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Toward Hybrid Position/Force Control for an Active Handheld Micromanipulator

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Abstract—**Vitreoretinal microsurgery requires precise hand-eye coordination to manipulate delicate structures within the eye on the order of tens of microns. To achieve these tasks, surgeons use tools of diameter 0.9 mm or less to access the eye's interior structures. The level of force required during these manipulations is often below the human tactile threshold, requiring the surgeon to rely on subtle visual cues or to apply larger forces above the tactile threshold for feedback. However, both of these methods can lead to tissue damage. Excursions can be made into tissues which are not felt by the surgeon, while larger forces have a higher chance of damaging tissue within the eye. To prevent damage to the retina and other anatomy, we present the implementation of hybrid position/force control operating in the sub-tactile force range for a handheld robotic system. This approach resulted in a 42% reduction in the mean force and 52% reduction in maximum force during peeling tasks.**

I. Introduction

Surgical intervention by membrane peeling is one of the most common procedures performed in ophthalmology. Multiple diseases result in the need to remove the inner limiting membrane (also known as the internal limiting membrane, ILM), epiretinal membrane, or both. The ILM is a natural, thin (1 to 4 µm) membrane in the eye that separates the retina from the vitreous body (a gel-like substance that fills the interior space of the eye). Epiretinal membranes are prevalent in 4-11% of the population age 50 and up [2]. The epiretinal membrane consists of fibrous tissue that forms on the surface of the ILM, typically less than 5 µm thickness [1]. As the epiretinal membrane thickens the patient's vision becomes distorted due to retinal traction. In serious cases the stretching will cause the retina to tear, leading to a macular hole. Without treatment the macular hole can progress to retinal detachment and ultimately a loss of vision.

To remove the forces on the retina creating the macular hole, it has been demonstrated that peeling the ILM and epiretinal membrane is the most effective treatment option for long-term recovery [3][4]. To remove the membrane the surgeon first visually scans the retina surface to identify an appropriate edge for beginning the peel. A hooked tip or microforceps is then used to carefully lift the membrane from the identified edge. However, if the membrane tears or part of the membrane is fully removed, the surgeon must return to the retina surface to begin another peel. The process of removing the membrane requires surgeons to perform multiple manipulations close to the retina surface where many factors contribute to decreased positioning accuracy [5] that may lead to retinal damage. In addition, one group discovered that more than 50% of patients experienced damage to the nerve fiber layer as a result of membrane peeling [6]. Those with damage had partial blind spots in their field of vision. Although the blind spots were unnoticed by the patients, damage to the nerve fiber layer does influence vision and is to be avoided by limiting the forces imposed on the retina.

To accomplish this task a handheld robotic micromanipulator designed for assisting vitreoretinal surgeons is proposed. The peeling task is divided into two tasks; grasping and peeling. During grasping, the surgeon must engage the membrane edge while minimizing contact and damage to the retina surface. After the edge is grasped successfully, the membrane is carefully peeled from the retina. This procedure is often repeated multiple times until the membrane has been completely removed.

To augment surgical performance there are a number of platforms which focus on providing robotic assistance for vitreoretinal surgery. Among these systems are the teleoperated microsurgical robotic system from the

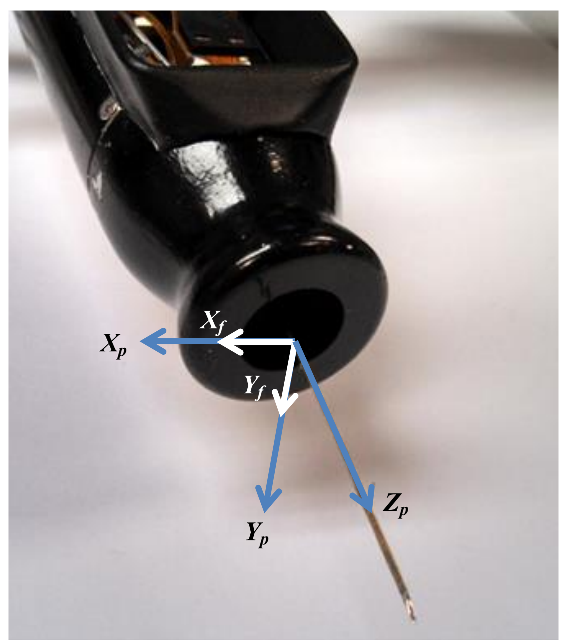

Fig. 1. Micron shown with FBG force sensor installed as the end-effector. Coordinate axes for Micron are shown in blue, denoted with the '*p*' subscript. Sensing axes for the 2DOF FBG sensor are shown in white, denoted with the '*f*' subscript. The sensor axes are aligned with the respective *X* and *Y* Micron handpiece axes.

