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Technical Note

"Real-time" monitoring of vibrissa contacts during rodent whisking

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Abstract

Rodent whisking behavior provides active touch as input into a widely studied model system of information processing and behavior. We previously developed a simple optoelectronic system to monitor *whisker movements* in "real time" in head held rats at rest or performing various tasks such as tactile discrimination. We now describe a simple piezioelectic film device for detecting initial *whisker contacts* during whisking also in real time. In some applications this is as effective as high-speed videos and can be configured to isolate the contacts from different whiskers. The construction of this simple device is detailed. In addition to providing information during recordings from awake animals, the device could be used, for example, as an operant "manipulandum" for contingent reinforcement of object detection with a whisker.

Key words: *whisking, vibrissa, instrumentation, contact sensor*

Introduction

The exploratory whisking behavior of the rat involves the generation of a rhythmic series of movements (protractions/retractions) usually terminating in contact with an object surface. Inputs generated during these contacts are critical in controlling the animal's discriminative behavior (e.g., Carvell and Simons, 1990). Neurobehavioral analysis of the rodent vibrissa system has been constrained by the absence of efficient methods for the high-resolution monitoring of whisking movements. Videography is extremely labor intensive and its low spatio-temporal resolution constrains both the characterization of movement kinematics and the detection of vibrissa contacts. We have previously described an optoelectronic system for "on-line" monitoring of whisking trajectories in a head-fixed preparation (Bermejo *et al.*, 1998), but the system provides no information on vibrissa contacts. We now describe the use of an inexpensive piezoelectric element as a sensor for the detection of vibrissa contacts during whisking. By combining the optoelectronic system and the contact detector it is possible to monitor both the trajectory of the whisking movement and the onset and offset of whisker contacts with an object surface.

Methods

The contact detector is a piezo-film sensor (Model LDT0–028K/L;Part #0–1002794–1: AMP Incorporated, Piezo Film Sensors, Valley Forge, PA). The piezo-film element is backed by a polyester laminate (25 × 13 mm) and covered by a protective coat. The piezo-film is off the neutral axis of the laminate and is strained more when flexed. When used in a bending mode, such laminated elements develop substantial voltage outputs (*c.* 100 mV) which are proportional to the rate of displacement, but the relationship is not a linear one. As with an accelerometer, a contact with the piezo-film should generate signals at both its onset and offset. A maintained contact should not activate the sensor but any variations in displacement during that contact (e.g., vibrations) should generate transient voltage changes. Voltage signals generated by contact with the device will be a complex, non-linear, function of the frequency, amplitude and velocity of the displacement. The device is not used commercially as an analog force transducer, but as a digital switch, in which voltages exceeding a certain predetermined level trigger specific responses—for example, a beam-type vibration sensor, such as those used in car alarms.

The optoelectronic system employs laser emitter/detector devices to monitor the whisker movement trajectory. Interruption of the emitted beam (laser curtain) by the shadow of a whisker produces a voltage shift in a subset of shaded sensors (CCDs) in the detector. Whisker movement results in successive displacements in the *position* of that voltage shift which are linearly related to whisker position. A comparator circuit identifies the successive positions of voltages above a preset threshold and outputs the data to a microprocessor for computation and

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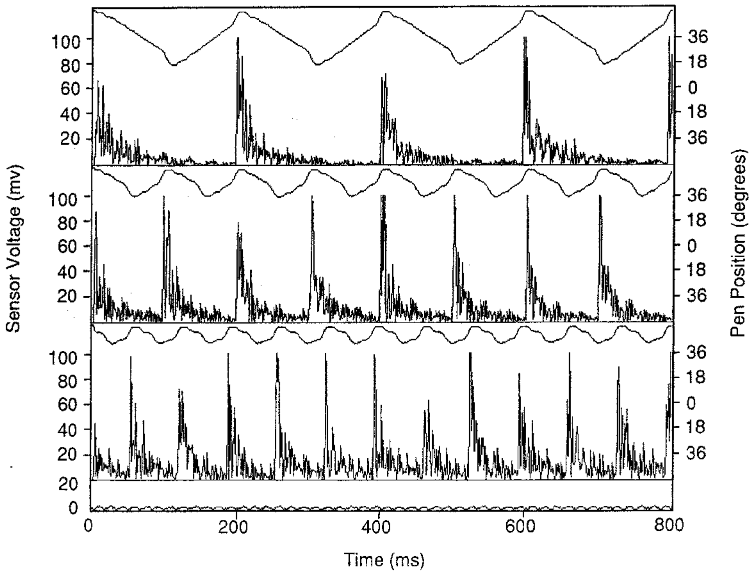

