Johns Hopkins
Whiting School of Engineering

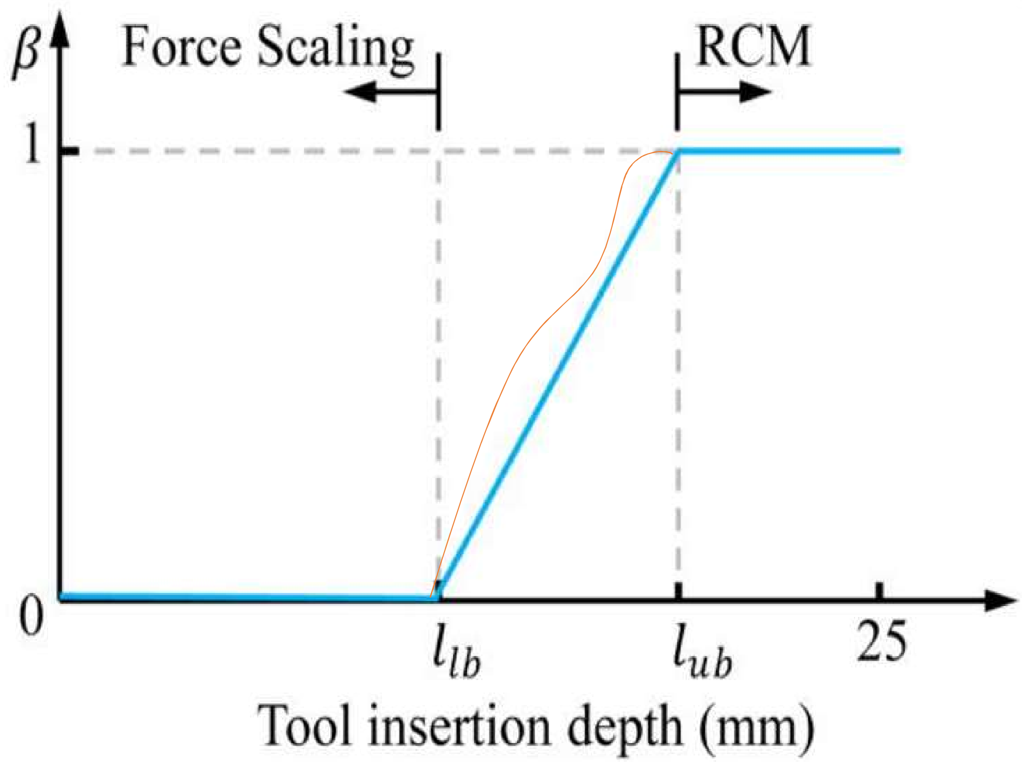
Force Control Algorithms for Sclera Eye Surgery

Paper Presentation Seminar : Ankur Gupta

Team Members: Ankur Gupta, Saurabh Singh
Mentors: Dr. Iulian Iordachita, Dr. Marin Kobilarov and Dr. Russell H. Taylor
Apr 27, 2017
Group #20

Project Objective

- To study the variation of forces on Sclera as a function of depth of insertion of the operating tool.
- Need careful experimental setup that gives consistent force measurements across trials and subjects.
- Data can be used to train/assess surgeons



Vitreoretinal Surgery: Background

- Retinal surgery requires manipulation of extremely small, delicate anatomy
- Desired tip forces are usually imperceptible to untrained humans. (typically below 8 mN)
- Human finger has a force sensing resolution of 500 mN
- Hand tremor is dangerous
- Potential risks – Retinal hemorrhage, Retinal Tear, Cornal Striae due to Sclera Buldge …
- Real-time force measurements/feedback can be useful

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Paper Selection

- 1st Paper: Balicki, M., Uneri, A., Iordachita, I., Handa, J., Gehlbach, P., & Taylor, R. (2010). Micro-force sensing in robot assisted membrane peeling for vitreoretinal surgery. *Medical Image Computing and Computer-Assisted Intervention–MICCAI 2010*, 303-310.
  - Why? Explains design decision and experimental setup required for a robust study in Eye Surgery. Overview of working of EyeRobot that we are using for our study.
- (If Time Permits) 2nd Paper: Ergeneman, O., Pokki, J., Počepcová, V., Hall, H., Abbott, J. J., & Nelson, B. J. (2011). Characterization of puncture forces for retinal vein cannulation. *Journal of Medical Devices*
  - Why? Another Force Sensing Data Collection paper, with non-linear regression analysis.

