An impact sensing platform for spinal cord injury experiments

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***Abstract*—Real-time measurement of rat/guinea pig spinal cord mechanics during ex vivo experiments remains a nontrivial task due to the small size of the cord and the short impulse duration. To address this issue, we present an inexpensive strain measurement platform. It consists of an array of flexible, Parylene-C-passivated, pointed cantilevers of polyvinyl fluoride (PVDF) that penetrate the wall of an acrylic chamber. When a spinal cord is placed in the chamber and stimulated mechanically, its vibrations translate onto the PVDF cantilevers which in turn generate an electrical signal for recording. Vibrometer experiments of the cantilever reveal a deflection of up to 58 nm at its resonant frequency (~50 kHz). Voltage from a cantilever in a cord phantom has been recorded at two distances from the point of impact, showing 37 mV at 5 mm and 21 mV at 20 mm for a 40 kPa impact pressure.**

I. Introduction

The severity of spinal cord injuries often results in devastating physical disabilities with no effective therapeutic options due to a poor understanding of the spinal cord physiological response to strong mechanical impulses [1-2]. Recent studies have implemented in vivo [3-4] and ex vivo [5] setups that evaluate the electrical performance of an isolated spinal cord after a high-speed pressure impulse of up to 50 kPa, typical of severe spinal cord accidents [6]. While these experiments provide a controlled test environment, they do not offer a means of electrically measuring spinal cord motion/strain in real time. Subpar analyses of the mechanical stresses in the cord typically require expensive high speed cameras and time-consuming image processing [6]. A simple electrical vibration/strain sensor would significantly improve the efficiency of the experiments and would make such measurements available to many spinal cord laboratories with access to inexpensive rapid prototyping equipment/services.

To address this issue, we present an inexpensive platform for measuring spinal cord strain in response to a pressure impulse. It consists of a polymeric chamber integrated with an array of flexible piezoelectric cantilevers. When a spinal cord is placed in the chamber and stimulated mechanically, its vibrations translate onto the piezoelectric cantilevers which in turn generate an electrical signal for recording. Thus, the platform enables simultaneous temporal and spatial recording of induced strain on the spinal cord. Furthermore, the platform is inexpensive and features a straightforward fabrication procedure requiring only economical rapid-prototyping equipment, which renders it an affordable and readily adaptable spinal cord test platform for labs around the world.

II. Design and Operation

The spinal cord strain sensing platform comprises an acrylic well with an array of Parylene-passivated polyvinylidene fluoride (PVDF) cantilevers penetrating the side wall, as illustrated in Figure 1. The well serves as a container for spinal cord samples during testing, while the cantilevers behave as high frequency strain sensors that are connected to external electronics.

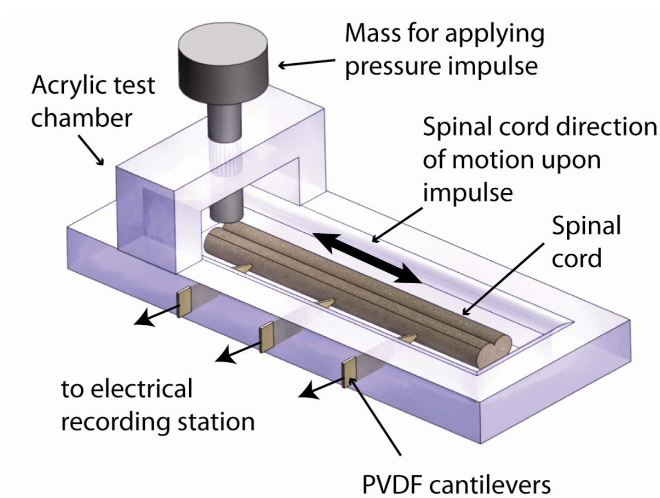

Figure 1. A conceptual illustration of the spinal cord test platform. A dropped mass causes a mechanical impulse that vibrates the spinal cord lengthwise. The vibrations transfer to the PVDF to generate an electrical signal for recording.

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When a spinal cord is placed in the well, the cantilevers penetrate slightly into the cord (< 500 µm). Spinal cord injury is then simulated by imparting a mechanical impact (e.g. by dropping a mass-loaded rod) onto the spinal cord at the desired location. Any resulting longitudinal motion of the spinal cord is then translated by the piezoelectric cantilevers into electrical signals, thus enabling real-time strain measurements along the length of the spinal cord. The platform can be further customized in terms of the quantity and orientation of the cantilevers (e.g. for vertical or transverse strain detection) or the location of the applied mechanical impulse.

III. Fabrication

The fabrication procedure for the spinal cord strain sensing platform is illustrated in Figure 2. The test chamber is fabricated by laser machining commercially available 2 mm-thick acrylic sheets. First, the base and side wall rectangles are cut using a CO_2 laser system (Universal Laser Systems, Scottsdale, AZ). One of the side walls is further modified to include slits (2 mm × 125 µm) for cantilever insertion (Figure 2a). The chamber is then assembled using a UV curable adhesive (Loctite® 3105).