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University of Tokyo [7], and the Johns Hopkins Steady Hand [8], which shares control between the surgeon and a rigid robotic arm in order to reduce tremor and provide more accurate positioning for the surgeon. To minimize cost and maximize the natural feel of instrument usage, our laboratory has developed Micron [9], a fully handheld micromanipulator which is discussed further in Section II.B.

Balicki et al. have shown success in improving peeling using auditory feedback [10]. However, this is focused more as a training aid for surgeons, and only during the peeling phase, not during the membrane-engaging or grasping phase.

Most recently, Kuru et al. [11] have integrated a small force sensor with microforceps for grasping tasks such as membrane peeling. The surgeon control is augmented by auditory feedback, and combined with the Johns Hopkins Steady Hand robot for peeling of bandages and the inner shell membrane of chicken eggs.

Becker et al. implemented vision-based control for limiting velocity of the tip during peeling [12]. Since a large portion of the membrane peeling is related to the viscoelastic properties of the membrane, as discussed in Section II, this velocity-limiting approach succeeded in limiting applied force. Although this showed promising results, the heavy reliance on visual-based methods does not allow an easy transition between the rubber-based model and a real eye.

Latt et al. have described the implementation of force control in a one-degree-of-freedom (1DOF) handheld micromanipulator [13]. To the authors' knowledge, the present work represents the first implementation of force control in a fully handheld micromanipulator with multiple degrees of freedom.

II. Background

A. Membrane Peeling

The internal limiting membrane is often 4 µm thick or less, making the likelihood of damaging the retina surface when grasping the membrane a high possibility without further assistance. Based on studies by Uneri et al., the initial point of failure for retinal membranes begins near 7.5 mN [8]. However, previous investigation has shown that surgeons are only able to detect roughly 19% of the events that occur near the 7.5 mN threshold [14]. Although the level at which damage occurs to the nerve fiber layer is still unknown, it is undoubtedly below the level of force required to tear the membrane.

B. Micron, a Fully Handheld Micromanipulator

To achieve greater accuracy and implement the hybrid position/force control for peeling tasks, a fully handheld micromanipulator, Micron, is used (Fig. 1). The aim of developing Micron has been to improve the precision and accuracy of the operator [9]. Micron is a 6DOF robot based on a miniature Gough-Stewart platform design, to achieve manipulation of its end-effector over a 4 mm × 4 mm cylindrical workspace. Stabilization of the end-effector is implemented using a 1.5 Hz lowpass filter for the purpose of cancelling normal hand tremor and a special shelving filter that optionally scales user motion by 1/3 when performing fine manipulation tasks.

The 6DOF pose of the handle and manipulator platform are tracked by a custom-built microscale optical tracker, ASAP (Apparatus to Sense Accuracy of Position) [15]. Six near infrared LEDs are affixed to the handle and manipulator platform which are detected by two position sensitive detectors (PSDs) at 1 KHz. The LED positions are determined with less than 10 µm RMS error over a workspace of 4 cm^3.

C. Millinewton Force Sensor

In order to provide force feedback of the direct tool tissue interaction, the force sensor must be able to provide real-time measurement from within the eye. In a previous approach by Berkelman et al. [16], the force sensor was placed at the proximal end of the shaft, closest to the tool handle, i.e., outside the eye. Although the tissue interactions at the tip were detected, interactions at the insertion point were an order of magnitude larger than the forces observed within the eye, making it impossible to distinguish the applied forces at the tip when inserted [17].

