Human Motor Performance in Robot-Assisted Surgery

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Presented by Allison Okamura for the

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Robotics for Medical Interventions

Rehabilitation

Prosthetics

Robot-assisted surgery

Robot-Assisted Minimally Invasive Surgery

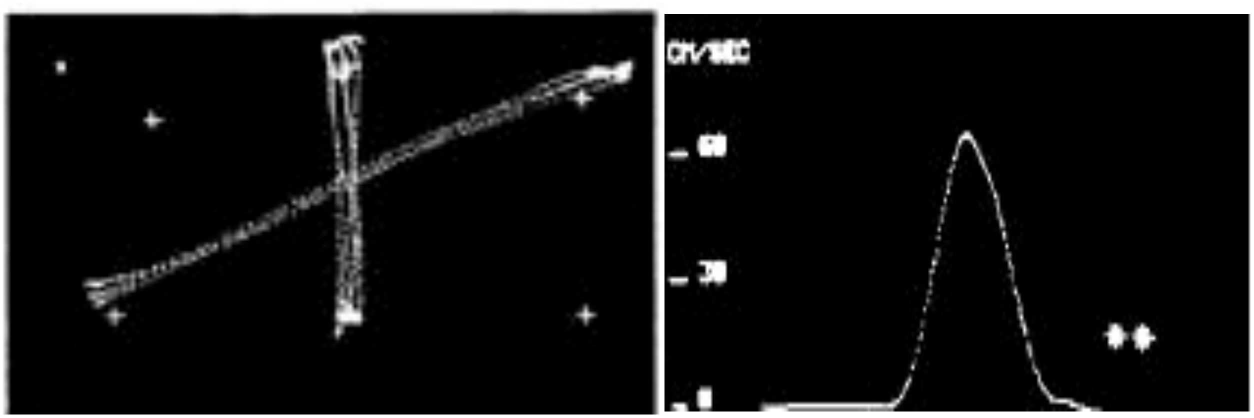
- Design does not fully consider the sensorimotor capabilities of the surgeon
- Training methods have not been optimized

Studying the sensorimotor system could impact both!

Computational Motor Control

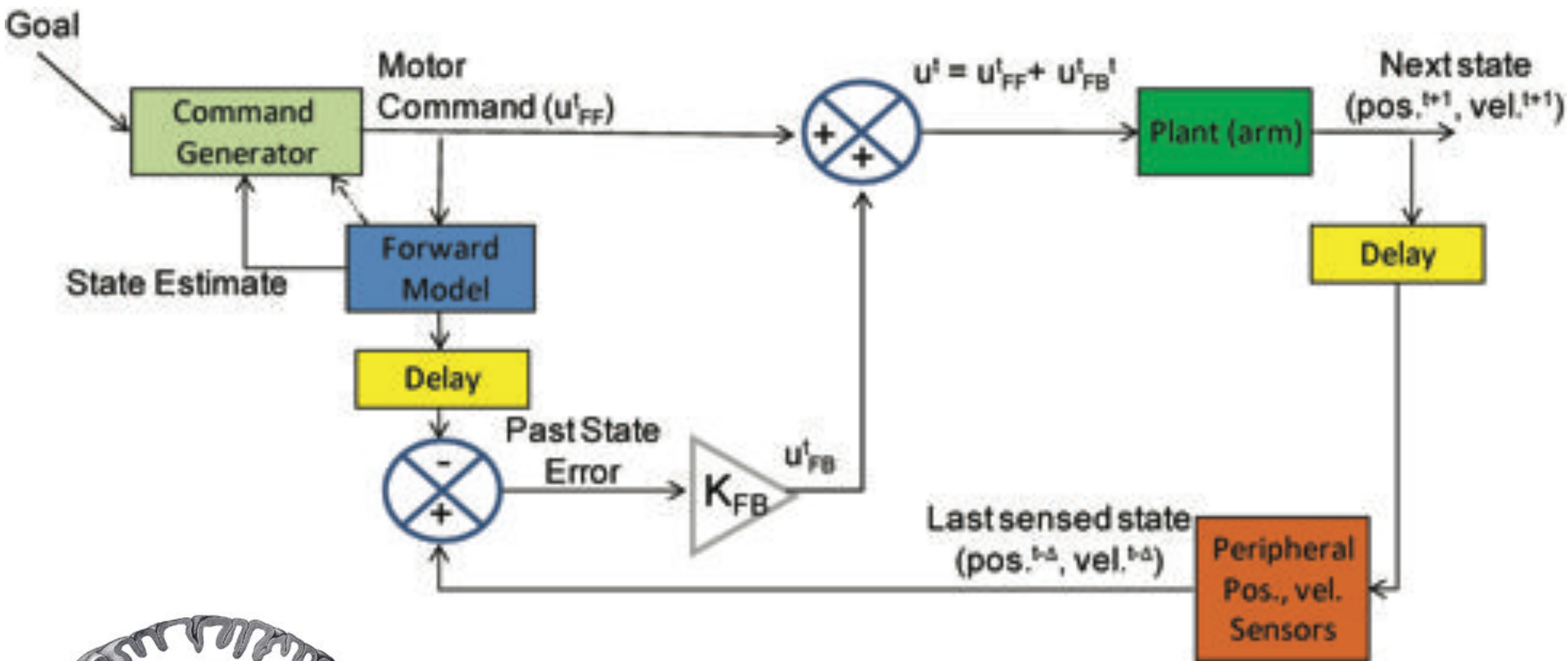
The science of how the brain controls motion and represents the external world

