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Design and construction of a photoresistive sensor for monitoring the rat vibrissal displacement

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ABSTRACT

Rats sweep their vibrissae in a rhythmic and coordinated fashion in order to acquire tactile information from their environment. Measuring vibrissae movement has become a matter of increased attention, from several labs, over the last few years. We describe the design and construction of an inexpensive photoresistive sensor that registers horizontal vibrissae movement. The device consists of an LED array and a light-dependent resistor (LDR) covered by a coating with varying transparency along its axis. When a vibrissa is located in the sensor, it generates a shadowy line over the photosensitive material, thus changing the LDR resistance. These changes are transduced into voltage changes. Our measurements on vibrissa show that this simple and inexpensive sensor effectively monitors the movement of a single vibrissa.

1. Introduction

An outstanding feature of many mammals is the presence of whiskers or "vibrissae" located on both sides of the muzzle (Ahl, 1986). The vibrissae work as a mobile sensor array for acquiring tactile information from their environment (Vincent, 1912). While exploring, the rats move their vibrissae rhythmically, which enable them to detect tactile stimuli in their environment. These rodents are able to discriminate the shape and features of the surface by using only their whiskers (Carvell and Simons, 1990; Guic-Robles et al., 1989; Harvey et al., 2001; Albarracín et al., 2006). Rat whisking consists of repetitive movements forward (protraction) and backward (retraction) with frequencies ranging from 5 to 11 Hz (Welker, 1964; Winesky, 1985; Semba and Komisaruk, 1984; Carvell and Simons, 1990; Bermejo et al., 1998). The characteristics and the parameters of vibrissae sweeping have been a subject of investigation over the last years.

Carvell and Simons (1990) and Carvell et al. (1991) first studied the vibrissae movements, but, since they used only conventional videographic recording, this information was not accurate enough to monitor a trajectory requiring a high space–time resolution. Electrophysiological and behavioral studies of the rat vibrissal system require monitoring the vibrissae movements during a discrimination task in order to relate the electrophysiological findings with the physical parameters of movement (displacement amplitude, speed and vibration).

Bermejo et al. (1998), proposed two systems for the real-time recording and display of individual vibrissal movements in head-fixed rats. Both systems utilized high-speed, linear image sensors, each composed of an array of light sensitive elements (Bermejo et al., 1998). In one case, the light source was a pair of fiber-optic devices and, in the other, it was a laser-emitter. The photodetector had 2048 individual sensors (13 μ × 13 μ) arranged in a linear array spanning a distance of 26.6 mm (Bermejo et al., 1998; Bermejo and Zeigler, 2000; Harvey et al., 2001).

Video images are another alternative for monitoring vibrissae movements. However, special high-speed cameras are usually needed (100–500 frames/s) (Knutsen et al., 2005; Berg and Kleinfeld, 2003; Prigg et al., 2002). In general, videography requires complex processing techniques to identify the vibrissae studied, and thus, is strongly linked to image processing (Hartmann et al., 2004).

A sensor with high spatial and temporal resolution for monitoring vibrissae movements was proposed by Arabzadeh et al. (2005). This consisted of two-dimensional optic sensor in which each channel had two light tubes (one, a light source, the other, a linear sensor array (array of photodiodes)). The two channels were mounted normal to each other in a metallic ring and could detect whisker position with less than 3-μm spatial and 0.13-ms tem-

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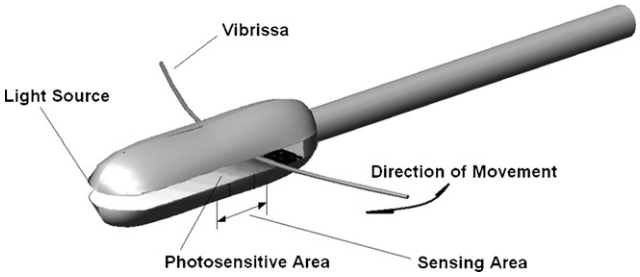

Fig. 1. The sensor and the location of the vibrissa between the photoresistive detector and the light source (LEDs). The vibrissa movement must be entirely within the measurement zone to obtain an accurate record.

poral resolution (Arabzadeh et al., 2005). This linear sensor array (100–1000 photodiodes, depending on their spatial resolution) requires complex processing techniques and control to interpret its output.