1st Paper: MICCAI 2010

Micro-force Sensing in Robot Assisted Membrane Peeling for Vitreoretinal Surgery

Marcin Balicki, Ali Uneri, Iulian Iordachita, James Handa, Peter Gehlbach, and Russell Taylor

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Goals of the paper

- To study robot regulated user-applied forces to the tissue, to minimize risks of eye surgery using JH EyeRobot
- Developing new surgical pick for integration of conventional surgical function and real-time force measurements
- Introduce variety of control algorithms during the surgery
  - Force Scaling
  - Velocity Liming
  - Proportional Velocity
- Study the effect of auditory feedback on force-exertion and completion time

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Key Results

- New Force sensing Instrument can measure sub mili-newton forces.
- Force Scaling control with Audio Feedback is a good control algorithm.
- Audio feedback decreased the maximum tip forces, as well as tip force variability
- Significant improvement in task completion rates(nuisances covered later)
- Continuous audio feedback may be disruptive or overwhelming

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Experimental Setup

- **Robotic Assistant**
- **Micro-force Sensing Instrument**
- **Membrane Peeling Phantom**

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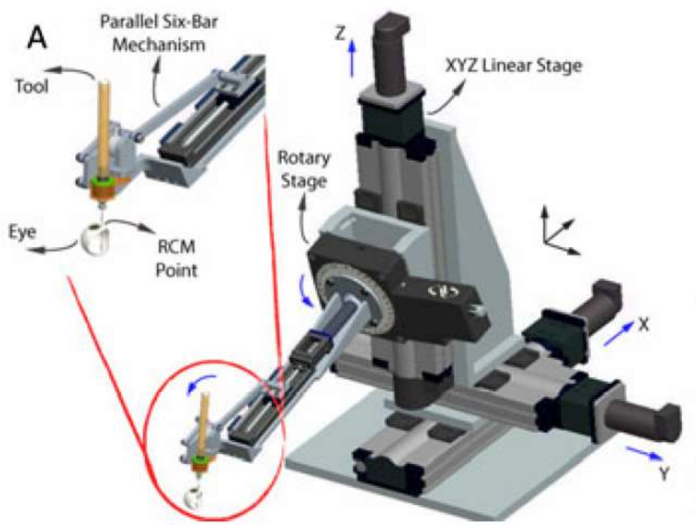
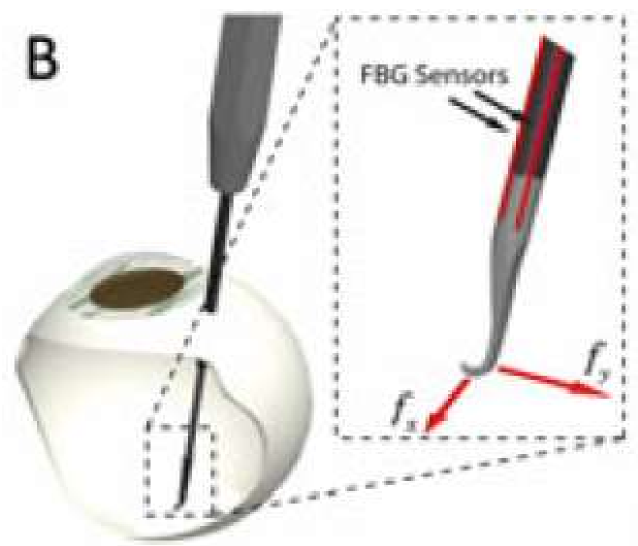


- 5-DOF system
- Filters physiological hand tremor
- 6-DOF force sensor mounted at tool holder (command input to robot)
- virtual RCM mode, which constrains the tool axis to always intersect the sclerotomy opening on the eye

Experimental Setup

- Robotic Assistant
- **Micro-force Sensing Instrument**
- Membrane Peeling Phantom



- Able to measure Force at the instrument's tip, below the sclera.
- Integrated with 3 fiber Bragg grating (FBG) sensors along the tool shaft
- FBGs are robust optical sensors capable of detecting changes in strain by measuring the bending of tool
- Sensitivity of 0.25 mN

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Experimental Setup

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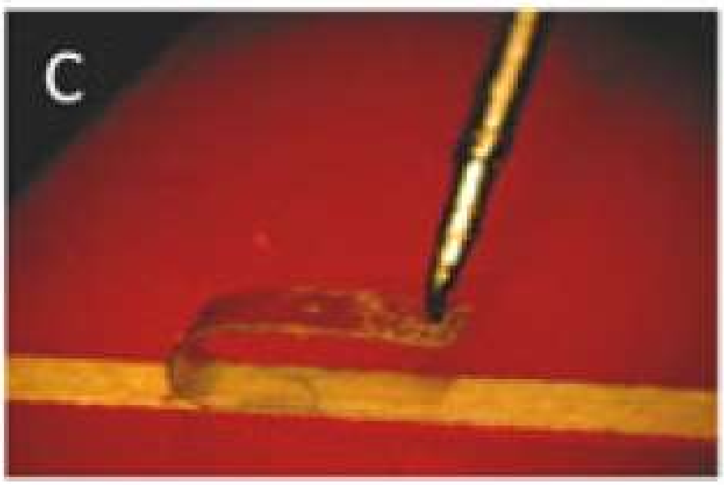
- **Membrane Peeling Phantom**



- 2mm wide strips of sticky tabs from 19 mm Clear Bandages (RiteAid)
- tool velocities 0.1–0.5 mm/s and forces are likely to be below 7.5 mN. Phantom is consistent with these readings
- Predictable behavior showing increase of peeling force with increased peeling velocity

Control Algorithms

- ***Proportional Velocity Control (PV)***
- ***Linear Force Scaling Control (FS)***
- ***Proportional Velocity Control with Limits (VL)***

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Control Algorithms

- ***Proportional Velocity Control (PV)***
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- Velocity at the tool is proportional to the user's input force at the handle
- Constant Gain, α = 1 mm/s/N
- Model is $v = \alpha F_h$

