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FBG-Based Transverse and Axial Force-Sensing Micro-Forceps for Retinal Microsurgery

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Abstract

Retinal microsurgery routinely requires the manipulation of extremely delicate tissues. Membrane peeling is a prototypical task where a layer of fibrous tissue is delaminated off the retina with a micro-forceps by applying very fine forces that are mostly imperceptible to the surgeon. Previously we developed sensitized ophthalmic surgery tools that can precisely detect the transverse forces at the instrument's tip via integrated fiber Bragg grating strain sensors. This paper presents a new design that employs an additional sensor to capture also the tensile force along the tool axis which can be significant in membrane peeling. We investigate two distinct fitting methods to compute the transverse and axial forces based on sensor outputs. Validation with random samples shows that the linear method closely predicts the transverse force but does not provide sufficient accuracy in computing the axial load. Our nonlinear method resolves this problem, providing a more consistent and accurate measurement of both the transverse and axial forces.

Keywords

fiber Bragg grating; force sensing; micro-forceps

I. Introduction

In retinal microsurgery, membrane peeling is a standard procedure requiring the delamination of a thin (micron-scale) fibrous membrane adherent to the retina surface. After firmly grasping the membrane with a micro-forceps tool, surgeons pull the membrane away from the retina surface very slowly trying to avoid deleterious force transfer to the retina (Fig. 1a). During the procedure, applying excessive peeling forces can harm retinal vasculature and cause serious complications potentially leading to irreversible damage and loss of vision [1]. Most of the peeling forces were shown to be less than 7.5 mN in porcine cadaver eyes [2], which is well below what surgeons can feel. Therefore, continual monitoring of tool-to-tissue interaction via a sensitized instrument is essential to limit forces at a safe level either manually through auditory feedback or via robotic assistance [3].

In order to measure the very fine peeling forces (typically less than 10 mN), sensing instruments with mN accuracy are required. The size and biocompatibility constraints limit the available sensors for this application. The force sensor has to be able to pass through a small incision on the sclera (max. $\varnothing$ 0.9 mm) so that it can be located close to the tool tip

inside of the eye. Only in this way can force measurements pertain solely to the instrument's tip, with no adverse contribution from the sclera [4]. Fiber Bragg grating (FBG) sensors, which are optical fibers that detect changes in strain, are able to address these limitations.

Using FBGs, we previously developed several force-sensing retinal microsurgery tools, including manually actuated [5], and motorized force-sensing micro-forceps for use with robotic systems [6]. These instruments were shown to accurately capture transverse forces during various tissue manipulation tasks; however they did not provide any axial force information, which can be important in case of membrane peeling. Previously, we developed a force-sensing pick instrument that can sense both transverse and axial forces [4]; nevertheless, it does not provide the necessary grasping functionality, and the implemented force sensing principle is not directly transferable to a micro-forceps due to the required open/close action at the jaws. In this study, we present a novel motorized force-sensing micro-forceps that can detect both the axial and transverse force during membrane peeling.

II. Tool Design

Our micro-forceps consists of a grasping mechanism and force-sensitive elements as shown in Fig. 1. The actuation unit houses a compact ($28 \times 13.2 \times 7.5$ mm) and lightweight (4.5 g) piezoelectric linear motor (M3-L, New Scale Technologies Inc., Victor, NY) with its embedded driver and encoder providing precise position control, which is used for opening and closing the forceps jaws. The normally-open compliant jaws are passed through a 23 Gauge guide tube and firmly anchored to the actuation unit via a set screw. The guide tube is attached to the shaft of the linear motor, so that when the motor is actuated, the guide tube is moved up and down along the tool axis, releasing or squeezing the forceps jaws.

In order to sense the applied forces after the membrane is grasped, the design employs 4 FBGs ($\varnothing 80$ μ m by Technica, GA, USA). Following a similar strategy as in our previous force-sensing tools [4–6], 3 lateral FBGs are fixed evenly around the guide tube to capture the transverse forces at the tool tip. This results in a sufficiently small tool shaft diameter of 0.9 mm. New in this work is the fourth FBG responsible for detecting the tensile axial forces while the membrane is pulled away from the retina. The location of this sensor is critical to maximize accuracy. Our initial concept hypothesized that centrally locating this sensor inside the guide tube at the distal end of jaws (Fig. 1b) could provide the best decoupling between transverse and axial forces. In this configuration, although the sensor is positioned along the neutral axis for transverse loads and thus should sense only the axial loads, our preliminary experiments have shown that the frictional and elastic deformation forces generated at the guide tube/jaw interface during tool actuation significantly degrades the response of the sensor. As a remedy, we studied an alternative concept, where the forceps jaws are modified by flattening one arm (Fig. 1c). When the guide tube is moved up and down, the flat arm is kept straight always while the other bent arm in contact with the guide tube elastically deforms to open/close the jaws. The central FBG is fixed on the flat arm of the jaws, where the sensitive region of the fiber is maintained close to the jaw tip outside the guide tube, bypassing the undesired actuation forces at the guide tube/jaw interface.