To provide force feedback from within the eye, a 2DOF optical force sensor has been developed at Johns Hopkins with the specific aim of detecting sub-tactile forces [18]. To achieve this, three optical fibers, 160 µm in diameter, each with a 1-cm-long fiber Bragg grating (FBG), are arranged along a thin shaft in cylindrical configuration 120° apart. The FBG is placed close to the tip such that the interactions at the insertion point are not detected. A calibration procedure is then used to relate the amount of deflection in each FBG to 2DOF force. The three fibers provide temperature compensated measurements with a resolution of 0.25 mN. The sensor package is 0.5 mm in diameter with a hooked end-effector for use during a standard membrane peeling operation. The sensor has been installed at the tip of Micron in order to provide force feedback to the control system.

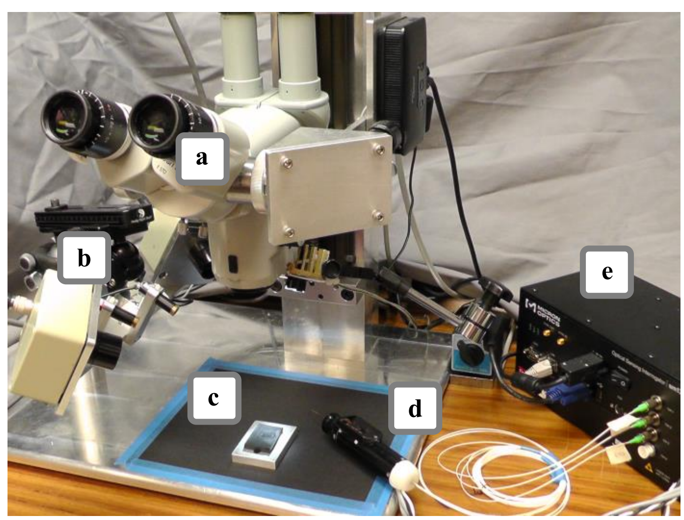

Fig. 2. The system setup is shown with (a) surgical microscope, (b) optical tracker ("ASAP"), (c) Sorbothane and PDMS platform, (d) Micron with FBG sensor installed, and (e) optical interrogator.

D. System Setup

The system setup is shown in Fig. 2. All ophthalmic procedures were performed under high magnification due to the small anatomy of the eye. Accordingly, all peeling procedures in this study were performed under 16X magnification, provided by a Zeiss OPMI 1 surgical microscope. Deflection of each FBG is measured by a Micron Optics SM130-700 optical sensing interrogator which detects the wavelength rejected on each FBG at 1 kHz at a resolution of 0.25nm. Video of the peeling procedures was acquired at 30Hz through two Flea2 1024x768 cameras from PointGrey for post-procedural review.

III. METHODS

A. Position Control

A position control system similar to that used by Becker et al. [12] is implemented. This experiment utilizes a more recent iteration of the Micron device with increased degrees of freedom and manipulation range. The position feedback control of the hybrid position/force control consists of a lowpass Butterworth filter with a corner of 1.5 Hz, used to filter hand tremor. A shelving filter can also be implemented which scales the user input by a factor of 1/3 in order to increase positioning accuracy. Further details on the position loop and Micron can be found in MacLachlan et al. [19]. Similar to Becker et al. [12], the shelving filter was activated for the manipulations occurring close to the surface, when engaging the membrane edge. After the membrane was secure on the sensor hook, the task was continued with only the lowpass filter activated.

B. Force Control

The control system combines the advantages of Micron's fine position control with the FBG force sensor's millinewton sensing for the task of membrane peeling. As Micron improves the positioning accuracy of the surgeon, it does not address the issues relating to the lack of tactile feedback and depth perception during peeling operations. The addition of force sensing enhances the surgeon's tactile feedback and depth perception by detecting the tip's interaction with structures in the eye and responding with a tip movement in the opposing direction. A hybrid position/force control system is implemented to accomplish this goal [20]. The block diagram of the system is shown in Fig. 3. When no force is present, the system operates under position control. When a force is sensed that exceeds any of the constraints an error is generated in the force control loop which is then processed and added as a corrective term to the output position.