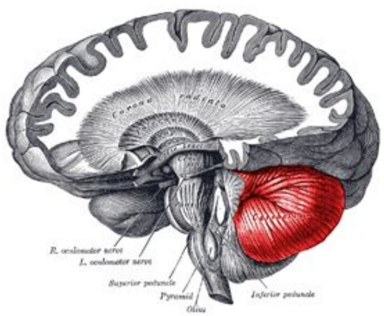
We move in surprisingly regular ways…



Morasso, 1981

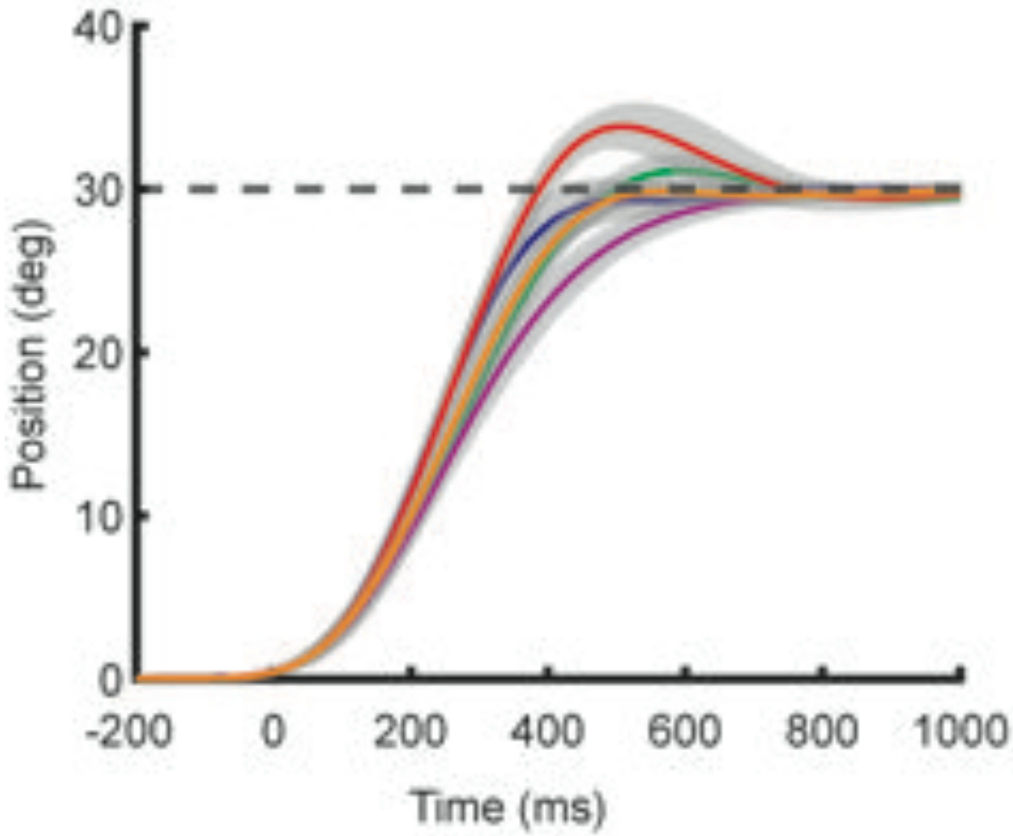
A Simple Model of Motor Control





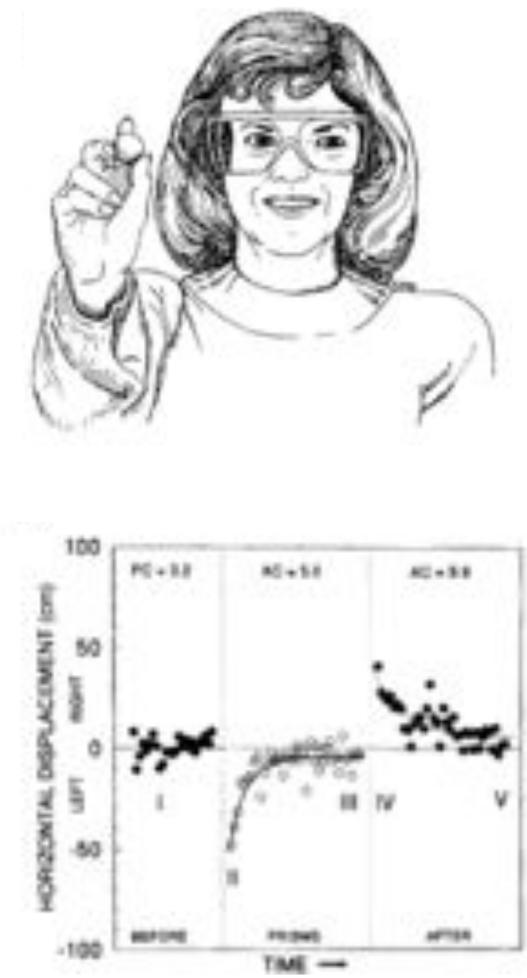
Bhanpuri et al. Brain 2014

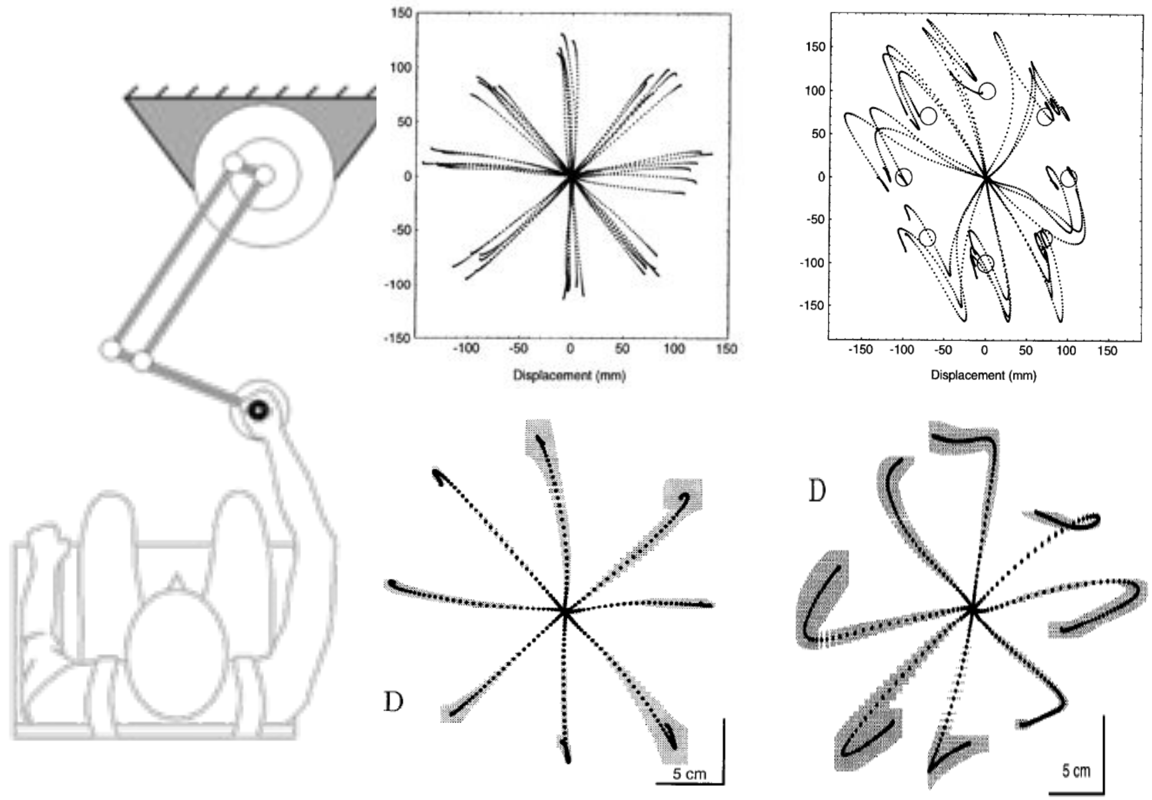
Effects of Arm Dynamics



Bhanpuri et al. Brain 2014

Adaptation to Perturbations