Control Algorithms

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- *Proportional Velocity Control (PV)*
- ***Linear Force Scaling Control (FS)***
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- Linear Combination of Handle and Tip Forces amplifies human-imperceptible forces
- Constant Gain, α = 1 mm/s/N
- Model is $v = \alpha(F_h + \gamma F_t), \quad \alpha = 1$
- Low tip forces => Low velocity. Sometimes a problem

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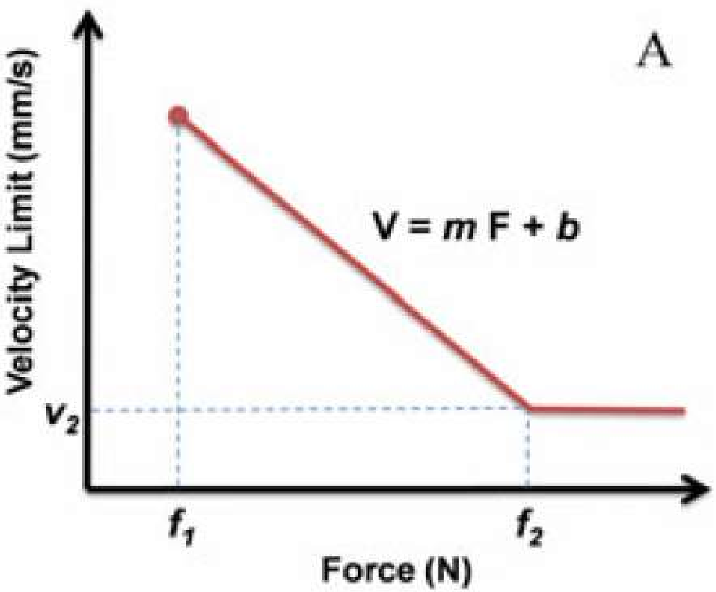


- Increases maneuverability when low tip forces are present
- Clips velocity to a minimum at higher Force values
- Model is

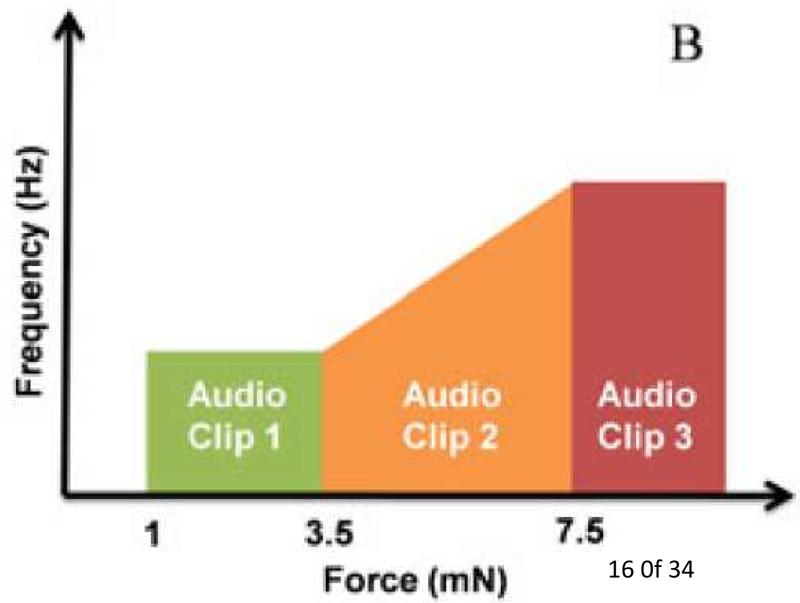
$$\dot{x} = \begin{cases} V_{\lim}(F_t), & -F_h < V_{\lim}(F_t) \wedge F_t < 0 \\ V_{\lim}(F_t), & -F_h > V_{\lim}(F_t) \wedge F_t > 0 \\ \alpha F_h, & otherwise \end{cases}$$

Force-to-Auditory Sensory Substitution

- Typically, surgeons use Force-to-visual Sensory Substitution
  - i.e visual interpretation of changing light reflections from deforming tissue
  - Requires significant experience and concentration
- Authors give audio feedback to surgeons by directly measuring Force from Micro-force Sensing Instrument
- Playback tempo of audio “beeps” are in three force level zones

  The audio is silent until 1 mN or greater force is measured

  1. “safe zone” : 1- 3.5 mN. Constant slow beeping
  2. “cautious zone”: 3.5–7 mN. Proportionally increasing tempo
  3. “danger zone” : > 7mN. Constant high tempo beeping