1) The Varying Task Frame

Due to the unique handheld nature of Micron, position control is executed in the fixed coordinate system of the ASAP tracking device. This provides a stationary reference frame for orienting the handpiece and executing tip position control relative to the handpiece [19]. However, a fixed frame is not conducive to interacting with a changing surgical environment. It is often the case that the peeling direction is dependent on the orientation of the instrument's

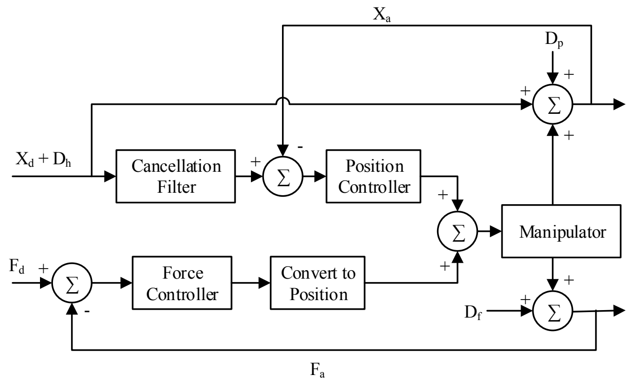

Fig. 3. Hybrid position/force control scheme. X_d+D_h is the respective goal and hand position desired. X_a and F_a are the actual measurements of the output. D_p and D_f are the system disturbance inputs for the respective position and force. The position loop runs independently when there are no forces acting on the tool tip. Once forces are sensed, a force error is generated based on the force constraints set. A corrective position term is then added to the output from the position loop.

hooked tip. For this reason a more intuitive frame was chosen which aligns the force frame with respect to the instrument tip orientation. This conveniently provides the benefit of allowing the coordinate axes to closely align with the current peeling direction. A least squares calibration is performed to align the force frame with the tip frame. Figures in this paper that display forces are presented in this calibrated coordinate frame, shown in Fig. 1.

2) Anisotropic Force Control

Anisotropic force control is implemented to minimize the force applied to the retina and improve surgeon performance during peeling operations. Soft and hard constraints were implemented in the peel direction to attenuate tip movement if the force exceeded the soft threshold. The error is then scaled linearly to the hard constraint, after which the control loop is in full effect according to (1).

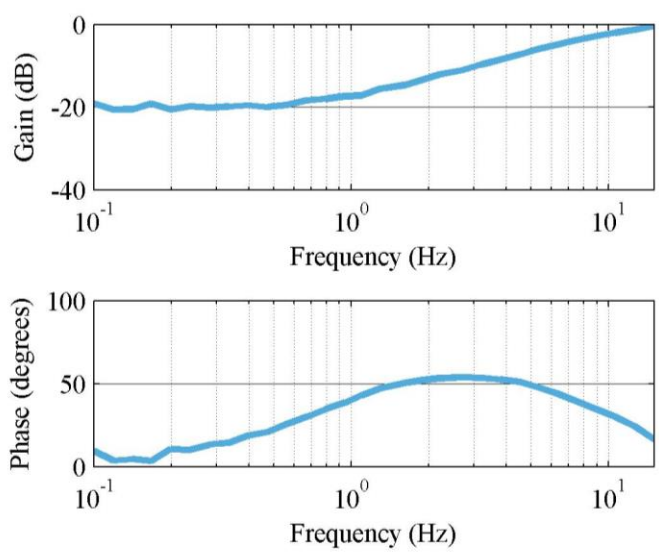

Fig. 4. Gain and phase of the control system under position input. Displacement is attenuated by 20 dB up to a corner of 0.5 Hz; the attenuation rolls off to 0 dB at approximately 15 Hz.

$$e_c = e(F\text{-}C_s)/(C_h\text{-}C_s) \quad (1)$$

Where the soft constraint, C_s, and hard constraint, C_h, scale the error, e, based on the force measurement, F, to yield a corrected error, e_c, used for determining the appropriate position offset.

Along the *Y* axis a soft constraint of 4 mN and a hard constraint of 7 mN was used in the direction of the peel (away from the retinal surface) based on tactile perception data [14] and the force threshold for tearing [8]. Only a hard constraint of 0 mN was set in the direction opposite from peeling (i.e., into the retinal surface). This low threshold is intended to minimize any force if the instrument comes into contact with the retina.

In the lateral direction (*X* axis), force control was scaled linearly from a soft constraint of 0 mN to a hard constraint of 1 mN. In previous experimental peeling trials a level of 1 mN was found to be sufficient for making minor changes in the direction of the peel during the task. For more severe directional changes, the tool tip would be rotated to realign the *Y* axis with the peeling direction and prevent the membrane from slipping off the hooked tip.