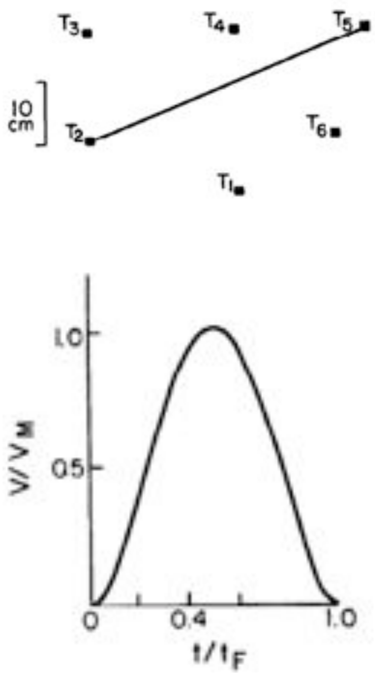
Martin et al., 1996

Shadmehr and Mussa-Ivaldi, 1994

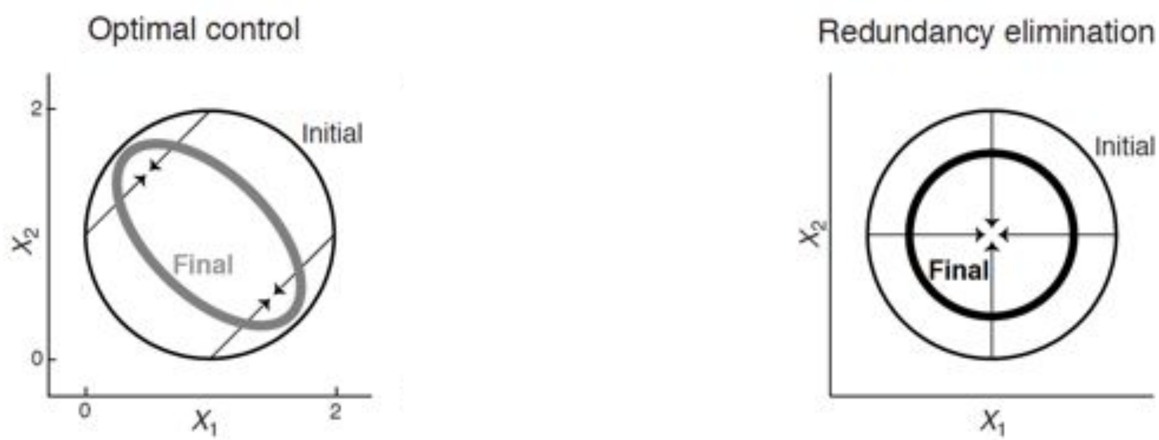
Optimality and Minimum Intervention

Trajectory Optimization:
Minimum Jerk

Optimal Feedback Control
Minimum intervention principle



Flash and Hogan, 1985



Todorov and Jordan, 2002

Take Home

To build robotic systems that are operated by **humans**, we should:

- Study the **human operator**
- Apply findings to design, control, and training

Operators interact with robotic devices

- This allows us to study the **human operator** in unprecedented ways

Surgery

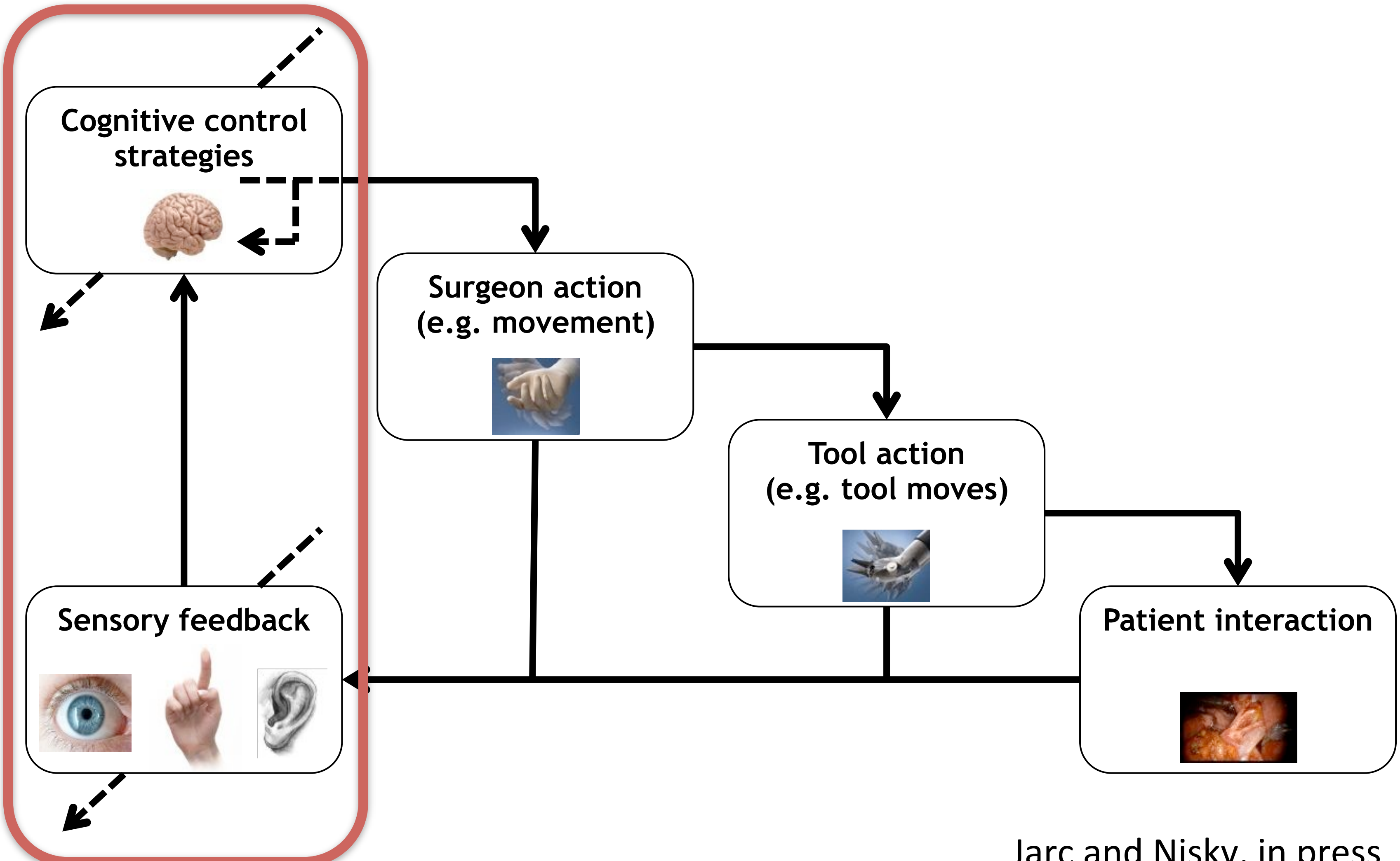
Open

Minimally Invasive

Robot-Assisted

Intuitive Surgical

Sensorimotor Performance in RAS



Jarc and Nisky, in press

Sensorimotor Performance in RAS

Can we use (and extend) what we know about

human motor control

to improve

design, control, and training

in

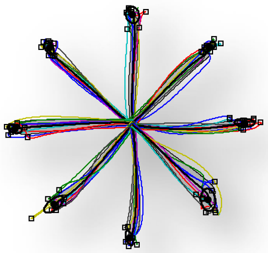
Robot-Assisted Surgery?

Sensorimotor Performance in RAS

Compare teleoperated vs. freehand movements, and expert vs. novice participants

- Teleoperation vs. freehand => robot design
- Experts vs. novices => skill evaluation and training