In this paper we report the development of a novel photoresistive sensor for measuring the displacement of one vibrissa. It is simple to construct and low cost (consisting of eight LEDs and a LDR or light-dependent resistor), and was developed in the Neuroscience Laboratory of the School of Medicine (Universidad Nacional de Tucumán, Argentina). In addition, the proposed sensor does not require complicated processing techniques; it generates an electrical output according to the whisking trajectory (protraction/retraction). Small size, an adequate shape and easy mobility are other of its advantages. The sensor design, several calibration tests and experimental tests for monitoring the vibrissa trajectory are presented in this paper.

The experiments consisted of electrophysiological studies under general anesthesia with vibrissa movements produced by muscular activation and electrical stimulation of the motor branches. The device has a frequency response of 0–100 Hz, and a surface detection area with a linear zone of 3.8 mm. Its construction is simple and inexpensive and it also allows following the vibrissa trajectory in real time and determining certain parameters of its horizontal movement.

2. Materials and methods

2.1. Sensor

2.1.1. Design and construction

The sensor was built, basically, with two elements: light emitting diodes (LEDS), and a light-dependent resistance (photoresistance) covered by a variable transparency mask. When the vibrissa is placed between these elements, its movements produce a shadowy line over the photosensitive material. The electrical resistance variations are transduced as voltage variations; thus, the successive voltage variations are linearly related to the temporary position of the whisker. A rapid event such as whisking needs a high space–time resolution device. We first tried building the device with a commercial slotted opto-coupler to follow the vibrissa trajectory. Although the device showed a rapid response to the light step, the linear area was too small, as the measurement zone (phototransistor lent) was very small and the light beam (infrared photodiode) not wide enough.

Since the commercial opto-coupler showed such low performance, a new device was constructed. This sensor consists of a circular hollow metal frame wired to a light source (LEDs) and a photosensitive material (LDR). The distal horseshoe-shaped end allows free displacement of the whisker. The LEDs are located on the upper side and the photoresistive detector on the lower side (Fig. 1).

2.1.2. The light source

The light source must be evenly focused over the photosensitive area in order to accurately measure the vibrissa movements; therefore the resistance variations must only respond to these events.

The evenly lighted zone was obtained with a 12 LED array (Fig. 2). The LEDs were: 204YD (yellow diffuse LED, 3 mm diameter, I_f = 25 mA, V_f = 2 V and intensity = 4.5 mCd). Each led was sanded to provide an evenly distributed light source on the photosensitive surface and to give it a square shape (Fig. 2(C)). LEDs were sanded using sandpaper # 220 (first) and then sandpaper # 600. The final shape of the LEDs and the pores due to sanding produced a diffuse light source, whose pattern of radiation was more uniform than conventional LEDs. The lighted area was approximately 7 mm long and 3 mm wide.

2.1.3. Photosensitive surface

The LDR is a light sensitive material which behaves as an ohmic resistance, consisting of semiconductor material bands of pure silicon (Si), alternating with conductive material (Cu). Silicon, when highly purified, is an insulator in darkness and at room temperature. Thus, the LDR has an almost infinite resistance in the darkness, but when lighted its resistance drops to a finite value (i.e. the resistance is an inverse function of the light intensity). The LDR also responds to a wide range of wave lengths (λ) from infrared to ultraviolet. These features make the LDR very sensitive in room light. The photosensitive surface design consisted of a rectangular shaped LDR modification (Fig. 3(A)), 8 mm long and cut parallel to the longest semiconductor bands (Fig. 3(B)). On the other side, the modified LDR was located at the lower distal end of the metal frame and parallel to its longitudinal axis.

