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Safe Tissue Manipulation in Retinal Microsurgery via Motorized Instruments with Force Sensing

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Abstract

Retinal microsurgery involves careful manipulation of delicate tissues by applying very small amount of forces most of which lie below the tactile sensory threshold of the surgeons. Membrane peeling is a common task in this domain, where application of excessive peeling forces can easily lead to serious complications, hence needs to be avoided. To quantify tool-tissue interaction forces during retinal microsurgery, various force-sensing tools were developed based on fiber Bragg grating sensors, yet the most beneficial way of using the acquired force information is currently unknown. In this study, using a motorized force-sensing micro-forceps tool, we develop an assistive method that enhances safety during membrane peeling by automatically opening the forceps and releasing the tissue based on the detected peeling forces. Through peeling experiments using bandages, we demonstrate that our method can effectively maintain the peeling force at a safe level even in case of non-homogeneous adhesion properties of the membrane.

Keywords

fiber Bragg grating; force sensing; micro-forceps

I. Introduction

In retinal microsurgery, precise manipulation of delicate tissues by applying very small forces is required. Membrane peeling is a typical task in retinal microsurgery, where micron-scale fibrous membrane adherent to the retina is delaminated, either by using a pick or a micro-forceps tool. The peel needs to be completed by exerting very fine forces with a small pace of generation on the retina [1], which routinely lie below the surgeon's sensory threshold. Application of excessive forces with abrupt changes may damage retinal vasculature [2], and lead to serious complications, such as iatrogenic retinal injury and breaks [3], vitreous hemorrhage, or subretinal hemorrhage [4]. Currently, surgeons adjust their peeling rate, and therefore applied forcing, based on indirect visual cues, such as changing light reflections from the deforming tissue, which requires a great concentration and significant experience.

Various techniques have been proposed for quantifying tool-tissue interaction forces in microsurgery and minimal invasive surgery (MIS), which nevertheless have several limitations that impede their application to retinal microsurgery. In order to measure the very small forces in retinal microsurgery (typically less than 10 mN based on studies using animal models [1]), sub-mN force sensing resolution and accuracy are required. Furthermore, in retinal microsurgery, the tools are inserted through a sub-millimetric incision on the sclera, and the contact forces at the insertion port are considerably larger than the tissue manipulation forces at the tool's tip. Therefore, a handle mounted force sensor is not practical as the measurements would involve not only the tool-tissue interaction forces but also the adverse effect of frictional and displacement forces at the insertion port [5]. This necessitates positioning the force sensor proximal to the tool tip inside the eye, which imposes strict dimensional constraints as well as biocompatibility, sensitivity and safety requirements.

Fiber Bragg grating (FBG) strain sensors can detect very fine changes in strain (less than 1με) in real time [11]. They are very small (Ø 60–200 μm) and hence can fit through narrow openings, inherently safe, biocompatible, sterilizable, relatively inexpensive, and highly sensitive; furthermore, their output is immune from electrostatic and electromagnetic noise. To provide the surgeon with real-time physiological information and assist maneuvers during retinal surgery, various force-sensing instruments have been developed based on FBG sensors. Some of these tools were motorized, which led to independently actuated modular tools and enabled their use in combination with robotic systems for precise manipulation without hand tremor [6,7].

Since tool manipulation and decision making while trying to maintain the exerted forces at a safe level relies on the real-time information received from the environment, this information needs to be presented to the surgeon in an intuitive, real time, easy to process and overlay means. Visual feedback was experimented with and found distracting by retinal surgeons, while haptic and auditory feedback have been identified as the potentially useful methods that can be directly perceived, and have minimal conflict with other human sensing channels [8]. For improved safety with reduced surgeon effort during the surgery, this study takes membrane peeling procedure as a testbed and contributes a new method to automatically release the grasped tissue in case the peeling forces reach a critical level to effectively prevent deleterious force transfer to and hence irreversible injuries on the retina.

II. Force-Based Automatic Tissue Release

By embedding FBG sensors around the tool shaft (Fig. 1) in our previous work, we developed micro-forceps tools that detect tool-tissue interaction forces transverse to the tool shaft at the tool tip with a fine enough resolution (0.25 mN), within an accuracy of 0.3 mN, and with immunity to ambient temperature changes [6]. Recently, this concept was extended to provide also the axial force sensing via an axial FBG in the center of the tool shaft (Fig. 1b) [7].

