to filter noise, which might filter part of the vibration information of the slip signals. In future work, the sensor sensitivity and signal processing technique should be improved. Finally, a more detailed and practical control strategy must be designed to realize actual application of the prosthetic hand with tactile and slip sensations.

V. CONCLUSION

In this pilot study, a thin-film piezoelectret was used as the sensor unit to produce possible sensation for a myoelectric prosthetic hand. By measuring the acting force applied on the senor-unit surface, the touching and slipping signals of the prosthetic hand could be recognized according to their different signal characteristics. Possible prosthesis control with involuntary feedback might be proposed based on the preliminary results of this work. It is also suggested that an improvement of the sensor technology and more detailed control strategy are necessary in the future.

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