(1) Tool-tip kinematics

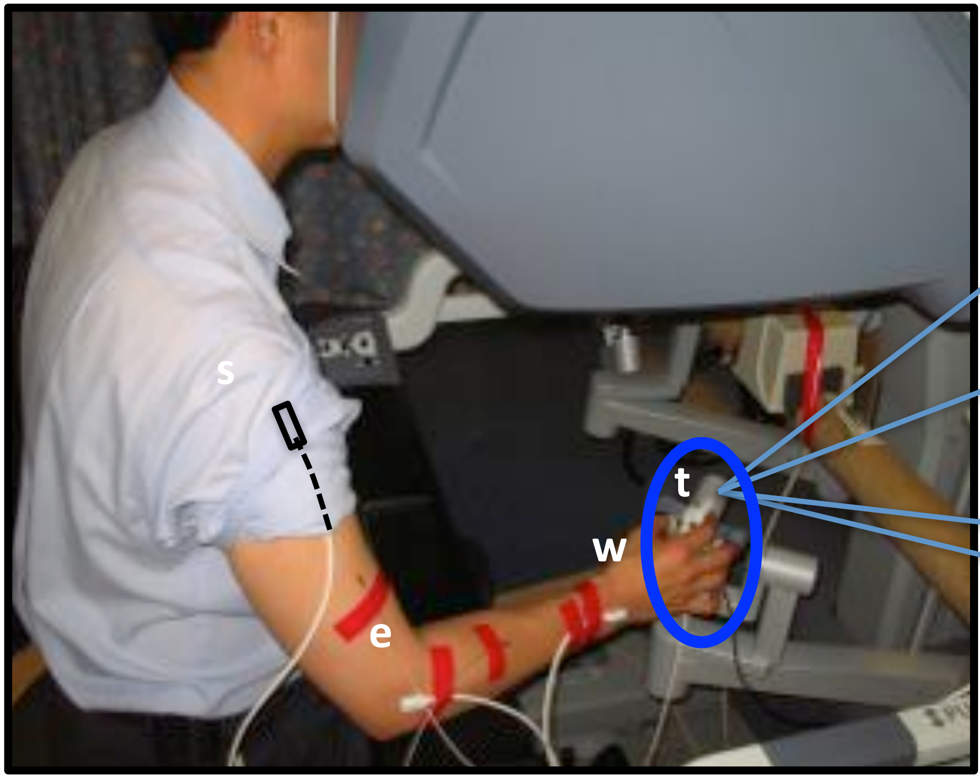


(2) Arm posture variability

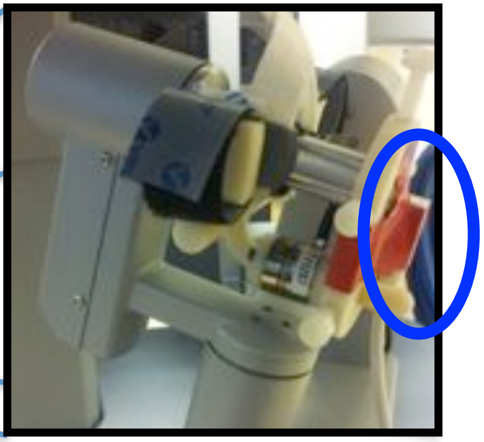
Experimental Setup

Experimental Setup