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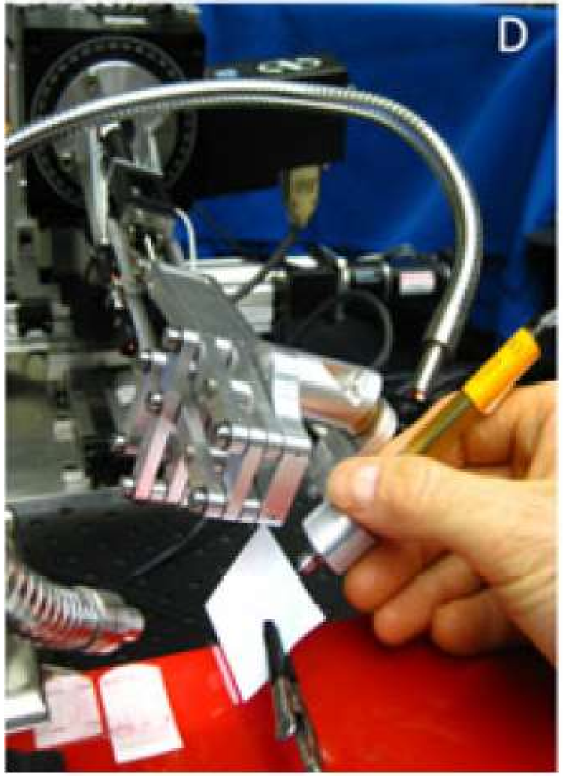
Experiments

- All experiments on Membrane Peeling
  - goal is to apply low and steady forces to generate a controlled delamination
- Single subject experiment
- Objectives
  - Decrease Mean of Peeling Forces
  - Decrease Maximum Peeling Forces
  - Decrease Completion Time
- Stable platform with double-stick tape
- Robot is positioned so the hook is ~1.5 mm above the peeling surface
- Tool shaft visibility obstructed to remove bias from tool bending
- Translations only
- No Magnification/Scaling



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Results

Forces(mN)	FH	FHA	PV	PVA	FS	FSA	VL	VLA
Mean	4.11	3.80	4.20	3.64	3.34	3.22	3.58	3.45
StdDev	0.97	0.59	0.95	0.51	0.54	0.40	0.36	0.33
Max	7.85	6.21	6.93	4.74	4.10	3.59	4.03	3.83
Time(s)	93.03	125.25	62.30	85.98	103.80	96.80	88.67	80.58

FH(A) = Free Hand (with Audio Feedback)

PV(A) = Proportional Velocity (with Audio Feedback)

FS(A) = Linear Force Scaling(with Audio Feedback)

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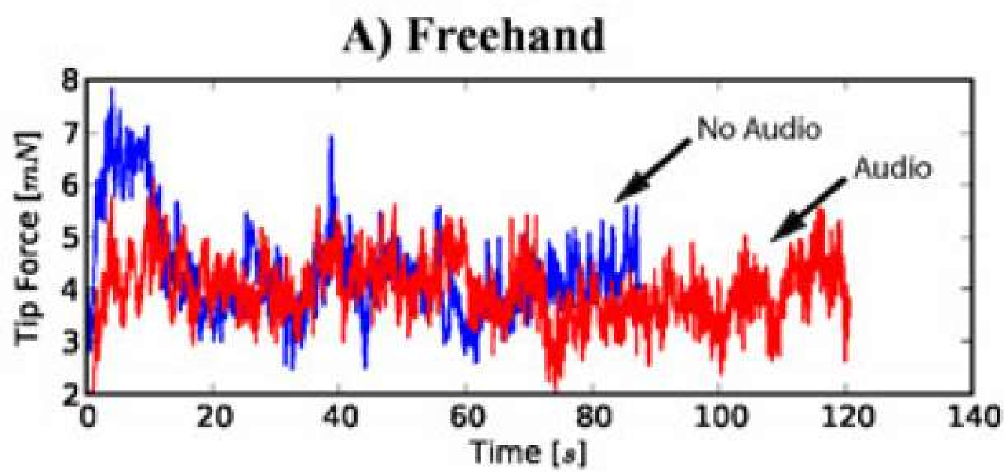
- FH: High force variation due to hand tremor. The mean force ~5 mN, maximum force ~8 mN
- FH with Audio feedback: helped to reduce large forces but significantly increased task completion time.



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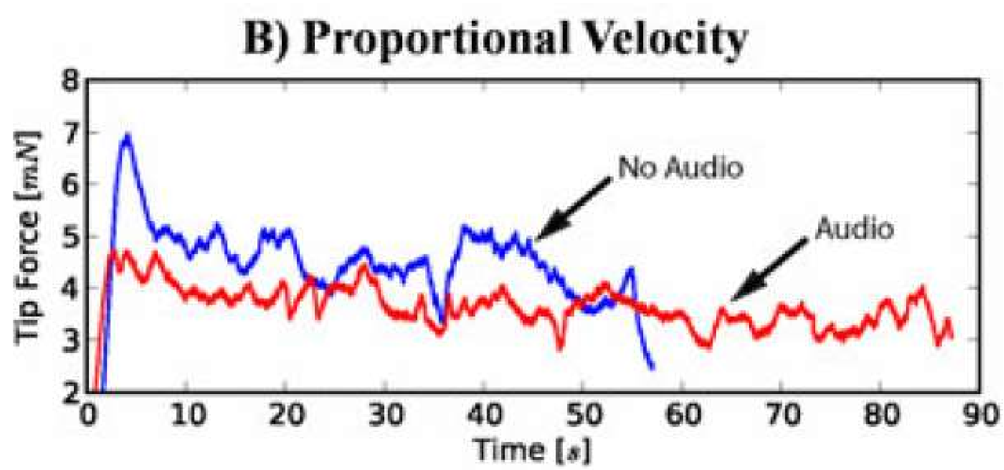
- Prop Velocity: increase stability smoother force application, range of forces same as freehand.
- With Audio feedback: Decrease in large forces but increased time to complete the task.