IV. Experiments

Two experiments were conducted to validate the performance of the hybrid position/force control system. The first characterizes the system performance under clamped settings and rigidly controlled conditions. The second tests the system under more realistic operating conditions in an artificial model. Both experiments were performed using the same tuning parameters, with the exception of the soft and hard constraints set to zero during the system response test.

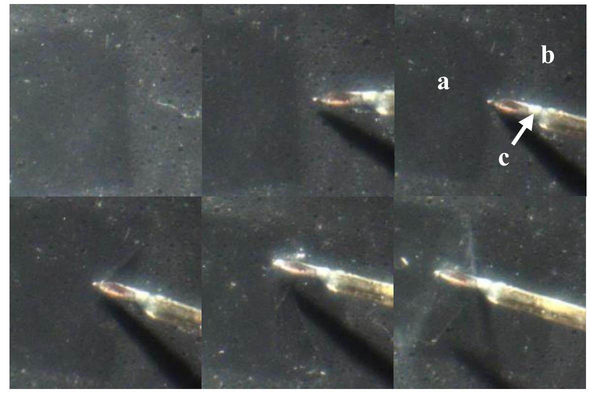

Fig. 5. The peeling process is shown above a) PDMS layer b) Sorbothane® rubber c) FBG sensor with a hooked tip for peeling. The tip is inserted beneath the PDMS layer and slowly lifted to separate the PDMS from the rubber.

1) The System Response

To test the efficacy of the force control in relation to real operating conditions the system is characterized using a position stimulus. As force is a function of the tip position this demonstrates the effectiveness of the force control to servo the tip appropriately for avoiding contact with structures and minimizing the force input.

The attenuation of the system at a range of frequencies was measured by clamping the handle of Micron to fixate it and then advancing the FBG tip into a rubber pad to fixate it as well, allowing force measurements to be correlated to any position disturbance. A sinusoidal position stimulus was then input with a peak to peak amplitude of 200 µm for 20 logarithmically spaced frequencies ranging from 0.1 to 10 Hz. The response at each frequency was sampled with a minimum n=2. Actual displacement of the tip was