Pose trackers on user arm

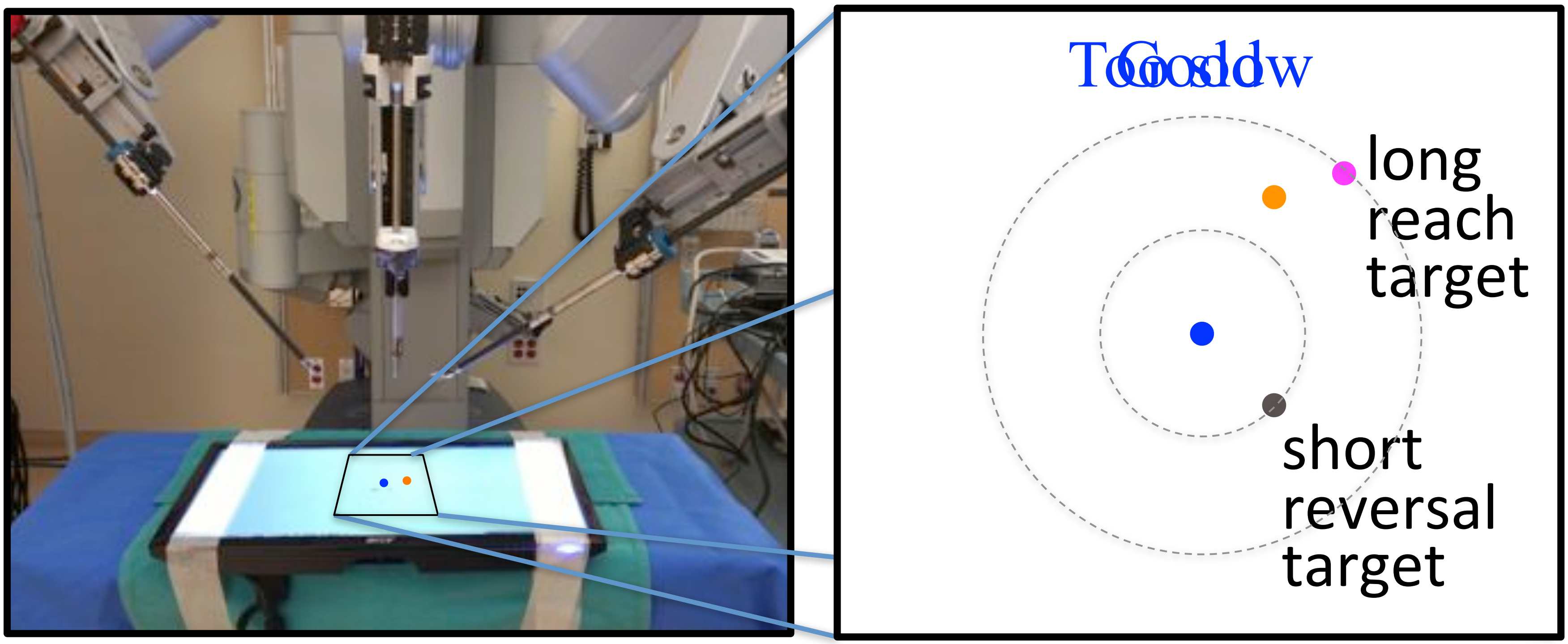


Grasp fixture –
position and force sensing
at tool tip



designed by Taru Roy

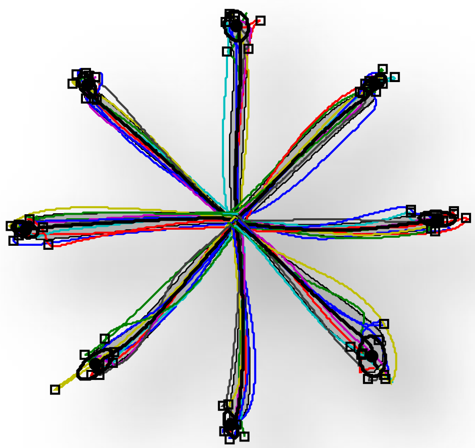