The way the vibrissa is located with respect to the photosensitive material is a very important detail in the transduction process of its relative position. It must be placed at the sensor window, so that when moving, it will produce a shadowy line perpendicular to the LDR photosensitive bands. Therefore, the LDR behaves like an even photosensitive surface in spite of the fact that, conductor material bands alternated with non-conductor bands. Under these conditions, the LDR resistance variations produced by the vibrissa shadow are constant because the vibrissa blocks a constant amount of light and the LDR is affected the same way all along its length. Resistance (ΔR) variations are needed in order to detect the position of the vibrissa, which was achieved by placing a variable transparency mask on the LDR (Fig. 3(C)). The mask was constructed with a thin layer of plastic. Its optical density varied linearly from a maximum (dark zone) to a minimum (transparent zone). Under

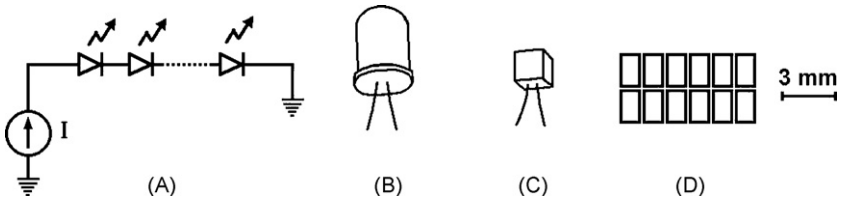

Fig. 2. Steps in the construction of the light source. (A) Electrical connections, (B) original LED, (C) modified LED, and (D) LED array (from above).