FIGURE 1. Signals generated by the optoelectronic and piezo-film devices during a series of contacts by the tip of a polygraph pen driven (from top to bottom) at 5, 10, and 15 Hz. The noise level of the device in the resting state is indicated at the bottom of the figure. The movement trajectory of the pen is plotted in degrees on the right-hand ordinate; voltage signals from the sensor are shown on the left.

display of the whisker movement trajectory (resolution: 13 μm; 1.4 ms). To monitor movements of an individual whisker, with all surrounding whiskers intact, we attach a light (3–5 mg) self-adhesive foam marker to the side of this whisker. The marker increases both the mass of the vibrissa and its relative "visibility" with respect to the surrounding whiskers but does not affect its kinematic properties (Bermejo *et al.*, 1998).

To characterize the response of the sensor to contact under controlled conditions we monitored the voltage signals generated by the piezo-film element in response to contact by the tip of a polygraph pen driven at various amplitudes and frequencies. Unfiltered sensor outputs were digitized through an A/D interface and the sensitivity of the device to displacement was adjusted using a software gain. The laser emitter/detector was used to track the trajectory of the pen movement. The three panels of Figure 1 display signals generated by the optoelectronic and piezo-film devices with the pen driven at 5, 10, and 15 Hz. The noise level of the device in the resting state is indicated at the bottom of the figure. At all three frequencies, a sensor signal substantially above noise level is seen for every occurrence of contact onset in the record. The signal then falls off in an oscillatory manner, eventually recovering to noise level. At the movement amplitudes used to obtain these records, the recovery time is about 100 ms at 5 Hz.

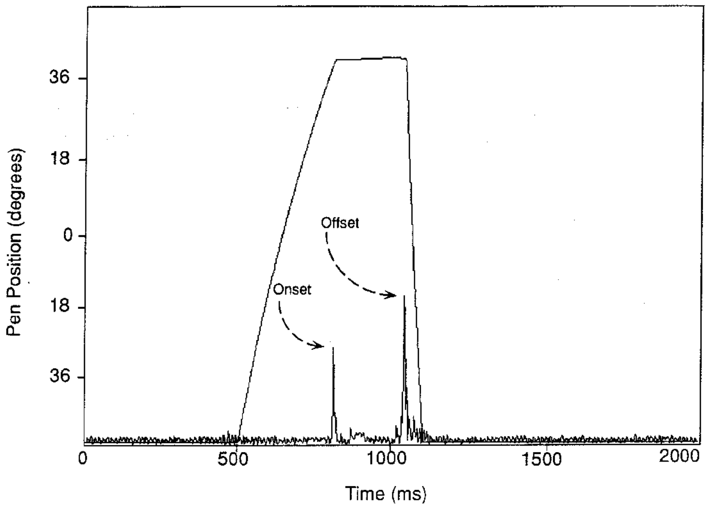

FIGURE 2. Signals generated by the piezo-film element in response to its perturbation by contact with the tip of a polygraph pen, driven at about 1 Hz. The trajectory of the pen movement is indicated on the record. The noise level under these conditions is indicated at the bottom of the figure. Large sensor signals are evident at the onset and offset of the movement, and voltages above noise level are seen during the interval between the two inflection points of the trajectory.

To further clarify the relation between movement topography, sensor contact and sensor output, we examined the signals generated by the sensor in response to contact with the pen tip during a single, brief oscillatory movement of the pen. Figure 2 illustrates sensor output produced when the pen tip, moving at about 1 Hz, contacts the sensor, during the ascending portion of movement trajectory. The "contact-event" produced by the pen–piezo interaction has three components. Voltage peaks are seen at the two inflection points of the trajectory, indicating detection of the initiation and termination of contact (onset and offset). Voltages between these two points, though lower, may rise above noise levels, reflecting maintained displacement of the sensor by the pen tip prior to offset. The difference between these two peaks provides a measure of contact duration. Note that the output of the device remains close to baseline levels during the ascending and descending portions of the movement trajectory, i.e., in the absence of contact.

