Paper Critical Review

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Group 20

Introduction

The goal of my CIS-2 project To study the variation of forces on Sclera as a function of depth of insertion of the operating tool. We need careful experimental setup that gives consistent force measurements across trials and subjects. This data can be used to train/assess surgeons

Paper 1: Micro-force sensing in robot assisted membrane peeling for vitreoretinal surgery [1]

Background and Motivation

Retinal surgery requires manipulation of extremely small, delicate anatomy Desired tip forces are usually imperceptible to untrained humans. (typically below 8 mN) whereas Human finger has a force sensing resolution of 500 mN. Hand tremor is also another potential source of inaccuracies in the surgery. Potential risks of inaccuracies include Retinal hemorrhage, Retinal Tear, Cornal Striae due to Sclera Buldge etc. Therefore Real-time force measurements/feedback can be exteremly useful, which is exactly what this paper establishes.

Goals of the paper

To study robot regulated user-applied forces to the tissue, to minimize risks of eye surgery using John Hopkins EyeRobot. They also Develop new surgical pick for integration of conventional surgical function and real-time force measurements. The paper is extensive and also introduces variety of control algorithms during the surgery including

1. Force Scaling
2. Velocity Liming
3. Proportional Velocity

One of the major contributions of this paper is to study the effect of auditory feedback on force-exertion and completion time using the tool and compares study from all these with augmented Audio Feedback.

Technical Approach

Experimental Setup

- Robotic Assistant
  It is a 5-DOF system with 3 Translations, Roll and Pitch. It is a Cooperatively Controlled system and filters physiological hand tremor. The force sensor mounted at tool holder is 6-DOF. Robot can also operate in "virtual RCM mode", which constrains the tool axis to always intersect the sclerotomy opening on the eye.
- Micro-force Sensing Instrument
  The Force Sensing Intrument is able to measure Force at the instrument's tip, below the sclera. It is 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. The tool has an overall sensitivity of 0.25 mN
- Membrane Peeling Phantom
  Phantom is made from 2mm wide strips of sticky tabs from 19 mm Clear Bandages. In a real world surgery velocities are kept at 0.1–0.5 mm/s and forces are likely to be below 7.5 mN. The phantom is consistent with these readings. It also follows predictable behavior showing increase of peeling force with increased peeling velocity.

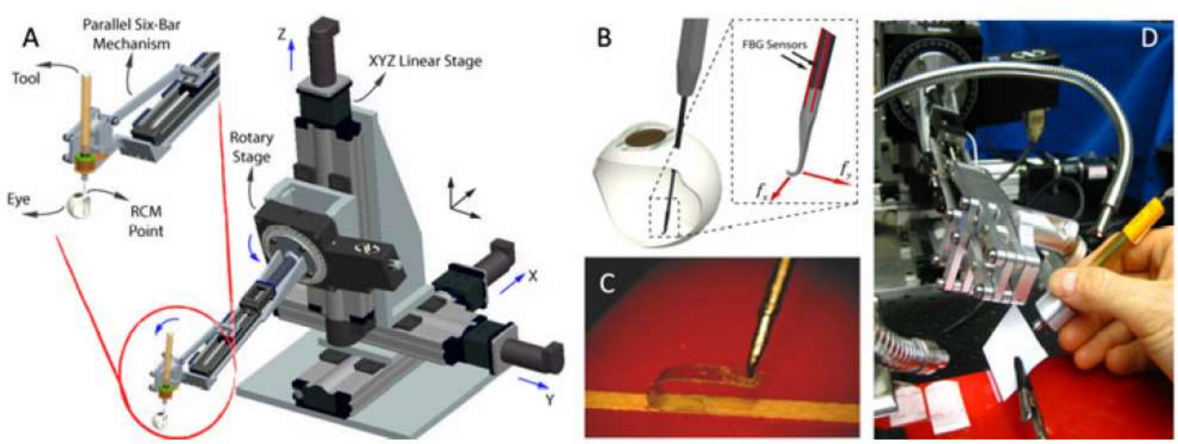

Fig 1 A) Robot with RCM mechanism [11]; B) Force Sensor Instrument Concept [6]; C) Peeling sample and hooked force sensor instrument; D) Experimental setup