Experimental Procedures



Teleoperation

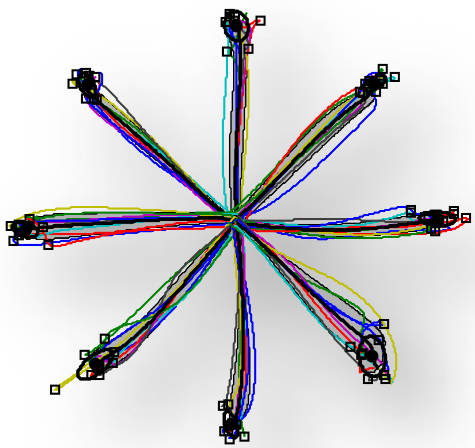
Freehand

Kinematics

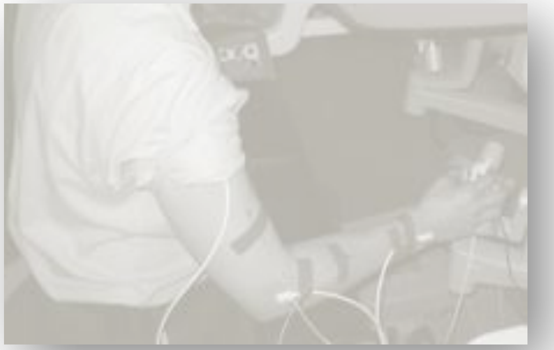


Variability

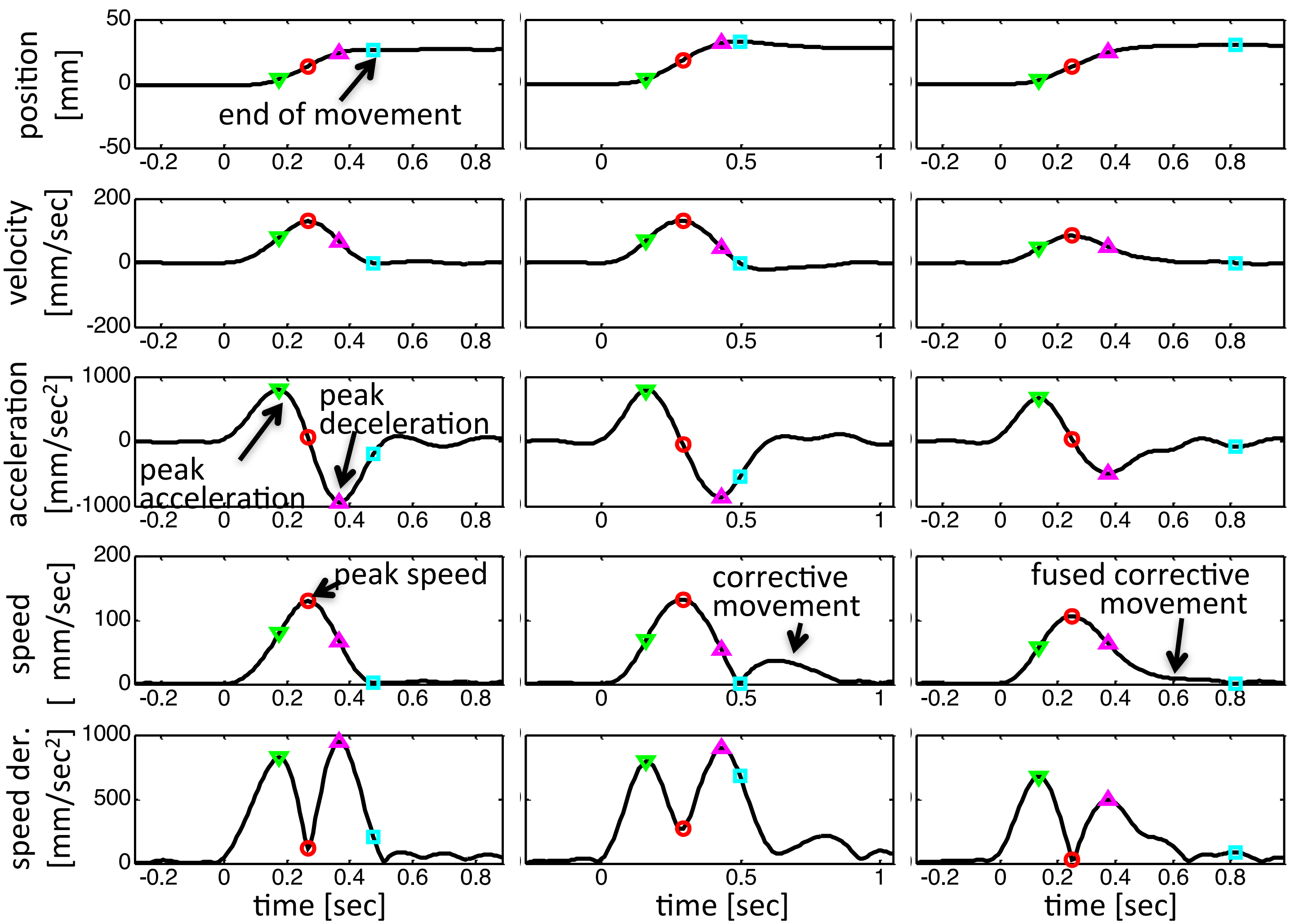