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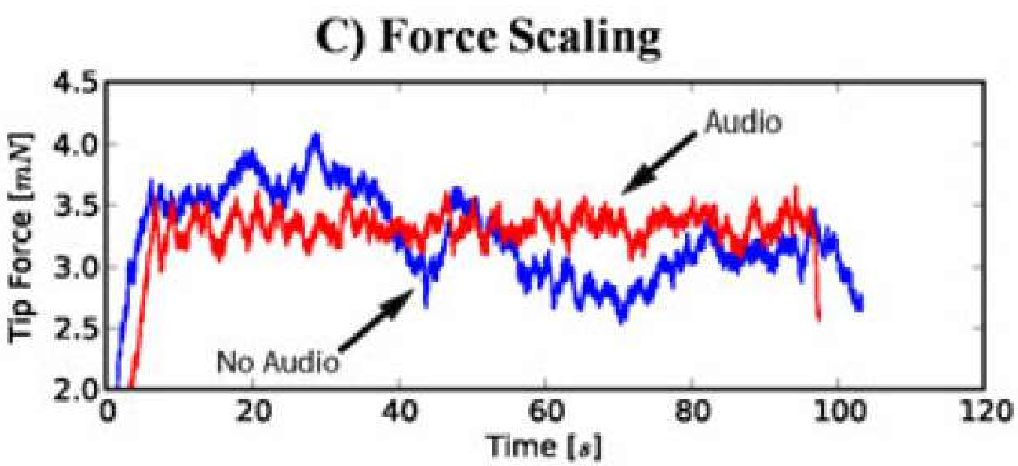
- Force Scaling : best overall performance wrt Mean and Average Forces, with and without Audio Feedback
- Maximum Time for completion



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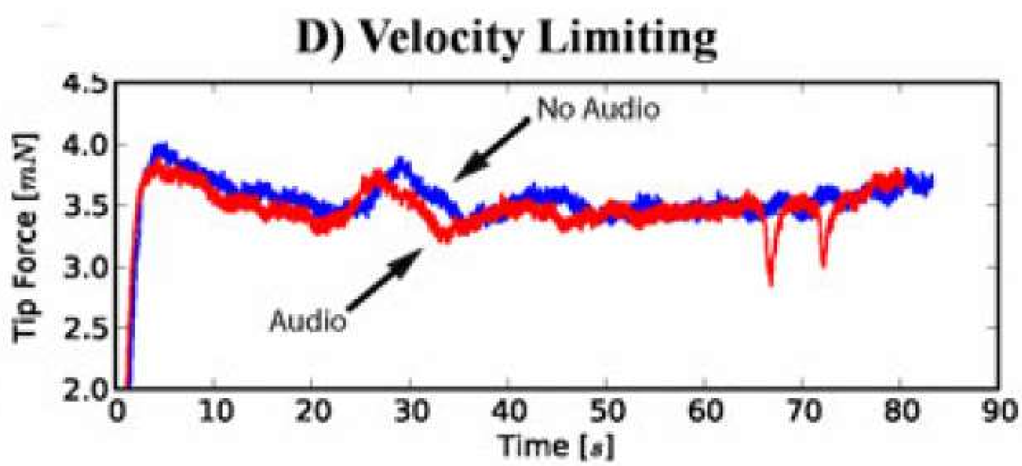
- Velocity Limiting: Very smooth response
- With Audio Feedback: Negligible effect because velocity and audio had matching thresholds



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Conclusion

- The proposed micro force sensing instrument is capable of measuring and reacting to forces under 7.5 mN
- Force scaling with audio-feedback results in lowest maximum force and most intuitive response
- System parameters can be easily modified for other micro-surgical tasks
- Future Work
  - Multi-user study
  - Verify and improve the artificial phantom by characterizing in-vivo membrane peeling forces
  - Conduct study to explore better(intuitive) ways for feedback suitable in an operating room

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My View

- Takeaways
  - Real-time Force sensing on the tool shaft is a game changer
  - Carefully designed experiments and well presented results.
  - Audio Feedback has mixed results when it comes to time of completion, but always reduces tip forces.
- Weakness
  - Some parameters choice is not supported by enough evidence, e.g in Velocity Limiting thresholds and "Zone cutoffs" of audio feedback
- Relevance
  - I could understand the nuisances of setting up a complicated experiment. Sometimes, creative use of materials is required such as Clear Bandages for Membrane Peeling Phantom in this case
  - Our current project will try to come up with evidence in support of Force vs Sclera-Depth, which can be treated as a surrogate for Force vs Audio

2nd Paper : Journal of Medical Devices

Characterization of Puncture Forces for Retinal Vein Cannulation

Olgac Ergeneman, Juho Pokki, Vanda Pocepcova, Jake J. Abbott
Bradley J. Nelson
Institute of Robotics and Intelligent Systems,
ETH Zurich, 8092 Zurich, Switzerland

