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Technical note

Development of an instrumented spinal cord surrogate using optical fibers: A feasibility study

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ABSTRACT

In vitro replication of traumatic spinal cord injury is necessary to understand its biomechanics and to improve animal models. During a traumatic spinal cord injury, the spinal cord withstands an impaction at high velocity. In order to fully assess the impaction, the use of spinal canal occlusion sensor is necessary. A physical spinal cord surrogate is also often used to simulate the presence of the spinal cord and its surrounding structures. In this study, an instrumented physical spinal cord surrogate is presented and validated. The sensing is based on light transmission loss observed in embedded bare optical fibers subjected to bending.

The instrumented surrogate exhibits similar mechanical properties under static compression compared to fresh porcine spinal cords. The instrumented surrogate has a compression sensing threshold of 40% that matches the smallest compression values leading to neurological injuries. The signal obtained from the sensor allows calculating the compression of the spinal cord surrogate with a maximum of 5% deviation. Excellent repeatability was also observed under repetitive loading.

The proposed instrumented spinal cord surrogate is promising with satisfying mechanical properties and good sensing capability. It is the first attempt at proposing a method to assess the internal loads sustained by the spinal cord during a traumatic injury.

1. Introduction

Traumatic spinal cord injury (TSCI) occurs at an annual incidence of 10–60 cases per million inhabitants depending of the country [1]. In the United States, the annual incidence is about 40 cases per million and the prevalence is estimated at 721 per million [1]. TSCI can potentially damage motor and sensory function, leading to a loss of autonomy and a poor quality of life. Burst fractures and fracture dislocations are responsible for respectively 30% and 40% of all TSCI [2]. They are often accompanied by a certain degree of spinal cord canal occlusion due to bone fragment, ligaments or other structure compromising the spinal canal and compressing the spinal cord. The amplitude and distribution of stresses and strains in the spinal cord influence the potential of neurological impairment [3]. The compression rate of the spinal cord during the trauma is also known to be a determinant factor of the neurological outcome [4].

Spinal cord residual compression is diagnosed by clinical X-ray observations performed after the injury. But despite their clinical relevance, imaging techniques can only give information about the post-injury compression. They do not provide insight about the acute compression. This is of critical relevance knowing that no correlation was found between the post-injury compression and the long term neurological outcome [5], probably because the residual compression is not necessarily related to the acute compression [6,7].

Accordingly, global and local spinal cord deformation occurring during those injuries is poorly understood [8]. A better knowledge of the injury's biomechanics could lead to improved understanding of the extent of neurological injury due to the impaction of the spinal cord during the trauma, and improved prevention devices and cares. In order to obtain such information, *in vitro* repro-

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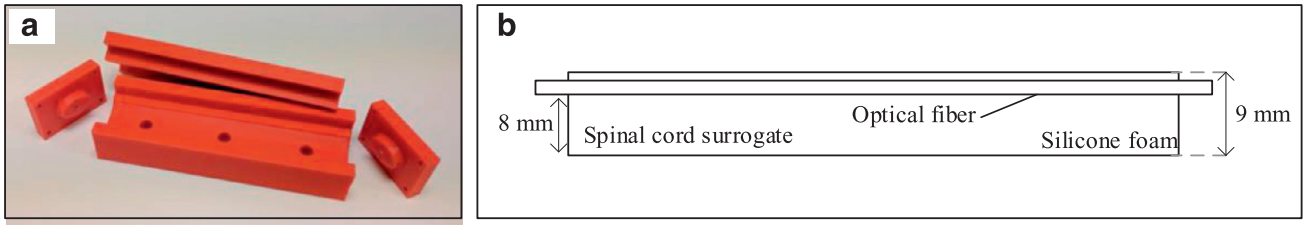

Fig. 1. (a) Picture of the 3D printed ABS casting mold and (b) schematic representation of the instrumented spinal cord surrogate.

duction of the trauma is necessary and must be combined with a spinal canal occlusion measurement technique.

Several studies have been published about the development of technologies capable of recording the spinal canal occlusion. Some authors used a water filled, flexible polymer tubing, which is inserted into the spinal canal of cadaveric spine segments prior to *in vitro* fracture replication [9,10]. Changes in the tubing diameter were evaluated by recording changes of the water pressure. Such technology allows the evaluation of the spinal canal occlusion both statically and dynamically but does not reproduce the mechanical properties of the spinal cord and its surrounding structures. Ignoring its mechanical properties can influence the recorded compression as the spinal cord may provide resistance to the compression and therefore, affect the spinal canal occlusion. Other used a saline filled polymer tubing as spinal canal occlusion transducer [11–14]. Canal occlusion was evaluated by measuring changes in the resistivity of the saline. Again, no attempt was made to reproduce the biofidelic mechanical properties of a real spinal cord.