The polyvinylidene fluoride (PVDF) cantilevers are prepared by using a tabletop CAMEO® craft cutter plotter (Silhouette America, Salt Lake City, UT). A 52 µm-thick, gold-plated PVDF sheet (Precision Acoustics, UK) is cut into pointed cantilevers (2 mm × 7 mm) using the craft cutter plotter (Figure 2b). Next, a layer of Scotch® tape is used as a mask to define electrical pads on the cantilevers (Figure 2c). The cantilevers are then passivated with a 0.5 µm coat of Parylene-C (Figure 2d). Next, the tape is removed, and the cantilevers are secured in the wall slits of the test chamber. Finally, electrical connections are made (Figure 2e) using a conductive silver ink (118-09, Creative Materials, Ayer, MA).

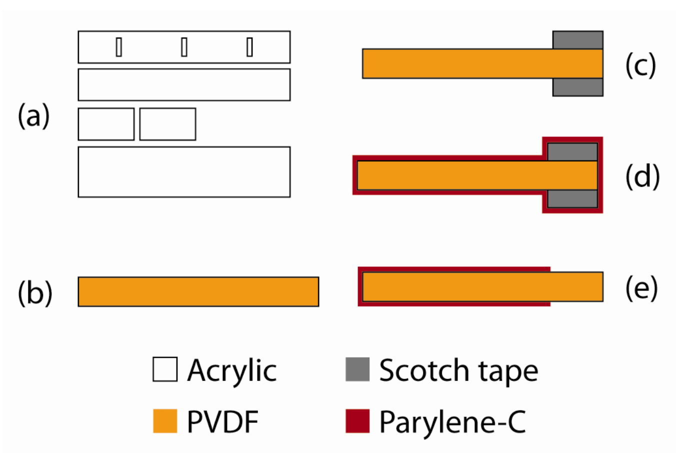

Figure 2. Fabrication process of the platform. (a) Laser-machine acrylic and assemble with an adhesive; (b) cut gold-plated PVDF into sharp cantilever shapes; (c) mask electrical contact regions with tape; (d) passivate with 0.5 µm of Parylene-C; (e) remove tape, attach to acrylic, and make electrical connections. (Illustrations b−e show PVDF crossection)

A spinal cord phantom for characterizing the platform is prepared using gel. A 3 mm-diameter Tygon® tube is filled with a warm 1% (w/v) Agarose solution and allowed to gel. Once cool, the gel is removed from the tube and cut to a 4 cm-long samples.

IV. Experimental

The mechanical response of the PVDF cantilever to vibration/strain is tested using a Polytec MSA-400 scanning laser Doppler vibrometer system. A PVDF cantilever is end-clamped onto the piezoelectric transducer of the vibrometer. The transducer then vibrates the PVDF at various frequencies (10−1000 kHz) while the cantilever tip displacement is recorded by the vibrometer.

In vitro characterization of the fabricated platform is performed using a gel-based spinal cord phantom. The cord is placed in the testing chamber, and the cantilevers are visually inspected to ensure their contact with the cord. Next, the electrical leads of the cantilevers are connected to an oscilloscope. A mass-loaded rod (28 g, 3 mm diameter) is dropped onto the gel from a height of 3 mm, imparting a 40 kPa mechanical impulse. The electrical output of the cantilevers at various distances from the point of impact is monitored for the duration of the impulse.

V. Results and Discussion

Figure 3 shows a photograph of the fabricated strain sensing platform. The use of a cutter plotter results in precise (down to 100 µm resolution) [7], well-defined cantilevers made of PVDF, a material that is often too delicate for processing via traditional clean room microfabrication techniques. The passivation layer on the PVDF cantilevers maintains them electrically isolated from each other for reliable measurements. The platform is robust, requires only straightforward assembly, and can be readily customized depending on application (e.g. rat vs. guinea pig spinal cord).

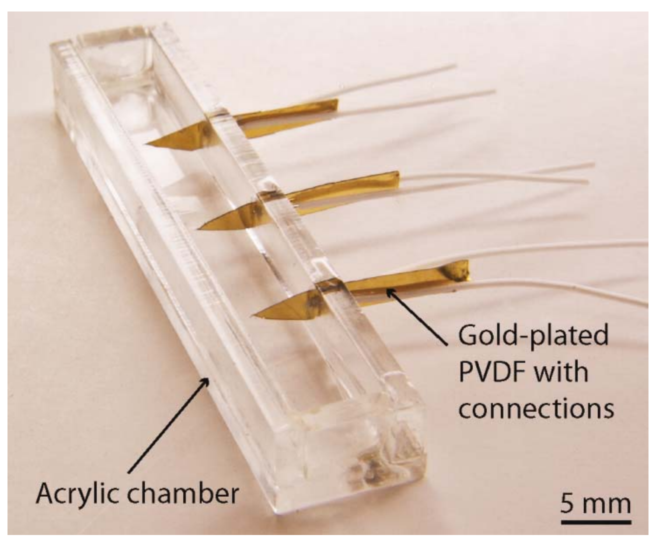

Figure 3. A photograph of the spinal cord strain sensor test chamber with three cantilevers. The number of cantilevers can be customizedq by laser and cutter plotter machining for future applications .