Control Algorithms

- Proportional Velocity Control (PV)
  Velocity at the tool is proportional to the user's input force at the handle. This model follows constant gain, α = 1 mm/s/N. The explicit model is

$$v = \alpha F_h \qquad Eq\ (1)$$

- Linear Force Scaling Control (FS)
  Previous model does not take Tip forces into consideration. FS corrects that. It follows linear combination of Handle and Tip Forces and amplifies human-imperceptible forces. Uses the same constant gain, α = 1 mm/s/N. The explicit model is

$$v = \alpha(F_h + \gamma F_t), \quad \alpha = 1 \qquad Eq\ (2)$$

- Proportional Velocity Control with Limits (VL)
  FS penalizes low tip forces since it is directly proportional to low velocity. VL increases maneuverability when low tip forces are present. It clips velocity to a minimum at higher Force values. Explicit Model, as shown in Fig 2A is

$$\dot{x} = \begin{cases} V_{\lim}(F_t), & -F_h < V_{\lim}(F_t) \wedge F_t < 0 \\ V_{\lim}(F_t), & -F_h > V_{\lim}(F_t) \wedge F_t > 0 \\ \alpha F_h, & otherwise \end{cases} \qquad Eq\ (3)$$

Force-to-Auditory Sensory Substitution

Typically, surgeons use Force-to-visual Sensory Substitution i.e visual interpretation of changing light reflections from deforming tissue to guide their decisions in the surgery. This requires considerable experience and concentration. Instead, authors propose audio feedback to surgeons by directly measuring Force from Micro-force Sensing Instrument. The playback tempo of audio "beeps" are in three force level zones, as shown in Fig 2B

- The audio is silent until 1 mN or greater force is measured
- "safe zone": 1- 3.5 mN. Constant slow beeping
- "cautious zone": 3.5–7 mN. Proportionally increasing tempo
- "danger zone": > 7mN. Constant high tempo beeping

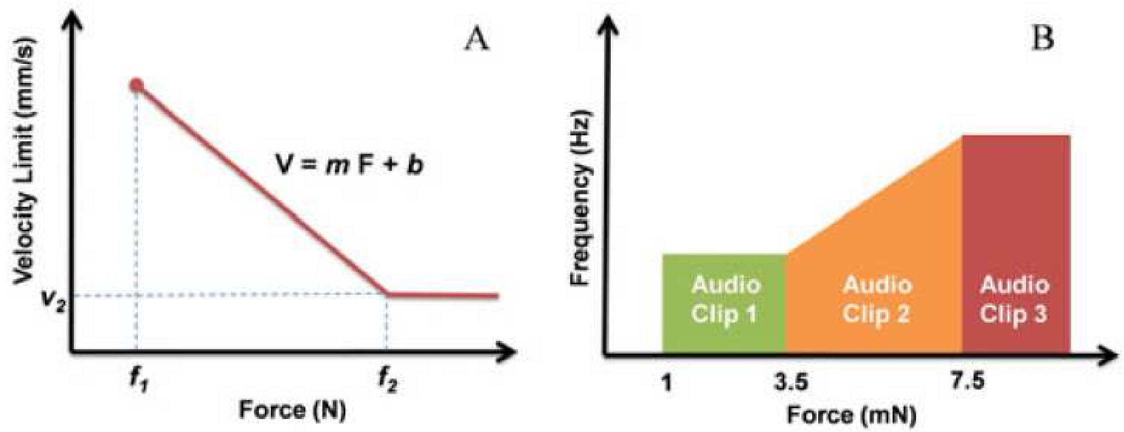

Fig 2 A) Velocity limiting function (symmetric about V = -F); B) Audio feedback zones

Experiments

All experiments are done on Membrane Peeling. The goal in these surgeries is to apply low and steady forces to generate a controlled delamination). The is performed by only one subject. The objective of these experiments to Decrease Mean of Peeling Forces, Decrease Maximum Peeling Forces, Decrease Completion Time. The robot is positioned so the hook is ~1.5 mm above the peeling surface. Tool shaft visibility is obstructed to remove bias from tool bending. Only translations are allowed with no visual magnification.

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

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

Fig 3 Tabular Representation of data from experiment. FH(A) = Free Hand (with Audio Feedback), PV(A) = Proportional Velocity (with Audio Feedback), FS(A) = Linear Force Scaling(with Audio Feedback), VL(A) = Velocity Limiting Control (with Audio Feedback)

As shown in Fig 3 and Fig 4, FH exhibits high force variation due to hand tremor. The mean force is around 5 mN, maximum force is ~8 mN. FH with Audio feedback helped to reduce large forces but significantly increased task completion time. Proportional Velocity increases stability and results in smoother force application but the range of forces is same as freehand.

Proportional Velocity With Audio feedback decreases large forces but increases time to complete the task. Force Scaling gives best overall performance wrt Mean and Average Forces, with or without Audio Feedback. But Force scaling also results in maximum time for completion. Velocity Limiting results in very smooth response. Audio feedback in this case has negligible effect because velocity and audio had matching thresholds.