More recently, an improved physical surrogate of the human spinal cord was developed using silicone rubber that can be made radiopaque [15]. The same radiopaque physical surrogate was used to measure the spinal canal occlusion *in vitro* with the help of a high speed fluoroscope [16]. This impressive work is however limited by a 1000 Hz frame rate which seems low considering that during burst type fracture, the retropulsed bone fragment can impact the spinal cord at 4.5 m s^{-1} [7]. This technique allows quantifying the spinal compression in the sagittal plane only and does not give information about the complete layout of injury. The high speed fluoroscope is also an advanced and costly equipment which might not be available to all research groups.

Unfortunately, there has been no attempt so far at measuring the internal forces and strains sustained by the spinal cord during the trauma. It appears necessary to develop an instrumented physical spinal cord surrogate that replicates the mechanical properties of the biological organ with compression sensing capability. In this study, we investigate the use of optical fiber as a hair-like sensing element embedded into a physical spinal cord surrogate.

Optical fiber bend loss is a well-known phenomena [17] and has been used for several sensing applications [18–23]. It refers to the optical power loss occurring when an optical fiber is bent to a given curvature radius. In this feasibility study, we propose the use of bare optical fibers as sensing elements to evaluate the compression of a physical spinal cord surrogate based on light intensity modulation. This paper presents the mechanical characterization of the manufactured surrogate as well as its sensing capability using one optical fiber.

2. Material and method

2.1. Physical surrogate production

The spinal cord physical surrogate was made of silicone rubber foam (FlexFoam-iT! III, Smooth-on, PA, USA) obtained by mixing the two liquid parts in adequate proportions. The liquid silicone foam was then quickly poured into the 3D printed ABS casting mold shown in Fig. 1(a). The resulting silicone cord was 20 cm long and had an ellipsoidal section (major diameter of 11 mm and minor diameter of 9 mm) replicating the human thoracic spinal cord transverse section [24]. During casting and curing of the silicone rubber foam, a 0.6 mm diameter nylon wire ran longitudinally through the surrogate. After silicone curing, the wire was removed and replaced by a 242 µm diameter bare optical fiber. With this technique, the fiber was free to slide with respect to the silicone rubber foam and could not significantly influence the mechanical properties of the surrogate. Also, in this configuration, the fiber was not subjected to axial strain during mechanical testing. Fig. 1(b) shows a schematic of the surrogate, with the optical fiber located 8 mm from its lower surface.

2.2. Mechanical characterization

Mechanical testing was performed using an Enduratec ELF 3200 Series (TA Electroforce, DE, USA). Mechanical characterization was performed with transverse compression loading at 0.5 s^{-1} (static), 5 s^{-1} and 50 s^{-1} (dynamic) strain rates as suggested by Fradet et al. [25]. Force was recorded using a miniature loadcell (0–400 N) while displacement was recorded using the linear variable differential transducer (LVDT) built in the testing apparatus. Displacement and force were recorded at 10 and 5000 Hz for the static and dynamic loading respectively using a NI USB 6212 data acquisition card (National Instruments Corporation, TX, USA) and a custom Labview program (National Instruments Corporation, TX, USA). The complete contact between the impactor surface and the sample was adjusted through the application of a pre-load of 0.2 N. Stress applied on the surrogate during compression was calculated as the force divided by the compression area of the 9.5 mm diameter steel impactor which has a size similar to impactors used in TSCI animal model investigation [26–29]. Transverse compression was calculated by dividing the displacement of the impactor by the thickness of the surrogate (9 mm). Compression was limited to about 65% to avoid permanent damages to the surrogate under repetitive testing. Fig. 2 shows a picture of the instrumented surrogate under testing.

2.3. Compression sensing

The sensing element is an embedded 242 µm diameter SMF28 single mode optical fiber (Corning Incorporated, NY, USA). As the surrogate is being compressed, the fiber bends to adapt to its geometry which leads to changes in the transmitted optical power due to bend-induced losses. To assess the compression sensing capability of the technology, the surrogate was statically compressed at 0.2 mm s^{-1} and dynamically at 500 mm s^{-1}. A 1550 nm wavelength source excitation was generated by a tunable laser (81682A model, Agilent Technologies, CA, USA). The transmitted optical power was continuously recorded at the optical fiber output using a PM100D power meter equipped with a S145C power sensor (both from Thorlabs Inc, NJ, USA). Recording of the output optical power

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