Figure 4 shows the cantilever characterization in response to vibrational frequencies between 10 kHz and 1 MHz, a range including typical impulse frequencies used during spinal cord injury experiments [6]. The data reveal a maximum cantilever deflection of up to 58 nm at its resonant frequency, near 50 kHz. The cantilever length and thickness can be modified to alter the resonant frequencies in order to achieve high resolution measurements at other frequencies. The cantilevers can, thus, be used for measuring strain in order to determine induced spinal cord stresses [8].

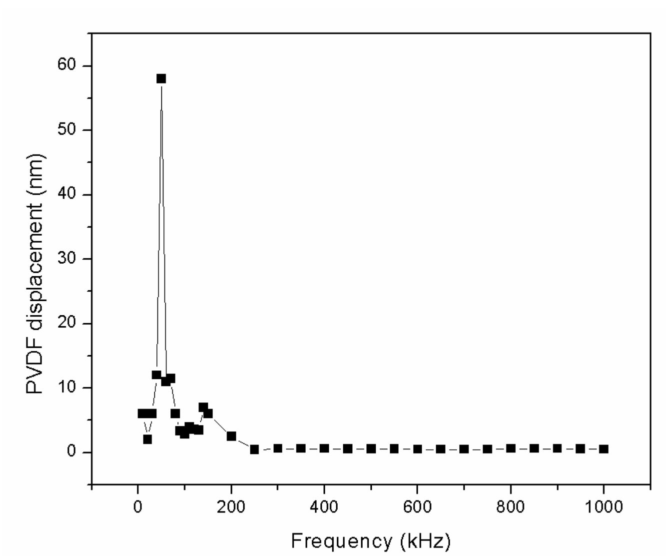

Figure 4. The PVDF cantilevers are characterized by mechanically stimulating a cantilever at various frequencies, revealing a deflection of 58 nm is at the cantilever's resonant frequency (~50kHz).

Validation of the sensor structure as a suitable platform for testing spinal cords is established by observing the voltage response of various cantilevers along a gel-based cord phantom. When the gel is impacted with 40 kPa of pressure, the voltage measurements recorded at two distances from the point of impact reveal significantly different magnitudes; in particular the voltage detected at 5 mm from the injury site is 37 mV and that at 20 mm from the site is 21 mV (Figure 5). In addition to the spatial response, Figure 5 shows the time response of the gel, allowing the strain velocity to be deduced from the data. These data can be calculated at enhanced precision simply by increasing the quantity of cantilevers along the spinal cord length.

VI. CONCLUSION

An inexpensive strain sensing platform for spinal cord injury (SCI) experiments has been fabricated and characterized. The platform consists of PVDF cantilevers lined along a wall of an acrylic open test chamber. The platform is fabricated by rapid prototyping techniques, using a laser system for fabricating an acrylic chamber and a craft cutter plotter for machining PVDF into cantilevers. When a spinal cord on the platform is mechanically stimulated, its strain response is converted to electrical signals via the PVDF cantilevers. The fabricated cantilevers exhibit a displacement of 50 nm at the resonant frequency (~50 kHz). Voltage from a cantilever in a cord phantom has been recorded at two distances from the point of impact, showing 37 mV at 5 mm and 21 mV at 20 mm for a 40 kPa impact. The chamber and cantilever geometry can be easily modified for use in custom SCI experiments around the world.

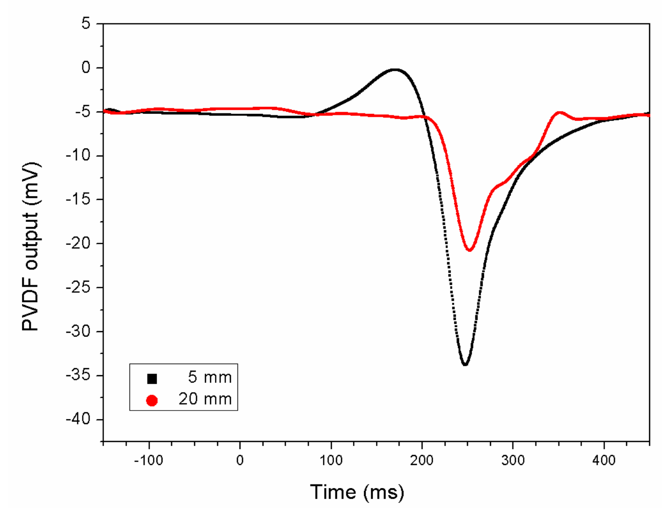

Figure 5. Electrical signals from a single cantilever recorded at 5 mm and 20 mm from the point of impact show a measurable difference in PVDF output voltage.

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