To assess the utility of the sensor as a device for detecting contacts during whisking, we monitored movements and contacts of a single vibrissa (C–1) on one side of the animal's face. Although contact by a *group* of whiskers can generate a signal voltage in the sensor, a single normal whisker has insufficient mass to do so. For this reason, the foam marker used with the optoelectronic system was attached to the whisker during testing. This made it possible to monitor both the trajectory of whisking movements made by a single identified vibrissa and the contacts associated with those movements.

Five rats of the Long-Evans strain were fitted with dental cement head-mounts and tested with the head fixed and the body restrained in a specially designed holder (Bermejo *et al.*, 1996). Whiskers rostral to the monitored whisker were clipped to insure triggering of the detector by an identifiable individual vibrissa. Figure 3 illustrates the experimental arrangements. We have found that the device is equally sensitive whether the front edge of the contact sensor is mounted perpendicular or parallel to the plane of the whisking movements.

An operant conditioning paradigm was used to elicit whisking responses terminating in contacts. To avoid habituation and generate sustained bouts of whisking, water-deprived subjects were initially reinforced with pulses of water on a variable interval schedule for protractions (without contact) meeting or exceeding a predetermined amplitude criterion (> 30°). In subsequent sessions, subjects were additionally reinforced for protractions followed by contacts with the sensor. Reinforcement delivery was followed by a 2 s intertrial interval.

Testing was carried out in 30 min sessions. Prior to each test session, the noise level of the device was recorded, its sensitivity was adjusted and a voltage output threshold (trigger voltage) was set at a value several SDs above the baseline noise level. During testing, the voltage output of the sensor was continuously monitored, and the first voltage peaks exceeding the trigger threshold triggered water delivery and the conclusion of a trial. Whisker movement and piezo-film sensor data for 1 s periods prior to and following the occurrence of an initial contact were saved to disk. These procedures generated a population of vibrissa contacts, each of which was associated with the trajectory of an identified whisker movement. Figure 4 presents some examples of the kinds of interactions between the vibrissa and the sensor seen under the present testing conditions. To clarify the interaction between whisker movement topography and sensor output a selected portion of each record is plotted on an expanded time scale in Figure 5. The trigger threshold voltage level is indicated, in both figures, by a dashed line at the bottom of each panel. The occurrence of the initial contact on each trial is indicated in Figure 5 by arrows. In interpreting the relation between the movement trajectory and the occurrence of sensor signals it should be noted that the optoelectronic system provides a continuous record of the angular position of the whisker with respect to a point on the (moveable) mystacial pad, not its absolute position in space. It should also be recalled that the device is extremely sensitive to changes in the rate of displacement of the piezo-film but insensitive to maintained contact.

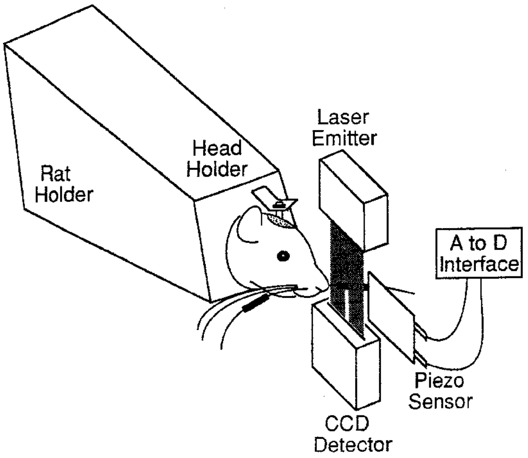

FIGURE 3. Schematic diagram of the test situation, illustrating the location of the contact sensor with respect to the laser emitter/CCD detector and the position of the head-fixed animal.