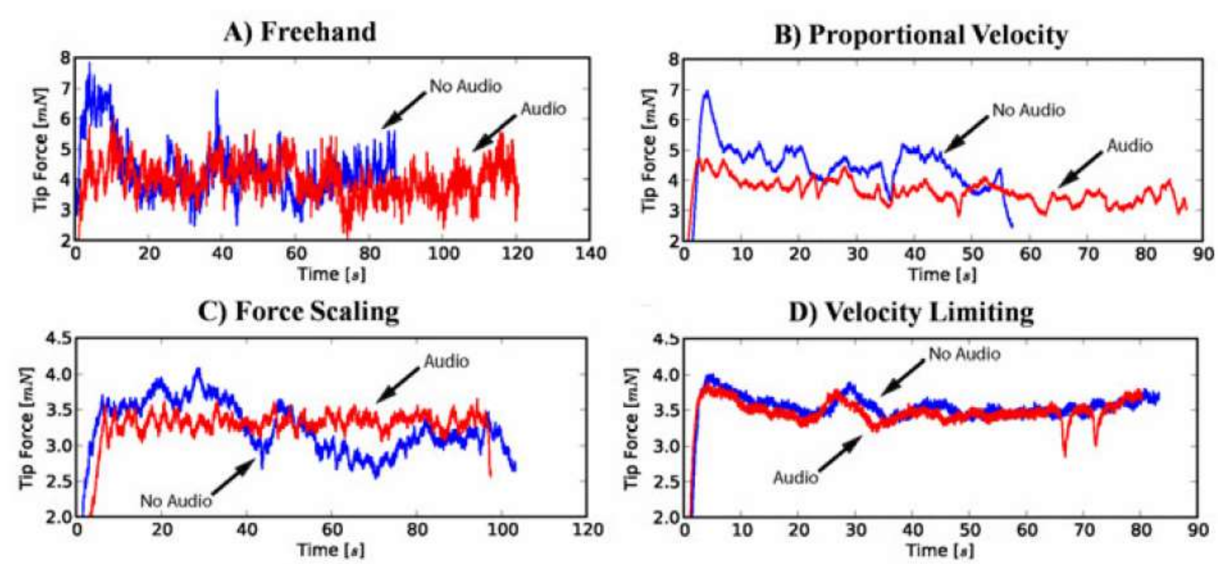

Fig 4 Plots of representative trials of each mode showing tip forces, with/out audio feedback

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. A good thing about the system is that its parameters can be easily modified for other micro-surgical tasks.

Relavance to my project

This paper carefully explains the design decisions and experimental setup required for a robust study in Eye Surgery. It also gives an overview of working of EyeRobot that we are using for our study. 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 : Characterization of Puncture Forces for Retinal Vein Cannulation [2]

Goal of paper

To collect puncture force data from chorioallantoic membranes (CAM) of developing chicken embryos. Along with this, authors also aim to study the effect of microneedle geometry and vessel size on puncture forces.

Technical Approach

Experimental Setup

- Chorioallantoic Membrane
  The chorioallantoic membrane (CAM) of developing chicken embryos has been used by ophthalmologists as a model system for studying photodynamic therapy and ocular angiogenesis. The CAM's anatomical features and physiologic and histologic responses to manipulation and injury make it an effective model of the retina and its vasculature. The vasculature of a twelve-day-old CAM and a human retina have roughly the same diameter and wall thickness.
- Microneedle: Two types of microneedles as blunt tips and beveled tips were prepared with five different outer diameters (OD). The needle tip ODs and bevel angles verified using an optical microscope.

- Calibration of 3-DOF Force Sensor
  Force Sensor was calibrated by the manufacturer Picodyne, MN, USA. The gain of the force sensor verified using known weights. Sensor is insensitive to Torque and the microneedle is mounted on the force sensor

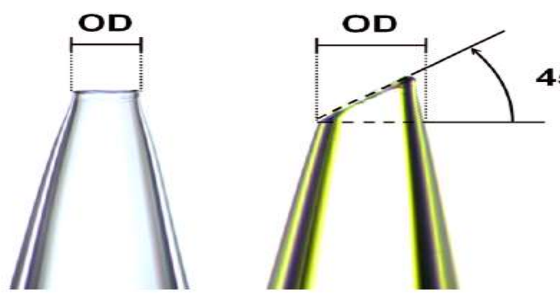

Fig 5 Two types of microneedles were prepared: blunt and beveled. The outer diameter (OD) and bevel angle is shown in the image.