To firmly hold the tissue in membrane peeling, our micro-forceps tools [6,7] work based on a grasping mechanism actuated by a motor inside the tool body (Fig. 1a). The motorized mechanism enables mechanically decoupled actuation of the jaws from the handpiece, remote control via a touch sensor and hence easier integration with robotic platforms (Fig.

1c), such as the handheld tremor canceling micromanipulator Micron [9]. The firm grasp provided by the forceps provides better control of the tissue with less slippage; however, this also leads to a more rigid tool-tissue coupling and hence a direct correlation between tool tip motion and the exerted forces on the retina. In addition, the adhesion between the membrane and the retina can vary locally. Adapting to the nonuniform peeling behavior and maintaining the applied force below injurious levels manually is not a trivial task. In case rapidly increasing forces are detected at a critical level, opening the forceps and releasing the grasped membrane can be an effective and simple aid to prevent direct transfer of excessive forces and hence damage to the retina. For a proper operation, though, the knowledge of critical force levels causing retinal injuries is needed, which has not been studied in human eyes yet, mainly due to the lack of force-sensitive functional instruments in vitreoretinal practice until this time. Earlier experiments using animal models reported that retinal injuries are associated with forces beyond 7.5 mN [10]. Taking this as a reference, we programmed our micro-forceps to automatically open and release the grasped tissue if the detected tissue manipulation forces reach 7.5 mN.

III. Experiments and Results

A. Experiment 1: Peeling a Non-Homogenous Membrane at Constant Rate

We tested our automatic tissue release feature by peeling a nonuniform bandage strip using our motorized force-sensing micro-forceps. In the setup shown in Fig. 2a, the force-sensing tool is attached to the Micron, which is held stationary clamped in a vise. The bandage phantom is placed on a linear stage to be driven relative to the micro-forceps at a fixed speed, and hence peeled off at a fixed rate of 0.15 mm/s based on the range encountered in an actual surgery. The total length of the bandage strip was approximately 9 mm taking around 60 seconds per peel. To introduce inhomogeneity, after about the 5th mm, an extra second layer (about 2.5 mm long, marked in orange in Fig. 2b) was attached onto the bandage strip, leading to a local change in the peeling behavior and emulating a stickier region in case of a real membrane peeling surgery. Experiments were performed in 2 sets, each set consisting of 3 trials, the first set using the default force-sensing mode and the second set using the automatic tissue release mode of our micro-forceps. Results in Fig. 3 show that all 3 trials in each set output similar behavior. Without the auto-release feature, the detected forces rapidly increase and go beyond the safe level (7.5 mN) right after reaching the double layered portion of the phantom. When the automatic tissue release mode is used, as soon as the force reaches the critical value, the jaws are opened by quickly retracting the forceps motor and releasing the bandage. The peel could not be completed in a single grasp in this case, but the transfer of forces beyond the safety threshold was successfully avoided.

B. Experiment 2: Auditory Force Feedback vs. Automatic Tissue Release

This experiment aimed at comparing the performance with the developed tissue release aid versus the previously used auditory feedback mechanism [8] in the presence of varying peeling properties. Different than the previous experiment, the phantom was maintained fixed while the micro-forceps tool was moved by hand to approach, grasp and peel off the bandage. During the first trial, the user was provided with auditory feedback to help maintain the forces below 7.5 mN manually. Despite the effort, forces exceeding 7.5 mN still appear in Fig. 4a. When the automatic release feature was used, the forceps let go of the bandage as soon as the applied force reached 7.5 mN threshold, which happened 8 times in total, mostly while peeling off the double layered sticky segment of the phantom. After each release, the bandage had to be grasped again to continue the peel. This caused a slight delay, leading to a task completion of 141.96 seconds in comparison to 106.30 seconds with the default auditory force feedback mode. Nevertheless, forces were successfully maintained below the safety threshold, 7.5 mN, throughout the peel (Fig. 4b).