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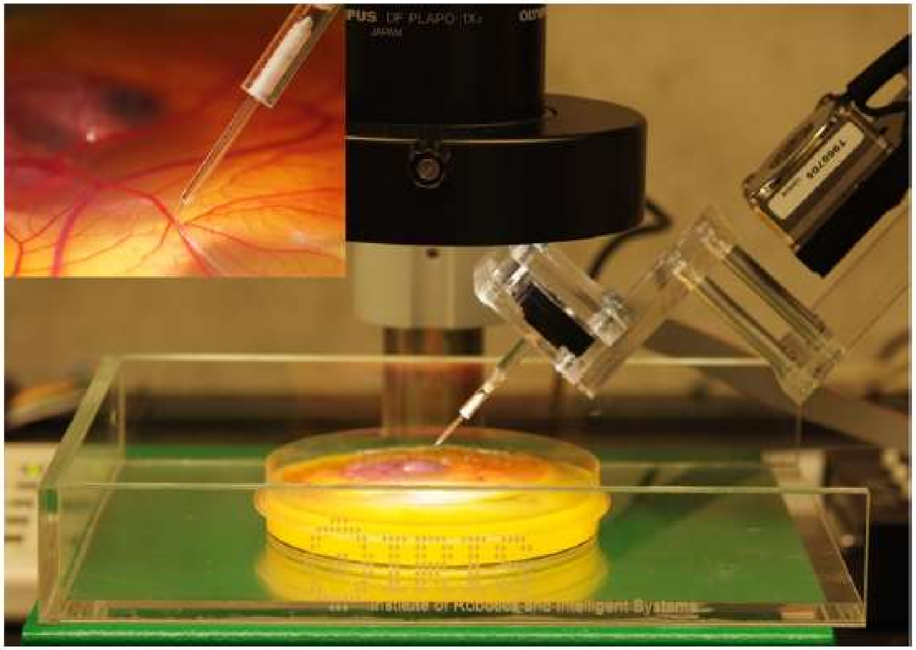
Goal of the paper

- To collect puncture force data from chorioallantoic membranes (CAM) of developing chicken embryos.
- To study the effect of microneedle geometry and vessel size on puncture forces.



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Key Results

- Statistically significant effects of the vessel size, microneedle size, and microneedle type on the puncture force
- The beveling of the microneedle decreased the forces necessary to puncture the vessels, especially at larger microneedle sizes

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Experimental Setup

- Chorioallantoic Membrane
  - CAM of a 12-day-old chicken mimics human retinal conditions(blood vessels with 50–400 um outer diameter)
- Microneedle: The needle tip ODs and bevel angles verified using an optical microscope
  - Blunt
  - Bevelled
- Calibration of 3-DOF Force Sensor
  - Calibrated by the manufacturer (Picodyne, MN, USA)
  - Gain of the force sensor verified using known weights
  - Sensor insensitive to Torque
  - Microneedle mounted on the force sensor

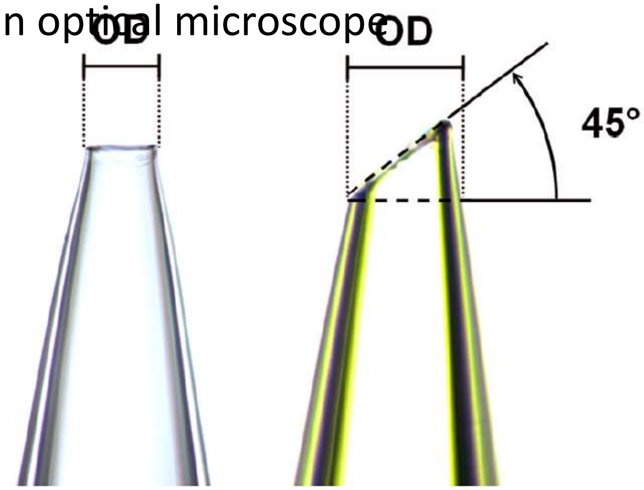
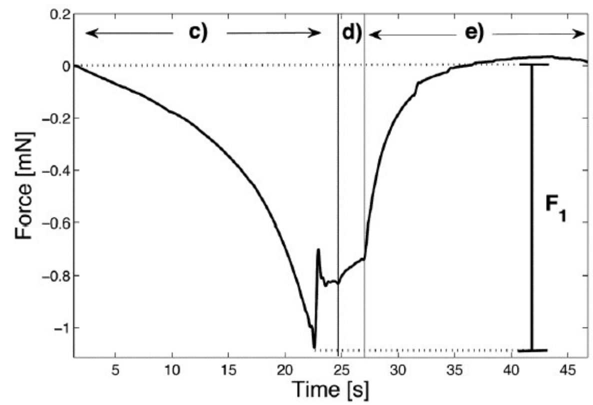


Fig. 1 Two types of microneedles were prepared: blunt and beveled. The outer diameter (OD) and bevel angle is shown in the image.