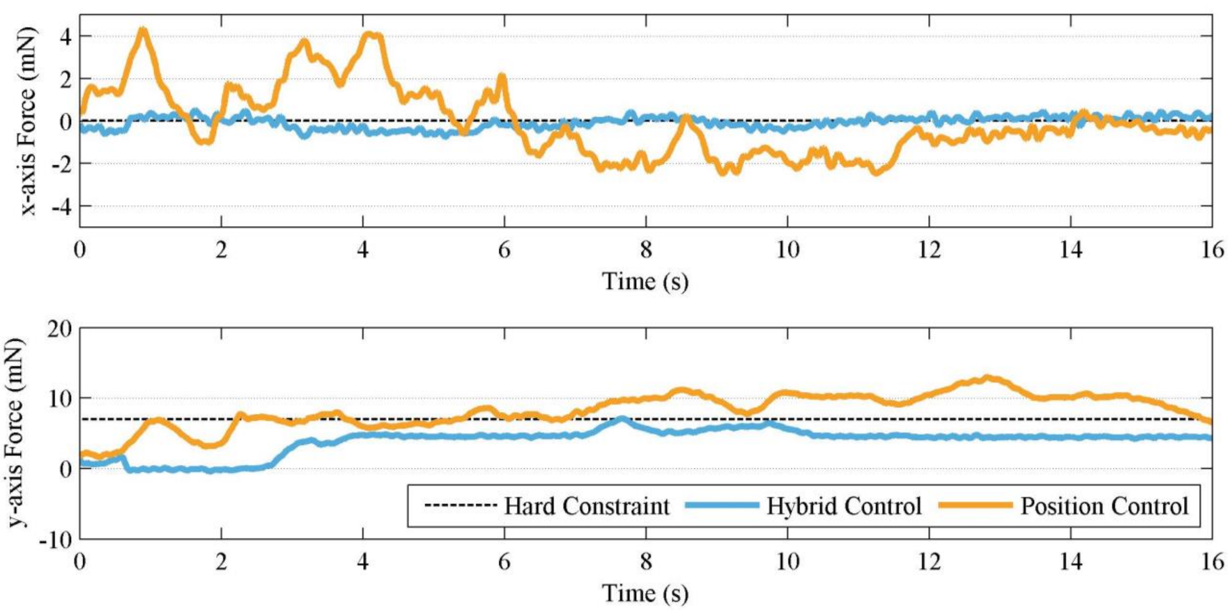

Fig. 6. A sample 16-second data set for peeling trials under hybrid position/force control and also under position control only. The hard constraint is shown as the horizontal dashed line in both the upper and lower plot. The hard constraint is set for 1 mN and -1 mN in the *X* axis and 7 mN and 0 mN in the *Y* axis. A scaling mode is active in position control during the initial engaging of the membrane; afterwards the position control uses a lowpass filter to improve precision. The force control is uniformly active or inactive depending on the trial performed. The above data has been lowpass filtered at 40 Hz to remove noise.

determined using ASAP and compared to the stimulus input in order to generate the system response shown in Fig. 4. The gain is shown to be -20 dB up to a corner of 0.5 Hz. Since most operations in the eye are slow and deliberate due to the delicate nature of the surgery, most voluntary movements occur at or below a frequency of 2 Hz [21], at which the input is still attenuated by at least 12 dB.

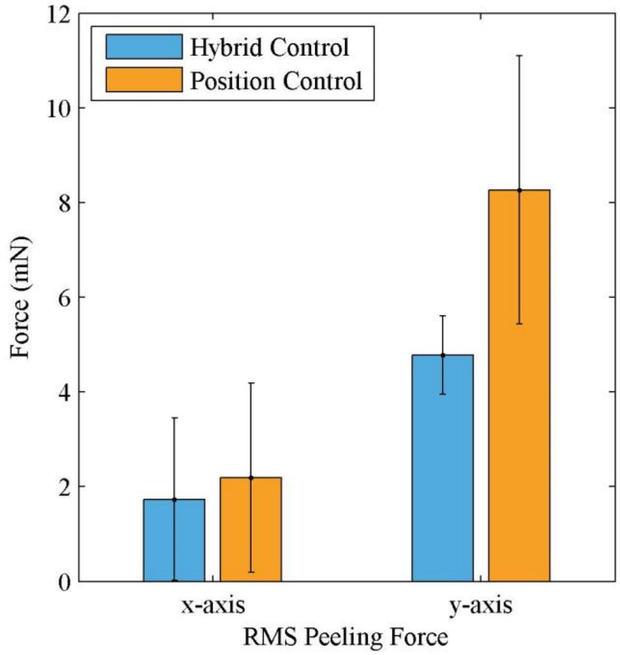

Fig. 7. RMS peeling force during position-controlled and hybrid position/force-controlled peeling tasks. There is a significant reduction in force by 42% along the *Y* axis; however, the *X* axis shows very little improvement, possibly due to the linear nature of the peeling task performed.

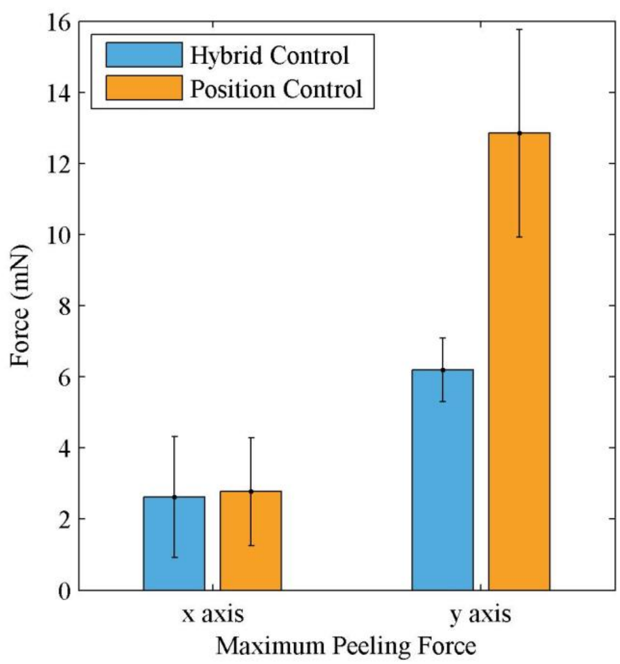

Fig. 8. Maximum peeling force during position-controlled and hybrid position/force-controlled peeling tasks. There is a significant reduction in maximum force along the *Y* axis by 52%, however the *X* axis is nearly identical, which is most likely due to the linear nature of the peeling task.