III. Force Computation Algorithm

A. Linear Method

■ **Transverse Force Computation**—The elastic deformation of the guide tube can be modeled as an Euler-Bernoulli beam under transverse (F^{tr}) and axial (F^{ax}) loading at the tool tip, inducing a linearly proportional local elastic strain on each of the attached lateral FBGs and thus a linearly proportional shift in the Bragg wavelength of each sensor. In addition, even slight variations in ambient temperature (T) may cause a drift in the Bragg wavelength. Then, the combined Bragg wavelength shift ($\Delta\lambda_i$) for each lateral FBG (FBGs 1, 2 and 3) can be expressed as

$$\Delta\lambda_i = C_i^{F-tr} F^{tr} + C_i^{F-ax} F^{ax} + C_i^{\Delta T} \Delta T, \text{ where } i = 1, 2, 3 \quad (1)$$

where C_i^{F-tr} , C_i^{F-ax} and $C_i^{\Delta T}$ are constants. As detailed in [4], the effect of temperature and axial load in eqn. (1) can be eliminated by subtracting the common mode from the individual wavelength shift of each sensor. The transverse force is computed using the remaining differential mode ($\Delta\lambda_i^{diff}$) in the linear mapping given by eqn. (2), where C^{tr} is a coefficient matrix found by calibration [4].

$$F^{tr} = C^{tr} [\Delta\lambda_1^{diff} \quad \Delta\lambda_2^{diff} \quad \Delta\lambda_3^{diff}]^T \quad (2)$$

■ **Axial Force Computation**—In our design, in addition to the elastic strain due to axial load, the axial FBG (FBG 4) experiences also a bending moment induced by the transverse force at the tool tip. Furthermore, changes in ambient temperature will induce a drift in the measured Bragg wavelength. Since the axial and transverse FBGs share the same environment, we hypothesize that the thermal drift of the axial FBG and that of the common mode of the three lateral FBGs are linearly correlated. Based upon this hypothesis, multiplying the common mode of lateral FBGs (λ^{mean}) with a proper coefficient (κ) and subtracting it from λ_4 , the effect of temperature change can be eliminated.

$$\Delta\lambda_4^{diff} = \Delta\lambda_4 - \kappa \Delta\lambda^{mean} = C^{ax} F^{ax} + C_4^{F-tr} F^{tr} \quad (3)$$

Since F^{tr} is already found based upon lateral FBGs, the axial load can be computed after C^{ax} and C_4^{F-tr} constants are identified via calibration.

$$F^{ax} = (\Delta\lambda_4^{diff} - C_4^{F-tr} F^{tr}) / C^{ax} \quad (4)$$

B. Nonlinear Method

Due to the very small dimensions and imperfections in tool fabrication, it may not be possible to accurately decouple the effect of axial and lateral loads using a linear model, especially on the axial FBG. We hypothesize that such a linear fitting may perform well only locally, when the transverse forces are much smaller than the axial load. In order to obtain a global estimate of force, a nonlinear fitting method based on Bernstein polynomials can be used as

$$F = \sum_{i=0}^n \sum_{j=0}^n \sum_{k=0}^n \sum_{l=0}^n c_{ijkl} b_{i,n}(\Delta\lambda_1^*) b_{j,n}(\Delta\lambda_2^*) b_{k,n}(\Delta\lambda_3^*) b_{l,n}(\Delta\lambda_4^*) \quad (5)$$

$$\begin{bmatrix} F^{tr} & F^{ax} \end{bmatrix} = B C^{Bernstein}$$

where the coefficients in $C^{Bernstein}$ can be found by applying known forces (F^{tr} and F^{ax}) in various directions at the tool tip and monitoring the corresponding FBG data ($\Delta\lambda_i^*$).

IV. Experiments and Results

A. Calibration

In order to identify the constants used in our force computation algorithm, we performed a set of calibration experiments. The goal in our first experiment was to test the hypothesis of linear correlation between the temperature drift in common mode of lateral FBGs and the axial FBG. Using an optical sensing interrogator (sm130-700 from Micron Optics Inc., Atlanta, GA), we recorded the Bragg wavelength of all FBGs during a 180 minute period with 15 minute intervals while exposing the tool to routine changes in room temperature. The wavelength shift of the lateral FBGs were observed to be almost identical (Fig. 2b). The change in the common mode of lateral FBGs and the shift in the axial FBG could be linearly correlated as shown in Fig. 2c ($R^2=0.93$). The corresponding proportionality constant was found to be $\kappa = 0.69$.