Precautions and Standardization

There were many standardization setps taked by the authors. This is one of the best aspects of this paper. I am listing some of them. 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 are used together to determine vessel OD. Force data recorded before penetrating to correct for gravitational forces. The axis of microneedle perpendicular to the vessel axis. The needle was moved at constant speed of 55 um/s until puncture was detected. A puncture is detected when there was a drop in the realtime force data, the needle was seen to penetrate into the sample and it was also verified by bleeding of the vessel.

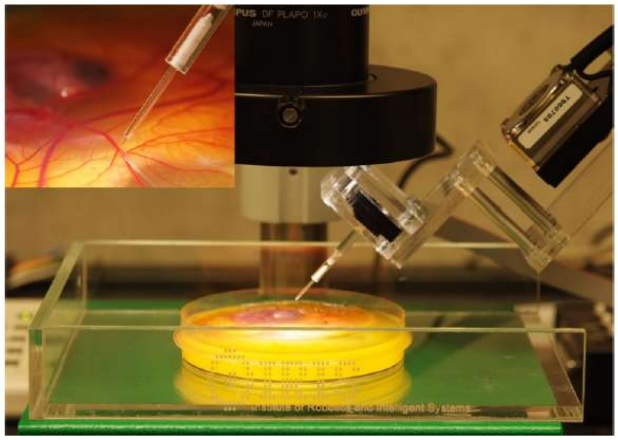

Fig 6 Setup for puncture-force experiments. A microneedle is attached on a force sensor, which is mounted on a micromanipulator. The puncture events were observed using a microscope and images were captured by a camera. On the top left, a microneedle advancing toward a blood vessel is shown. The microneedle was mounted at 45 from the normal of the plane of the petri dish and was advanced in its axial direction. The petri dish was oriented to have the vessel axis perpendicular to the microneedle axis.

Results

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

As shown in the histogram (Fig 5), 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

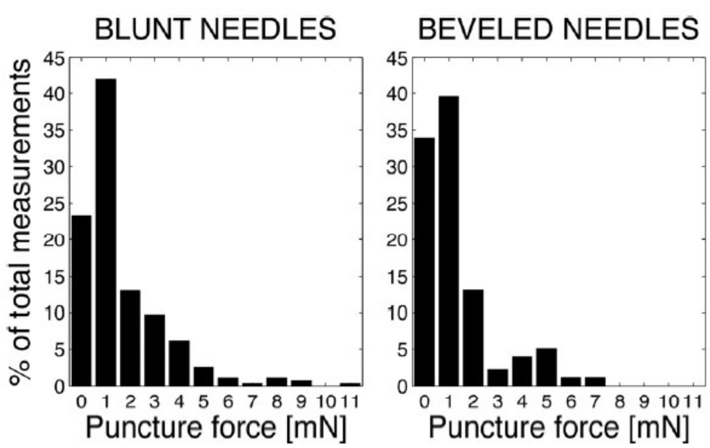

Fig 7 Histogram of magnitude of forces as percentages of all measurements. Vessels in 80–400 lm OD range were considered.

Regression Analysis

As given by Eq 4, Authors use a log-quadratic model though they drop the pairwise terms later and end up using a log linear model. As given in Fig, Normal Q-Q is nearly perfect in both cases.