In the top panel of Figures 4 and 5, the whisker movement terminating in contact begins as a high velocity protraction and then continues at a greatly reduced velocity over the next 100 ms. The peak voltage signal coincides with the maximum point of the whisker excursion. The sensor output remains below noise levels for the remainder of the record. In the middle panel the initial, high velocity portion of the protraction ends at about −130 ms (first inflection point) and the whisker reduces its velocity and maintains a relatively constant position. Activity in

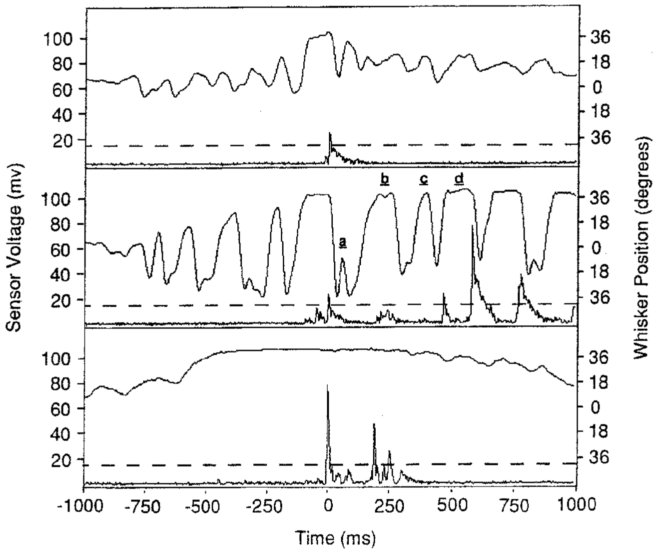

FIGURE 4. Several examples of vibrissa contact detection and the whisking trajectories with which these contacts were associated. In each panel, the top trace displays movement data for a 1 s period prior to and following a defined initial contact. The bottom trace presents a continuous record of variation in the voltage output of the piezo-sensor during the same period. The contact "threshold" of the device is indicated by a dashed line at the bottom of each panel. To cover the entire 1 s period prior to and following the first contact signal, only 1/3 of the data points are plotted.

the sensor begins to increase at about −120 ms, exceeding the trigger threshold at the start of retraction (second inflection point), and triggering a reinforcement. This initial contact is followed by a series of whisker movements (*a* to *d*), only one of which (*d*) is associated with sensor signals above trigger threshold. The first of these occurs at the first inflection point in *d* (i.e., at the point of maximum protraction); a second, larger signal occurs just prior to retraction. The interaction between sensor output and whisker contact in this movement (onset, maintained contact, offset) is very similar to that for the "contact event" shown in Figure 2, generating clear signals only during displacement of the sensor. The movement record in the bottom panel of Figure 4 includes a period during which the whisker remains protracted in the vicinity of the sensor, suggesting maintained contact, followed by several above-threshold signals. We suggest that these signals may originate in transient displacements of the sensor (vibrations) or they may reflect forces generated *isometrically* by the whisker.

Discussion

Piezoelectric elements have previously been used to generate precisely calibrated *passive* deflections of an individual vibrissa in electrophysiological studies (e.g., Simons, 1983; Sheth *et al.*, 1998). We now describe a piezoelectric device that may be used to detect contacts with an object surface by *actively*

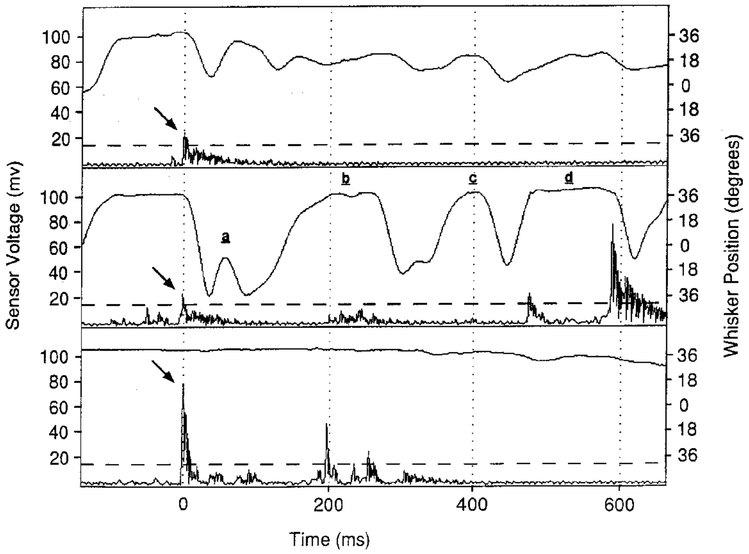

FIGURE 5. Selected portions of the records in Figure 4, replotted on an expanded time scale. Conventions as in Figure 4. The initial contact event in each panel is marked with an arrow.