Precautions and Standardization

- Phosphate buffer solution applied to the CAM for surface moist and improved visualization through microscope
- Each chosen vessel on CAM had ~constant OD* for atleast 2 mm
- All the vessels were attached to the yolk to avoid complex fixation(?)
- Microscope and the digital camera to determine vessel OD*
- Force data recorded before penetrating to correct for gravitational forces(Bias?)
- Axis of microneedle perpendicular to the vessel axis
- Moved at constant speed of 55 um/s until puncture
- A puncture is detected when
  - Drop in the realtime force data was observed
  - Needle was seen to penetrate into the sample.
  - Was also verified by bleeding of the vessel.



(b) Typical punctures with ≥10 μm OD tips

Results: Histogram of Forces

- 85% of the puncture forces of all measurements were under 5 mN.
- 64% of forces below 5mN (0.64 x 85% = 41.6%) were also below 2.5mN

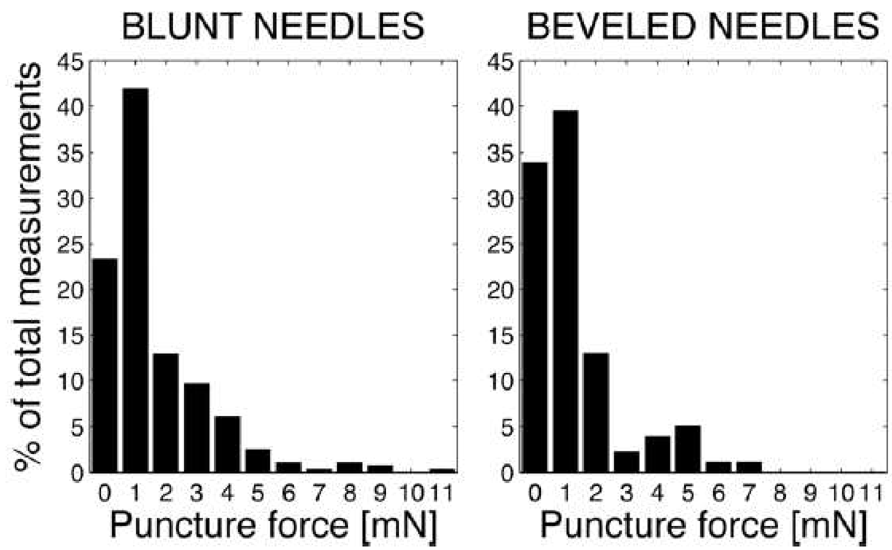


Fig. 4 Histogram of magnitude of forces as percentages of all measurements. Vessels in 80–400 μm OD range were considered.

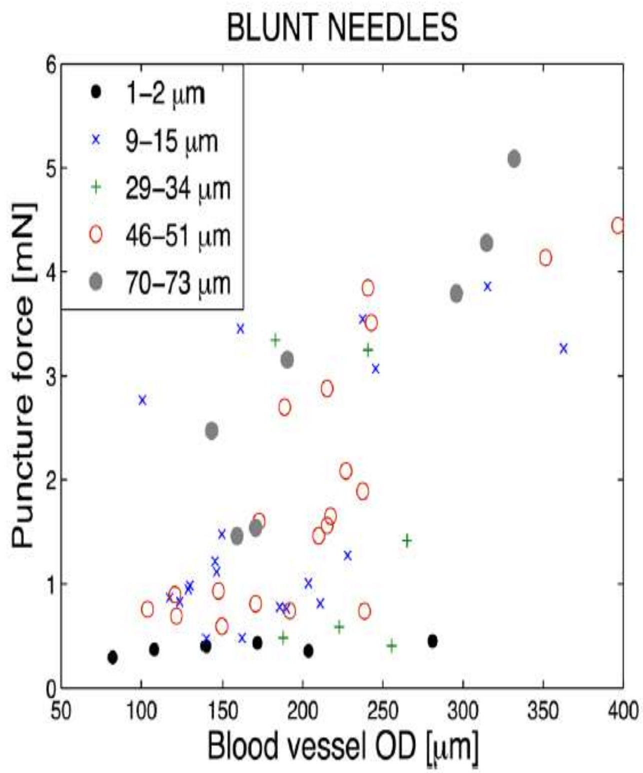


Fig. 5 Average puncture forces for 1-2 μm, 9–15 μm, 29–34 μm, 46–51 μm, and 70–73 μm tip OD for the blunt microneedles (306 individual punctures)