Our second experiment was for modeling the lateral and axial FBG response under various forces. For this, we mounted our forceps on a rotary stage and used the jaws to grasp a wire hook (Fig. 2a). By hanging various loads on the hook and modulating the tool orientation (θ) the axial and transverse forces at the tool tip were changed. Measurements were taken for loads ranging from 0 to 25 mN with 5 mN intervals and at angles from $\theta=0^\circ$ (entirely axial loading) to $\theta=90^\circ$ (entirely transverse loading) with 15° intervals. This produced 42 distinct loading cases; and at each orientation, the tool tip was repeatedly loaded/unloaded 3 times. The obtained response for 3 illustrative orientations is shown in Fig. 3. When the tool was held at $\theta=0^\circ$, the entire loading was axial, therefore affecting only the axial FBG linearly with a slope of 0.78. This suggests $C^{ax}=0.78$ pm/mN in eqn. (3). At $\theta=90^\circ$, the induced force was purely transverse which caused a linear response in all FBGs. The sensitivity of the axial FBG in this orientation revealed $C_4^{F-tr} = 2.32$ pm/mN. Based upon the slope of

lateral FBG response curves, the coefficient matrix in eqn. (2) was found as $C^T = [-0.0342 \ 0.089 \ -0.0548]$ mN/pm. The wavelength resolution of our interrogator is 1 pm, which propagates to a transverse force resolution of 0.17 mN and an axial force resolution of 1.8 mN considering the identified coefficients for the linear method. Finally, using the entire data set of 252 measurements, the least squares problem formulated in eqn. (5) was solved to find $C^{\text{Bernstein}}$. The identified coefficient provided a transverse force resolution of 0.08 mN and an axial force resolution of about 1.08 mN. The fit polynomial could estimate the transverse and axial forces in the calibration data set with mean absolute residual errors of 0.11 mN and 1.23 mN and RMS errors of 0.15 mN and 1.69 mN, respectively.

B. Validation

Forces ranging from 0 mN to 25 mN were applied on the tool with 5 mN intervals at 20°, 40° and 70° orientations; each test was repeated 6 times, producing 108 measurements. The data set was extended by adding 15 more measurements at randomized angles (0°–90°) and forces (0–25 mN). Our first attempt to estimate applied force using a linear model performed well for the transverse load with an RMS error of 0.13 mN (Fig. 4a), though did not provide an adequate accuracy in finding the axial force (Fig. 4b). The linear method produced an RMS error of 2.05 mN for cases with a transverse force less than 5 mN, but when larger (up to 25 mN) transverse loads were involved, the RMS error in the computed axial force rose up to 5.14 mN. This indicates that the linearity of sensor response is lost when large transverse forces are applied at the tool tip in addition to axial loads. Our second approach, the Bernstein polynomial method, showed similar success in estimating the transverse force with an RMS error of 0.22 mN (Fig. 4c). More importantly, the accuracy in axial force estimation was significantly improved with a much smaller RMS error of 1.99 mN (Fig. 4d) for the entire force range (0–25 mN), which is closer to the required accuracy for feasibility in membrane peeling. Our future work aims at investigating other tool architectures preserving the axial symmetry of the tool and providing better axial force sensing accuracy.

Acknowledgments

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Figure 1.

Force-sensing micro-forceps conceptual overview. (a) Epiretinal membrane peeling. (b) Axial FBG in the center: actuation force (F^{act}) degrades the sensor reading. (c) Axial FBG attached on the flattened arm of the jaw: bypassed F^{act} and direct exposure to tool tip forces (F^{ax} and F^{tr}).

Figure 2.

(a) Fabricated prototype and experimental setup. (b) Thermal drift in lateral (FBGs 1–3) and axial (FBG 4) sensor readings. (c) Linear correlation between the common mode of lateral FBGs and the axial FBG.

Figure 3.

Lateral (FBGs 1–3) and axial (FBG 4) sensor response to loading (0–25 mN) at the tool tip for three different orientations ($\theta = 0^\circ, 45^\circ, 90^\circ$).

Figure 4.

Computed transverse and axial forces vs. the actual values. Similar accuracy for both methods in estimating the transverse load, better performance with the polynomial method for estimating the axial load.