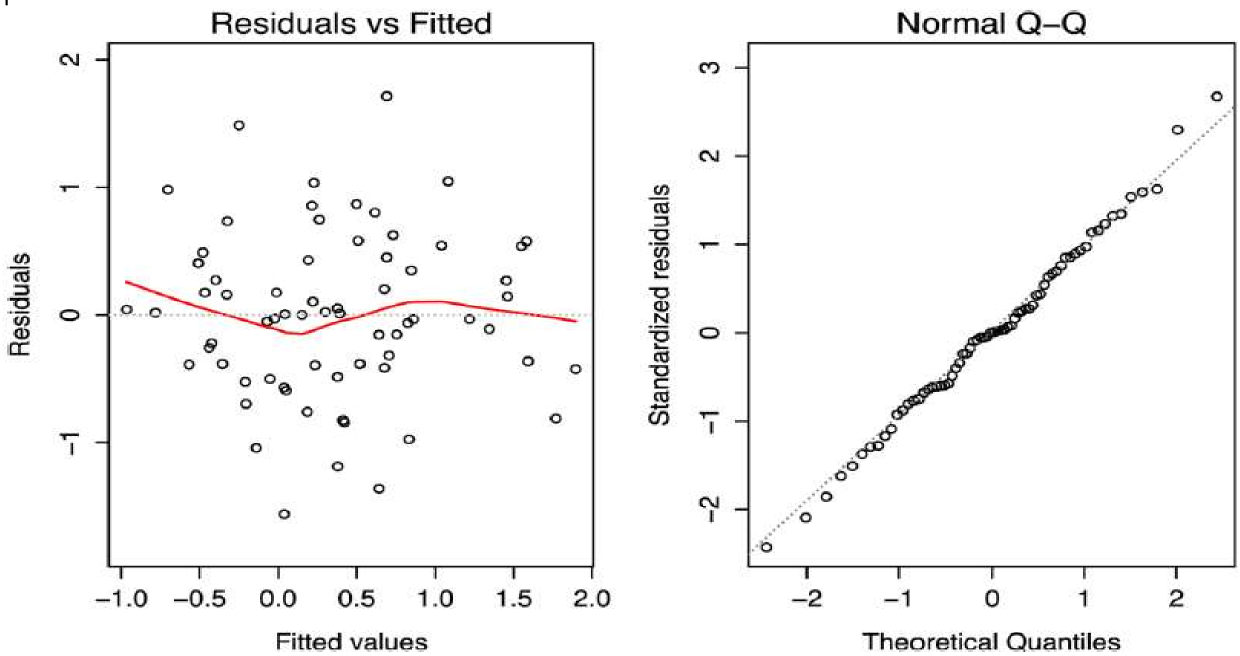

Fig 8 Residual analysis for the regression model using the force data with blunt needles

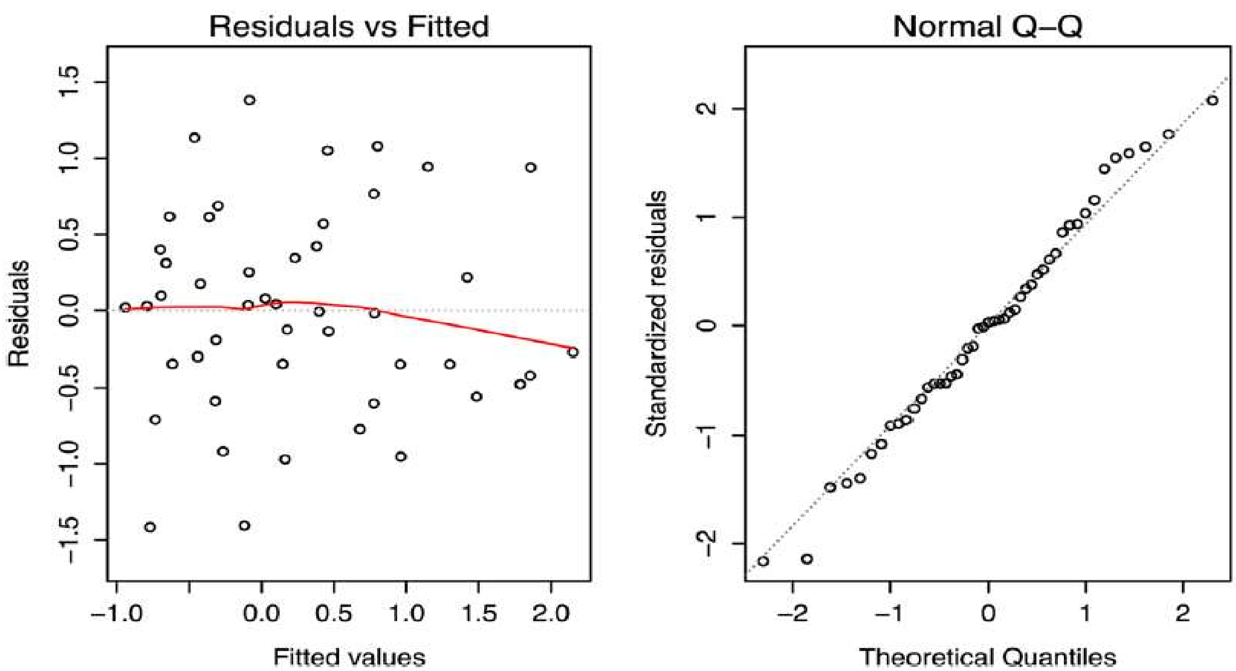

Fig 9 Residual analysis for the regression model using the force data with beveled needles

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 = $2x10^{-8}$ for beveled needles)

$$\log(F_p) = \beta_{00} + \beta_{01}\phi_v + \beta_{10}\phi_n + \beta_{11}\phi_v\phi_n + \beta_{02}\phi_v^2 + \beta_{20}\phi_n^2 \qquad \text{Eq (4)}$$

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

Relevance to my Project

We also to collect data, setup our experiment and present results convincingly. This paper is statistically complete. They reduced multiple sources of error and documented it. We can learn from their setup and implement similar safety guards.

References

[1] 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.

[2] 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