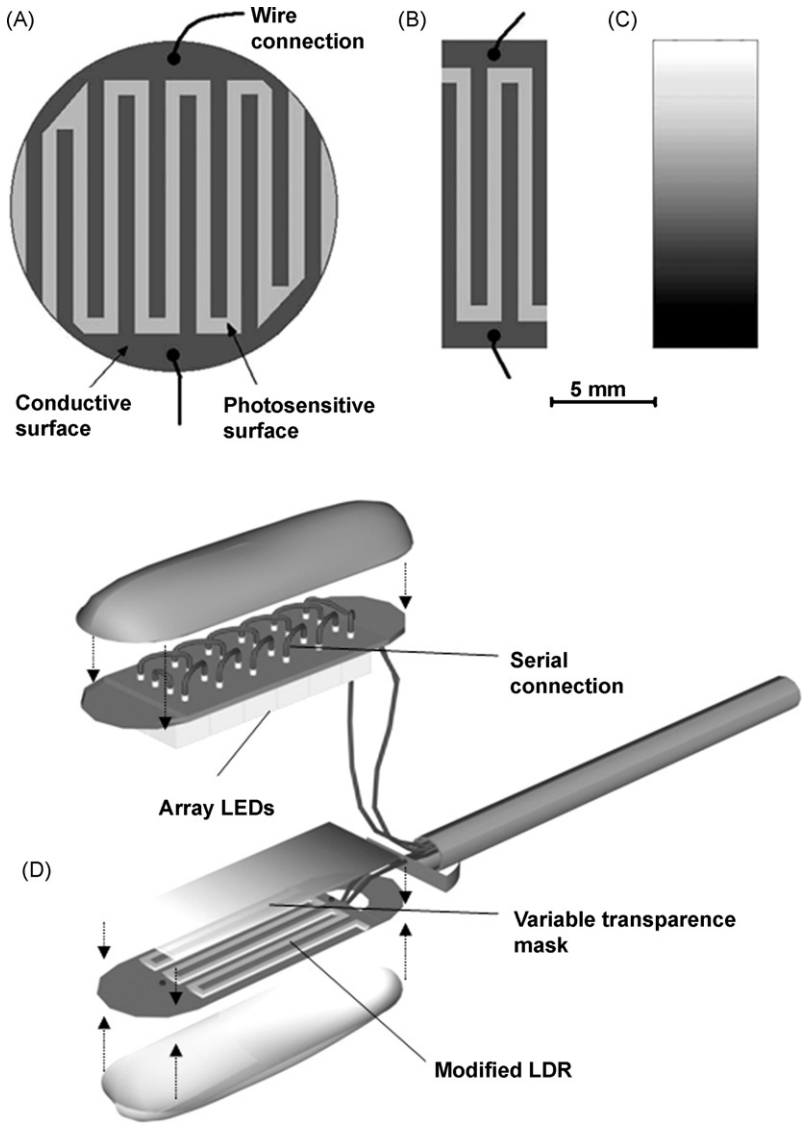

Fig. 3. Steps for the construction of the photosensitive surface. (A) Original LDR, (B) modified LDR, (C) variable transparency mask, and (D) assembling of sensor photoresistive components.

these conditions, the LDR acquired a variable sensitivity to light: high sensitivity in the transparent area, low in the dark area and a uniform gradient in between them.

2.1.4. Transduction process

If the vibrissa moves, the LDR resistance will vary from a higher value, when going through the transparent area of the mask, to a lower value when going through the dark area. Therefore, the relative position of the vibrissa is a direct function of the LDR resistance variations. The transduction process occurs wherever the vibrissa generates a shadow, because the photosensitive area has a light sensitive gradient.

2.2. Static and dynamic calibration tests

2.2.1. Static test

An average diameter rat vibrissa was placed on a Vernier scale micromanipulator (Fig. 4(A)) and moved in the sensor all along its range, 1 mm at a time, producing the following curve (Fig. 4(B)). We conclude that the sensor has a linear zone of about 3.8 mm; therefore, we can record the whisking trajectory under certain stimulation conditions.

2.2.2. Mechanical test of the frequency response

A vibrissa displacement which described sinusoidal waves of different amplitudes and frequencies was analyzed in this test. The experimental setup is shown in Fig. 5(A).

A vibrissa was fixed onto a mechanical holder joined to a speaker cone and sinusoidal waves applied to the speaker with an amplifier whose frequency was controlled by a function generator. A vibrissa vibration generated a displacement all along the sensor axis, which was recorded by the sensor and could be observed on the oscilloscope.

An electronic dynamometer of high response speed (10 kHz) was used to fix the amplitude at a constant value in each frequency test and to record the voltage variations. A rubber band, placed between the dynamometer and the holder, made the dynamometer more sensitive and able to register slight variations. The rubber band worked as a spring which transformed the holder movements into forces. The equation which describes this action is $F = -kx$, where: F = force, k = spring voltage, x = movement.

The signal amplitude of the sensor was compared with that of the dynamometer in order to keep the movement amplitude constant when the frequency varied. The signals were fitted with the function generator to keep them constant as well.

