Quantitative Analysis of Instrument Motion Paths in Cataract Surgery Throughout a Resident's Training

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INTRODUCTION

- Surgical training ideally utilizes **objective** and **quantifiable** evaluation tools over subjective training methods
- Experienced surgeons develop **faster**, more **precise**, **efficient** movements over time
- **Motion tracking metrics** of surgical instruments can quantify these improvements in surgical skill level to develop objective assessment tools

OBJECTIVE

Track the motion paths of surgical instruments during cataract surgeries performed by a resident ophthalmologist to quantify their learning curve throughout training

METHODS

1. Dataset Preparation

100 cataract surgery recordings by 1 resident during 1st year of training (**cases 6-760**)

Instrument Classification: (1) Incision and Entry, **(2)** Manipulation and Tissue Handling, **(3)** Aspiration and Irrigation, **(4)** Phaco-emulsification, **(5)** Lens Implantation

2. Motion Tracking

Frame-by-frame, semi-automatic tracking of **11 surgical instruments**, capturing **6 motion path parameters**

Software: **CVAT** and **TrackerMIL**

Motion Path Parameters:
(1) Path Length: Total distance travelled
(2) Velocity: Speed of movement
(3) Angular Change: Directional adjustments
(4) Acceleration: Changes to speed
(5) Jerk: Smoothness of acceleration
(6) Workspace Coverage: Area covered by instrument motion

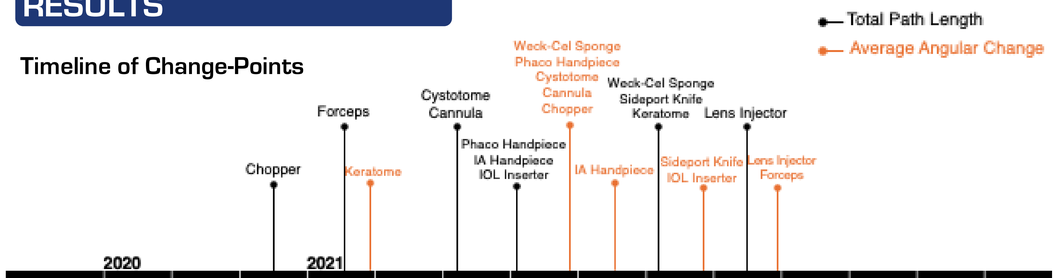
3. Quantitative Analyses

Assessed **improvement trends** (Mann-Kendall), **rates of skill progression** (Theil-Sen slope), and **change-points** (Pettitt's method)

Change-points: Moments of significant skill improvement

RESULTS

Timeline of Change-Points



Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Videos	1-5	6-14	15-25	26-32	33-37	38-45	46-56	57-63	64-75	76-82	83-86	87-93	94-99	100
Cases	6-20	21-51	58-79	87-140	152-212	215-292	298-342	347-353	356-384	416-472	544-559	582-646	658-724	760

Summary of the Results

1. All 11 instruments exhibited statistically significant trends in at least one motion path parameter
2. Cannula (-11.8%), phaco handpiece (-11.5%), and cystotome (-8.9%) had largest **path length** reductions; cystotome (-1.7°) and IOL inserter (-1.68°) had largest reductions in **angular changes**
3. **Median change-point** for **total path length** across all instruments occurred at **case 300**
4. Change-points for **angular change** differed from path length, with some earlier milestones (e.g., keratome) and delayed shifts (e.g., forceps)
5. Phaco handpiece had **strongest** correlation between reduction in path length and case number (ρ = -0.70, **$p < 0.001$**) and workspace coverage (ρ = -0.54, **$p < 0.001$**)

DISCUSSION

- Path length reductions reflect efficiency gains: IA tools showed greater, earlier reductions than lens implantation tools → **spatial navigation skills precede techniques requiring more refined motor control**
- Angular change reductions (e.g., cystotome & IOL inserter) vs. minimal changes (e.g., forceps & lens injector) suggest angular change is more relevant for tasks requiring dynamic repositioning than static precision → **different motion path metrics reveal different instrument- & task-specific learning curves**
- Tools for repetitive tasks (e.g., phacoemulsification) correlated more with case number than tools for varied or complex tasks (e.g., cannula or lens injector) → **repetition drives consistent skill improvement**
- This represents one of the most **comprehensive** motion tracking datasets in ophthalmology and surgery
- In future, AI models can be trained to enable automated skills assessment and personalized feedback