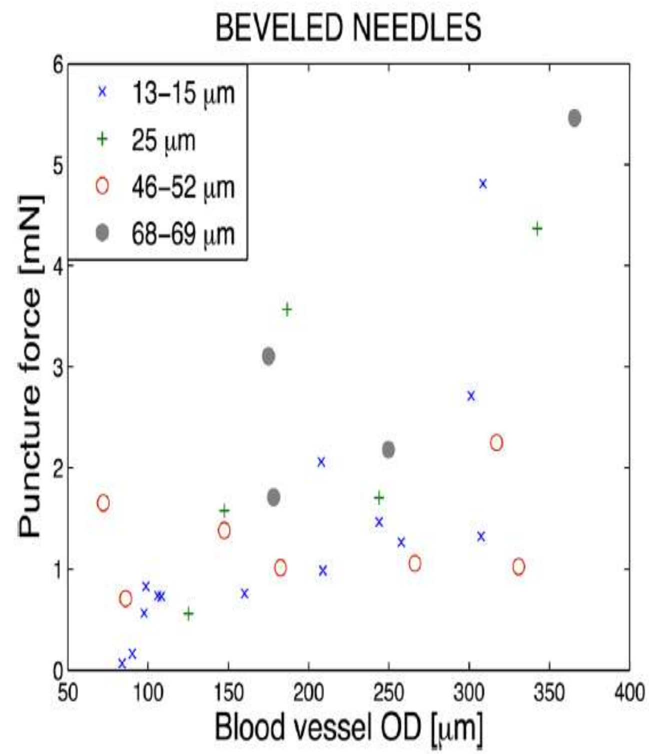


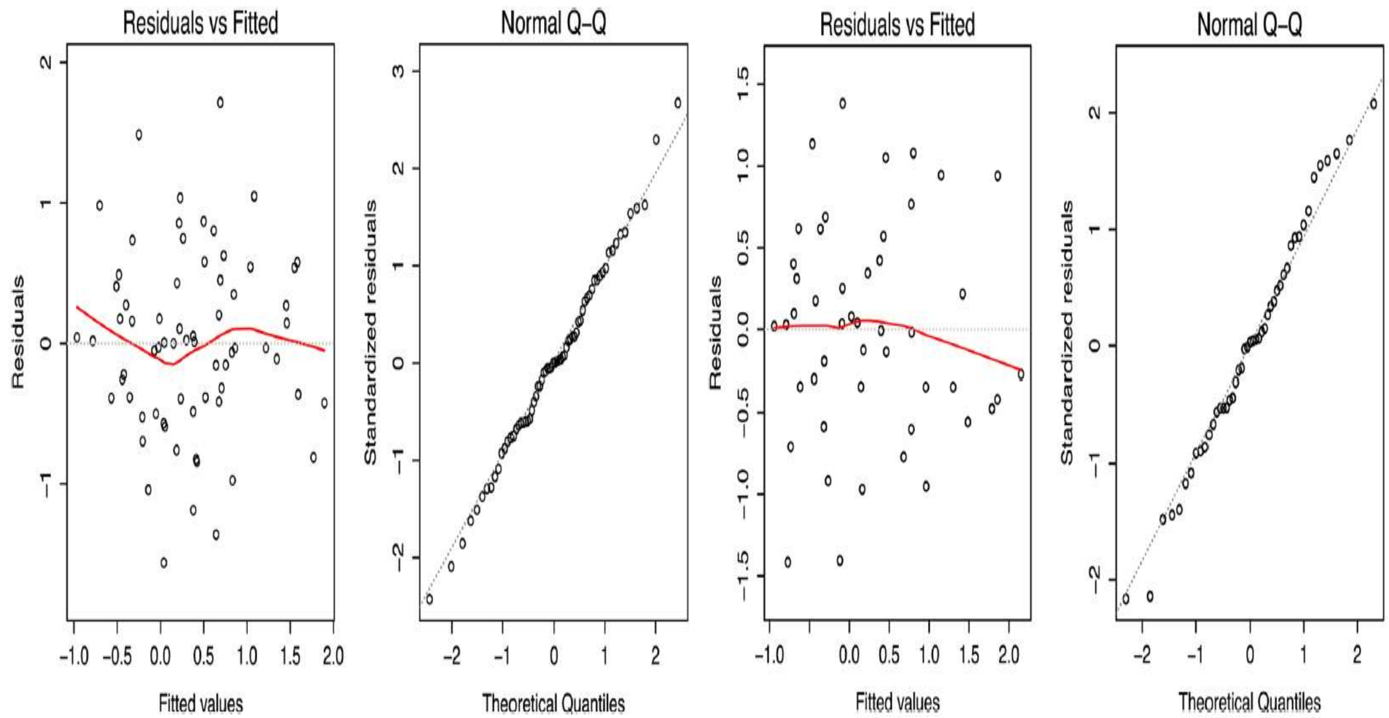
Fig. 6 Average puncture forces for 13–15 μm, 25 μm, 46–52 μm, and 68–69 μm tip OD for the beveled microneedles (153 individual punctures)

Results: Regression Analysis

$$\log(F_p) = \beta_{00} + \beta_{01}\phi_v + \beta_{10}\phi_n + \beta_{11}\phi_v\phi_n + \beta_{02}\phi_v^2 + \beta_{20}\phi_n^2$$

where, F_p = Force, $\Phi_v = OD\ of\ vessel$, $\Phi_n = OD\ of\ needle$

- Log-quadratic model but they drop the pairwise terms later. So they use a log linear model.
- Normal Q-Q is nearly perfect in both cases.
- Models indicates puncture forces increase with respect to microneedle tip OD (p-value = 0.0003 for blunt needles, and p-value = 0.0114 for beveled needles) and with respect to vessel OD (p-value = 0.000006 for blunt needles and p-value = 2×10^{-8} for beveled needles)



Blunt Needles

Bevelled Needles

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My View

- Takeaways
  - Statistically complete
  - Reduced multiple sources of error AND documented it.

- Weakness
  - No clear conclusion drawn from the data collected.
  - Lacks Intuition behind the log-linear model
  - P-values are mentioned for random variables but reference distribution is not mentioned(Gaussian?)

Q&A