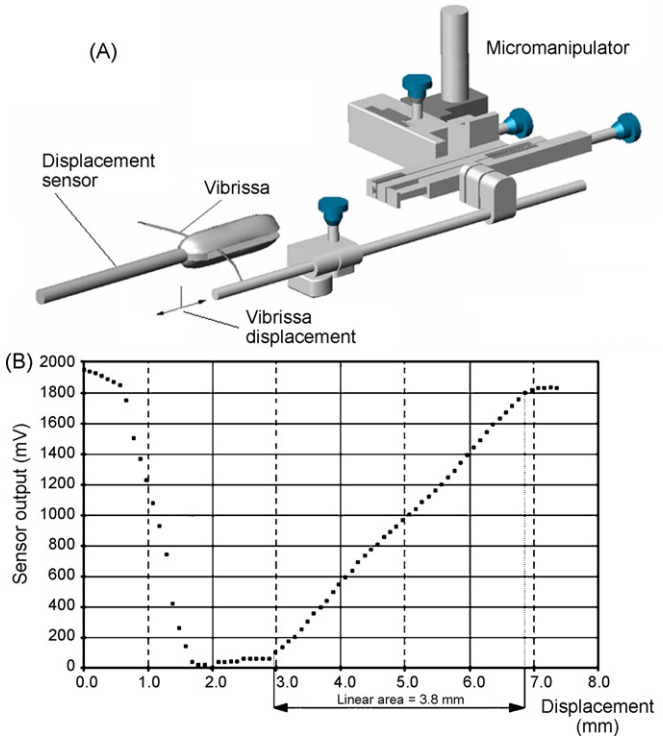

Fig. 4. Static test. (A) Arrangement of apparatus used for the test. (B) Response of the sensor to determine the linear zone.

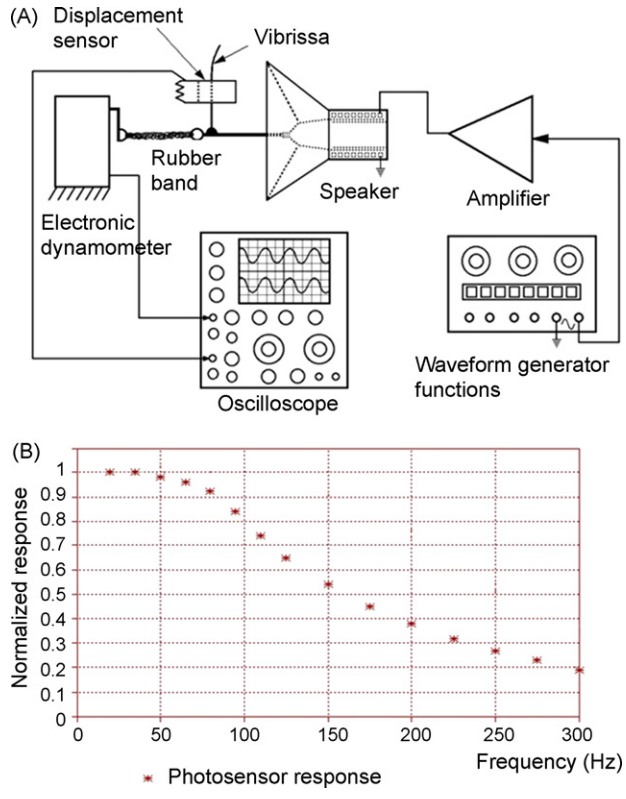

Fig. 5. Frequency response test. (A) Setup used to produce the vibrissa movement at different frequencies. (B) Sensor response curve.

The curve obtained is shown in Fig. 6(B) where the drop to −3 db (cut off frequency) is at 100 Hz, showing that the device response has a frequency range from 0 to 100 Hz.

2.3. Displacement angle measurement

Some considerations must be made in order to carry out a proper displacement measurement of the vibrissa.

- Skin-sensor distance: minimum (up to 10 mm). The length of the rear vibrissa varies from 40 to 60 mm. Therefore, the displacement area increases from the base to the tip while the range of the sensor is about 3.8 mm (Fig. 1). Thus, it is important to keep the vibrissae within this range while moving.
- Displacement angle determination (α): Δx value is determined from the electrical register and the static test (Fig. 4). Where: d, skin-sensor distance; h, sensor width; α, displacement angle; Δx, tangential displacement in the middle of the sensor.