IV. Conclusions

In this work, we presented an automatic tissue release feature which demonstrated a potential benefit of motorizing and sensitizing the ophthalmic instruments for enhanced safety during retinal microsurgery. The method is based on our previously developed force-sensing micro-forceps. The motorized grasping mechanism provides a firm grasp of the membrane for controlled peeling, but also automatically releases the grasped tissue quickly based on the detected peeling forces to avoid injurious force transfer on the delicate retina. Although this causes an intermittent operation overall with multiple grasp attempts, which may increase the overall operation time, our preliminary experiments using bandages demonstrated that with the automatic tissue release feature ensures completion of the peel without any forces beyond the set safety threshold. This is potentially beneficial especially in case of highly nonuniform adhesion properties across the membrane, where the operator is challenged by dynamically adjusting the peel rate. Our future work aims at assessing the feasibility of this method through peeling experiments using inhomogeneous phantoms and biological membranes.

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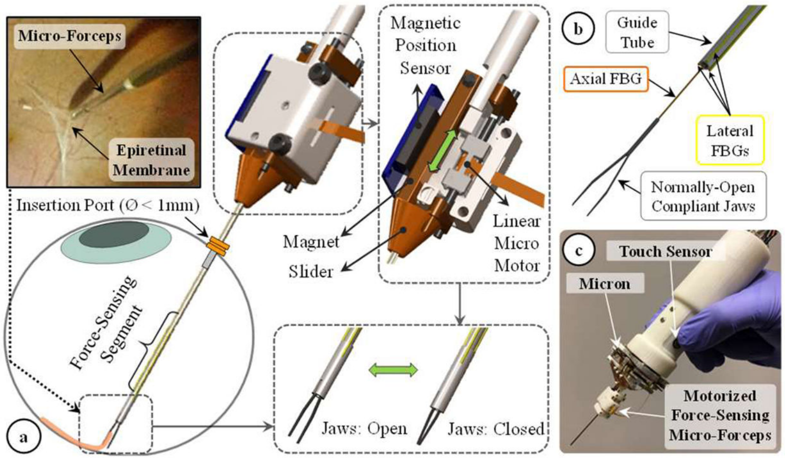

Figure 1.

Force-sensing motorized micro-forceps [6]: (a) The small motor inside the tool body provides a firm grasp of the membrane while peeling; (b) Integrated FBGs on the tool shaft measure tool-tissue interaction forces at the tool tip. (c) The tool can be combined with tremor canceling robots, such as the Micron system [9], and the grasping action can be remotely controlled by locating a touch sensor on the tool handle.

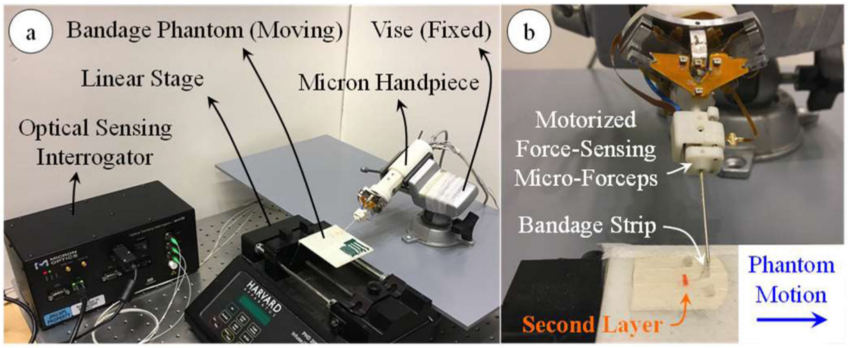

Figure 2.

Experimental setup for testing the automatic tissue release feature. (a) Micron with the motorized force-sensing micro-forceps was held fixed in a vise while the bandage phantom was mounted on a linear stage. (b) A bandage strip on the phantom was grasped with the micro-forceps and driven relative to the tool to perform the peel at constant speed. To introduce inhomogeneity, a second layer (shown in orange) was attached onto the bandage strip.