generated vibrissa deflections during whisking. The sensitivity of the device is such that it will detect interactions between a single whisker and the sensor that are unlikely to be detectable using videography. The device responds reliably to repeated contacts and its recovery time is sufficiently brief that it should be capable of detecting an *initial* whisker contact at rates within the normal whisking range (5–15 Hz). Because the piezo-film element is inexpensive and its associated instrumentation is simple the device could be useful in both behavioral and electrophysiological experiments. However, its utility for either situation requires an understanding both of physical properties of the sensor and of the nature of the interactions between vibrissa and sensor during whisking.

The physical properties of the piezo-film make it selectively responsive to changes in the *rate* of contact-generated displacements, but the relation between the rate of sensor displacement and voltage output is complex and non-linear. We have examined the response of the sensor under controlled conditions, using sinusoidal movements of a rigid level to produce a series of contact stimuli at several frequencies and amplitudes. Under these conditions the interaction of the stimulus and the sensor will generate a "contact event", including an initial voltage at the onset of contact and a second signal at its offset, but little or no voltage change during maintained contact. We have compared these findings with observations of the signals generated by the sensor to contacts with a single identified vibrissa during actual whisking movements. Our analysis suggests that the device will be extremely sensitive to transient vibrissa contacts, since these will produce displacements of the piezo-film element, but will be insensitive to maintained contacts.

In many episodes of whisking, there is an unambiguous relation between the appearance of an above-threshold sensor signal and clearly defined inflection points (protractions or retractions) in the movement record. In other cases, the angular position of the vibrissa remains relatively unchanged for extended periods of over 100 ms. The pattern of sensor outputs seen under both these conditions is consistent with the response properties of the device as described above.

It is important to stress that the device is not intended to provide data on the relation between the physical parameters of the vibrissa contact and the sensor voltage, but to function as an extremely sensitive event detector. It is best used as a digital switch, in which voltages exceeding a certain predetermined level trigger a specified output. In this respect, it functions much like the Schmitt-trigger device used to detect the occurrence of neural signals. For such a device, the identification of a voltage change as a signal depends upon the criterion used to distinguish signals from noise—and this must be in some sense arbitrary. The balance between false positives and negatives must be dealt with by adjusting that criterion according to the requirements of the experimental situation.

Because the piezo-film may be cut into different shapes without disturbing its response properties, individual sensors could be used as discriminanda in tactile discrimination paradigms. In behavioral experiments in which reinforcement is contingent upon the detection or localization of objects by a whisker, the detector would be analogous to an operant manipulandum, like a rat lever or a pigeon key. For such devices, a "response" is defined, arbitrarily, as a digital event (e.g., by the making or breaking of a relay). By analogy, a "contact" might be defined as the first voltage peak exceeding a predetermined (trigger) threshold output. The sensor would generate a uniform output signal for each above-threshold event, activating a counter or a reinforcement delivery system.

The device should also be useful in recording experiments with awake, behaving animals. In head-fixed, actively whisking animals, sensor signals indicating the initial contact with an object surface could be used to trigger peristimulus time histograms associated with contact onsets. The results of such experiments would be clarified by the availability of an associated record of the whisker movement trajectory. For example, whisking may generate both a *re-afferent* signal produced by the movement of the vibrissa and an *ex-afferent* signal indicating contact with a target surface. If the contacts made by a single whisker may be identified, and associated with a whisking trajectory, it should be possible to assess whether inputs from these events are coded at different levels of the trigeminal neuraxis. The combination of unit recording, contact detection and movement trajectory monitoring should advance our understanding of the functional organization of the rodent vibrissa system.

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