2) *Artificial Membrane Peeling*

To validate the system in actual peeling tasks, an artificial retinal membrane model was constructed for repeatability. The model consisted of Sorbothane® rubber and a layer of polydimethylsiloxane (PDMS). Sorbothane® rubber was specifically designed to mimic the properties of human tissue [22]. Although originally designed to mimic skin, it is a viscoelastic polymer that has properties similar to other biological tissue such as the retina. Sorbothane® rubber provides the most realistic artificial surface beneath the PDMS to mimic the response of the retina and subretinal tissues in vivo.

Other investigations into membrane peeling have used materials such as bandage strips and the inner shell membrane of raw eggs [23], or Glad® ClingWrap [24]. However, with surgeon feedback, it was determined that a thin layer of PDMS provided a best approximation to the epiretinal membrane and ILM. This also eliminates variability of biological tissue, allowing more repeatable results to be acquired among trials.

The PDMS was spin-coated onto wafers to a thickness of approximately 30 μm. The PDMS was then sectioned into strips 5.2 mm in width and transferred to the Sorbothane® rubber surface for peeling. As the force required to peel each strip is a function of the contact area between the PDMS and the rubber, the thickness of the strips was determined as to mimic the forces of membrane peeling in vivo.

The peeling procedure, shown in Fig. 5 then involved engaging an edge of the PDMS membrane by sliding the hook in between the membrane and rubber then lifting. This portion was performed under the scaling mode. After an edge had been successfully lifted, the membrane was peeled from the rubber surface with only lowpass filtering active. Engaging the membrane was a highly variable process; as a result, the decision to deactivate scaling mode was determined by the user once a secure engagement was achieved. This procedure was repeated with and without force control, for a total of 15 trials under each condition. A 16-second sample data set for each test condition can be viewed in Fig. 6, in which the data are lowpass-filtered at 40 Hz to remove noise.

To evaluate the effectiveness of hybrid position/force control for peeling, the engaging and peeling tasks needed to be separated for the *Y* axis. Since engaging the membrane occurs in the range of 1-2 mN, an upper limit of 2 mN was imposed to separate the tasks. Once separated, the RMS force across all peeling trials was calculated for each condition. Similarly, the maximum peeling force was selected from each trial and the RMS maximum force was calculated for each trial condition.

V. Results

From the tests of hybrid position/force control under both under clamped and handheld conditions, the displacement of the tip is attenuated by 20 dB up to a corner frequency of 0.5 Hz. The attenuation then decreases logarithmically until there is zero attenuation at roughly 15 Hz. As the typical human hand-eye feedback loop operates in the frequency range below 2 Hz [21], this attenuation is acceptable for compensating under normal operating conditions. In addition, when the scaling mode is active near the retina, the operator's movements are inherently slower due to the reduced speed enforced by the position control. By reducing the speed, the scaling mode moves the operator movements into a lower-frequency band of the force control, where higher attenuation is achieved.

During handheld trials hybrid position/force control demonstrated a reduction in both RMS and maximum force in the Y axis. The RMS force across trials was reduced by 42%, as shown in Fig. 7. The maximum force was reduced 52%, as shown in Fig. 8. There was no significant reduction in the X axis in either the RMS force or maximum force across trials.

VI. Discussion

An extension of the Micron control system has been described using a hybrid position/force control approach for membrane peeling. Hand tremor is reduced using the position loop while providing enhanced position control when below the specified force thresholds. When the force thresholds are exceeded, the applied force is limited by the force control loop. This method was found to reduce the RMS force by 42% and maximum force by 52% along the Y axis. Interestingly, the X axis showed no significant improvement during the experimental trials. This is most likely due to the linear path followed during the trials. In reality the goal is to remove a circular patch of membrane around the macular hole. In this situation it becomes much more necessary to control the direction of the peel by applying forces orthogonal to the peel direction.

We propose to continue this work by testing in more realistic models, both ex vivo and in vivo, and by extension of the force control to three degrees of freedom when a suitable 3DOF FBG force sensor becomes available.

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