Since Δxi is $<\Delta xe$, we assume that $\Delta xi = \Delta xe = \Delta x$. Given that, the sensor output is proportional to Δx, α is estimated as follows:

If α is non-significant: chord = arc (Fig. 6), then:

$$\alpha(\text{rad}) = \frac{\Delta x}{d + (h/2)}; 0$$

$$\alpha(\text{deg}) = \frac{\Delta x}{d + (h/2)} \frac{180}{\pi}$$

Then, the relation between the sensor output (mV) and Δx can be determined from Fig. 4(B) through:

$$\Delta x = 1\,\text{mm};$$

$$\Delta v = 975 - 550\,\text{mV} = 425\,\text{mV}$$

(determined from Static test, Fig. 4(B));

$$\frac{\Delta x}{\Delta v} = \frac{1}{425};\ \text{Then}\ \Delta x = \frac{\Delta v}{425}.$$

2.4. Recording of the vibrissa movement

2.4.1. Experimental protocol

Male Wistar rats, between 300 and 350 g, were prepared by exposing the facial nerve branches which innervate the intrinsic vibrissa muscles. Both nerves were dissected, proximally sectioned, and placed on electrodes connected to a stimulator (Fig. 7).

The movement of an average length vibrissa was induced through rectangular pulse stimulation (1–5 Hz, 30 μs). The sensor was placed 10 mm from the skin, so that, the vibrissa movement

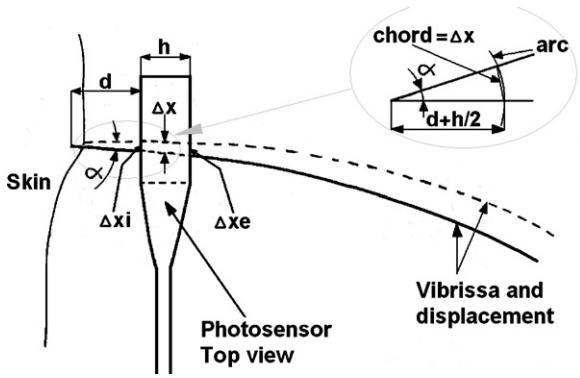

Fig. 6. Measurement of the displacement angle.

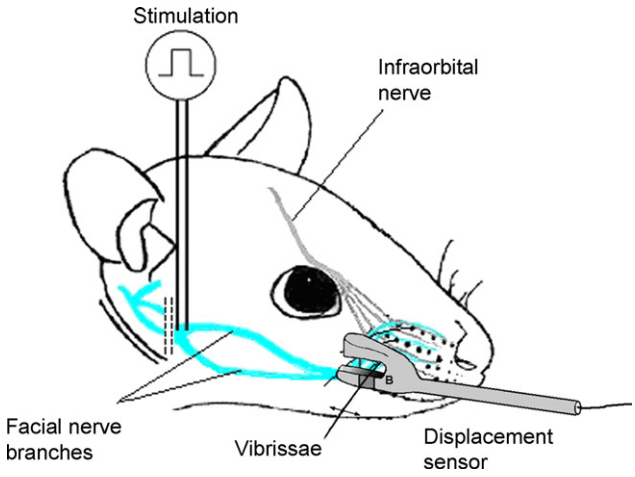

Fig. 7. Experimental design for recording vibrissa movement

could be detected not only at the base of the whisker, but also where it is within the sensor range. The other vibrissae were sectioned at skin level in order to allow the test vibrissa free movement. The laboratory lights were turned off during the recording to avoid interference with the photosensitive material. The signals were acquired and digitalized at a 20 kHz sampling frequency with an acquisition system and commercial software (Axon Instruments).

3. Results

A series of 50 whisking were recorded at 100 ms each, and an averaged signal was obtained. The maximum protraction was obtained at 30 ms. The displacement angle obtained at this time was 7.8° (Fig. 8).

The complete whisking cycle lasts about 60 ms, but a low amplitude displacement (<1°) is observed when the cycle ends, which might be associated with a vibration, due to the inertia of the initial movement. This movement lasts about 30 ms.

The velocity curve showed, during protraction, that the vibrissa reaches a maximum angular velocity of 850° s^{-1} at 15 ms from the beginning of the whisking, after which, a slower retraction is observed and which reaches a maximum 550° s^{-1} at 35 ms from the beginning of the movement.