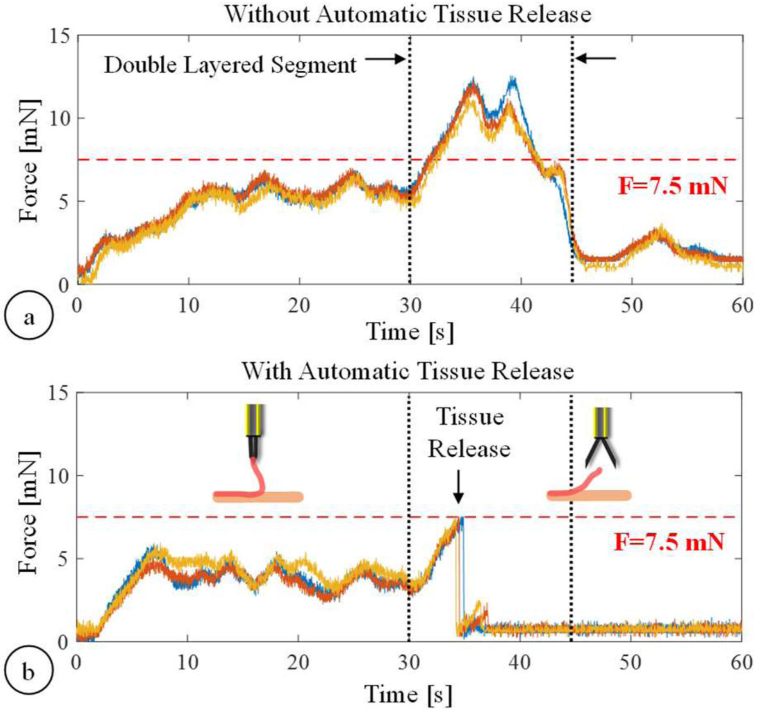

Figure 3.

Sensed forces while peeling off a bandage strip at a constant rate (a) without and (b) with the automatic tissue release feature. With the automatic tissue release, after reaching the double layered segment of the phantom, when the force reaches the defined threshold (dashed red line at 7.5 mN), the forceps jaws quickly open to release the tissue and prevent excessive peeling forces.

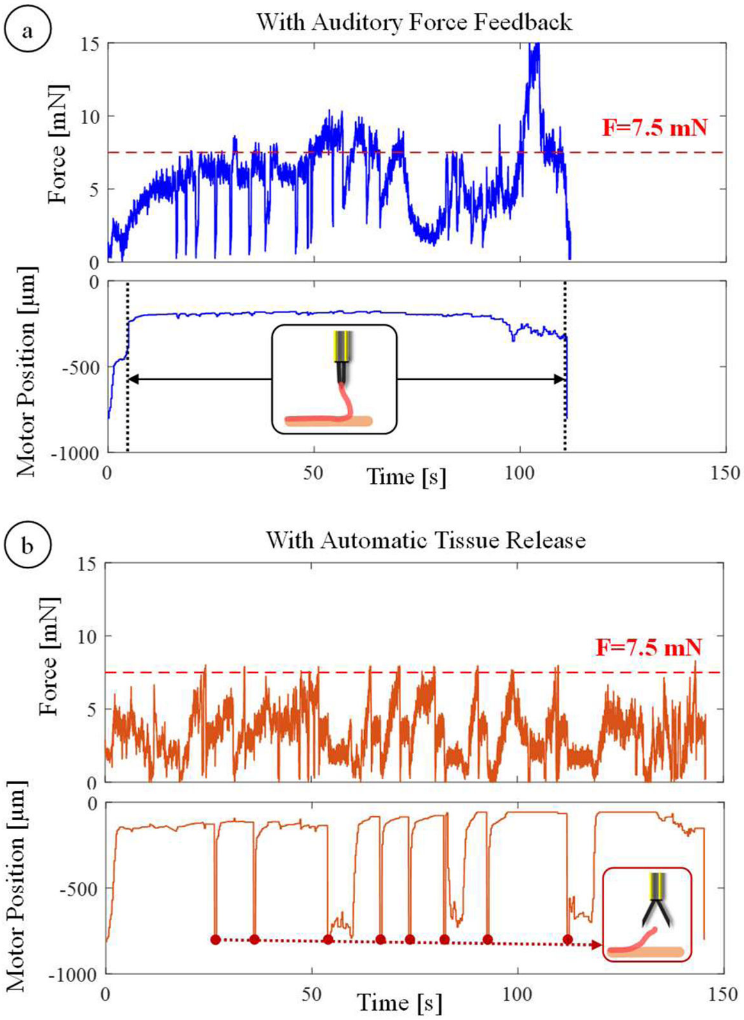

Figure 4.

The force and motor position of micro-forceps while peeling the bandage (a) with auditory force feedback and (b) with the automatic tissue release feature. With auditory feedback, its challenging to adapt to the changing phantom properties and peel off the double layered segment while maintaining the force below the safety threshold (dashed red line at 7.5 mN). The automatic tissue release mode prevents forces above the threshold, but the peel is completed in a longer time since the tissue needs to be regrasped after each tissue release (red dots on the motor position plot).