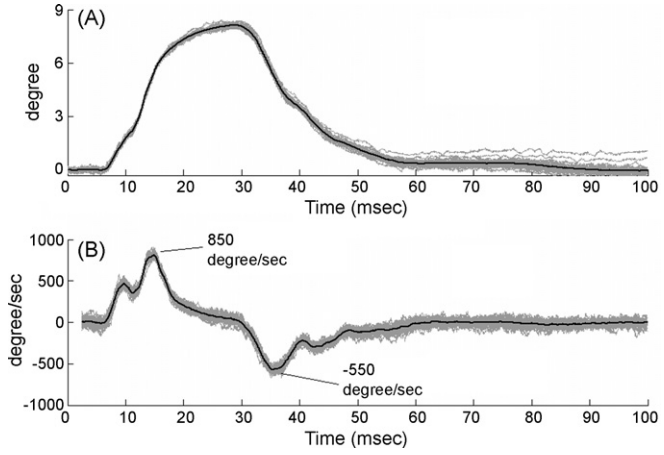

Fig. 8. (A) Recordings of the gamma vibrissa mechanical activity. The dark line is the average of the recorded sweeps. (B) Velocity curves obtained from figure (A).

4. Discussion

The measurements obtained with this sensor differ greatly from what has been reported by Carvell and Simons (1990) and Bermejo and Zeigler (2000), because our stimulation conditions are different. The stimulation trains used previously produce a continuous whisking quite similar to the one used by the rats while exploring (Zucker and Welker, 1969), but, this type of stimulation would not work for our experiments, which require single pulses. This is related to:

1) the characteristics of the sensor: the sensor has a limited range of measurement which could be exceeded when using stimulation trains. Moreover, single pulse stimulation allows monitoring the complete movement (protraction/retraction) of the vibrissa;
2) the possibility of simultaneous studies of the nerve and mechanical activity of the vibrissal system in electrophysiological studies. Although single pulse stimulation produces less angular displacement of the vibrissa than described in behavioral studies (Carvell and Simons, 1990), these studies would not have been possible with stimulation trains because the stimulus artifact would interfere with the nerve signal and would impair the recording (Albarracín et al., 2006).

Recently, studies in actively sensing rats have demonstrated that neuronal activity is significantly influenced by motor activation (Ferezou et al., 2007; Krupa et al., 2004; Szwed et al., 2003; Yu et al., 2006; Albarracín et al., 2006). The sensor described in this paper allows monitoring the displacement of one vibrissa in one plane while the afferent nerve activity is recorded. The frequency response of our sensor has an upper limit of 100 Hz which makes it unsuitable for studying the resonance phenomena known to occur at frequencies over 500 Hz (Hartmann et al., 2004). In spite of its clear technical disadvantage in comparison with the CCD technology (Bermejo et al., 1998), our sensor has the advantage of low cost.

5. Conclusions

The sensor presented in this paper has an appropriate size for the proposed procedures and components easily prepared for construction. It is inexpensive, rapid and simple.

The methodology described above is a new approach for studying rapid events such as vibrissa movement. The static and frequency mechanical tests allowed us to determine the linear zone of measurement (3.8 mm) and the maximum frequency detectable by the sensor (100 Hz), respectively.

This sensor only registers the horizontal vibrissa movement. However, these same principles could be used to construct a sensor to register the vertical movements.

Its major disadvantage is that it is highly sensitive to external light, mainly artificial light sources. The interference generated, when fluorescent light is applied, is twice the frequency (100 Hz in Argentina). This problem could not be easily solved because the photosensitive area is large and the LDR responds to a wide range of wavelengths. Working in the dark was the solution in the current experiments.

The sensor works properly as long as the whisking is within the measurement range. Therefore, it is designed to be used in electrophysiological tests and only under certain conditions which were analyzed and studied previous to its construction.

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