Kinematics



Variability

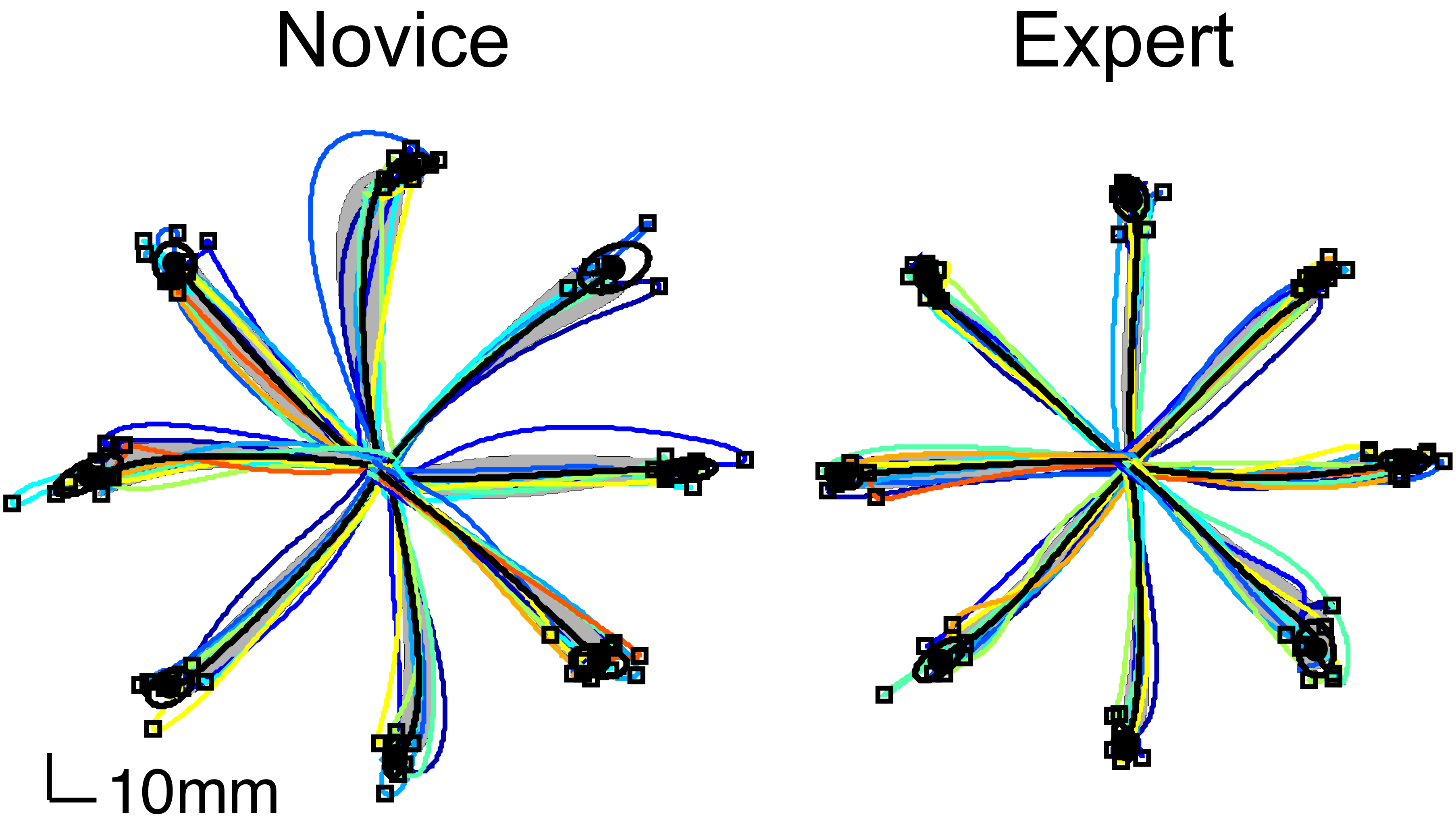


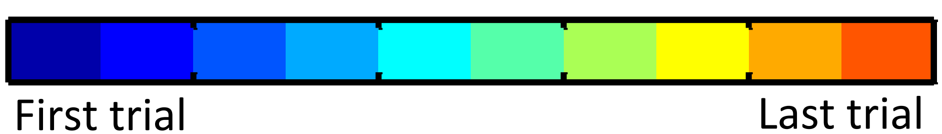
Data Analysis - Reach



Nisky et al., MMVR2013

Deviation from Straight Line

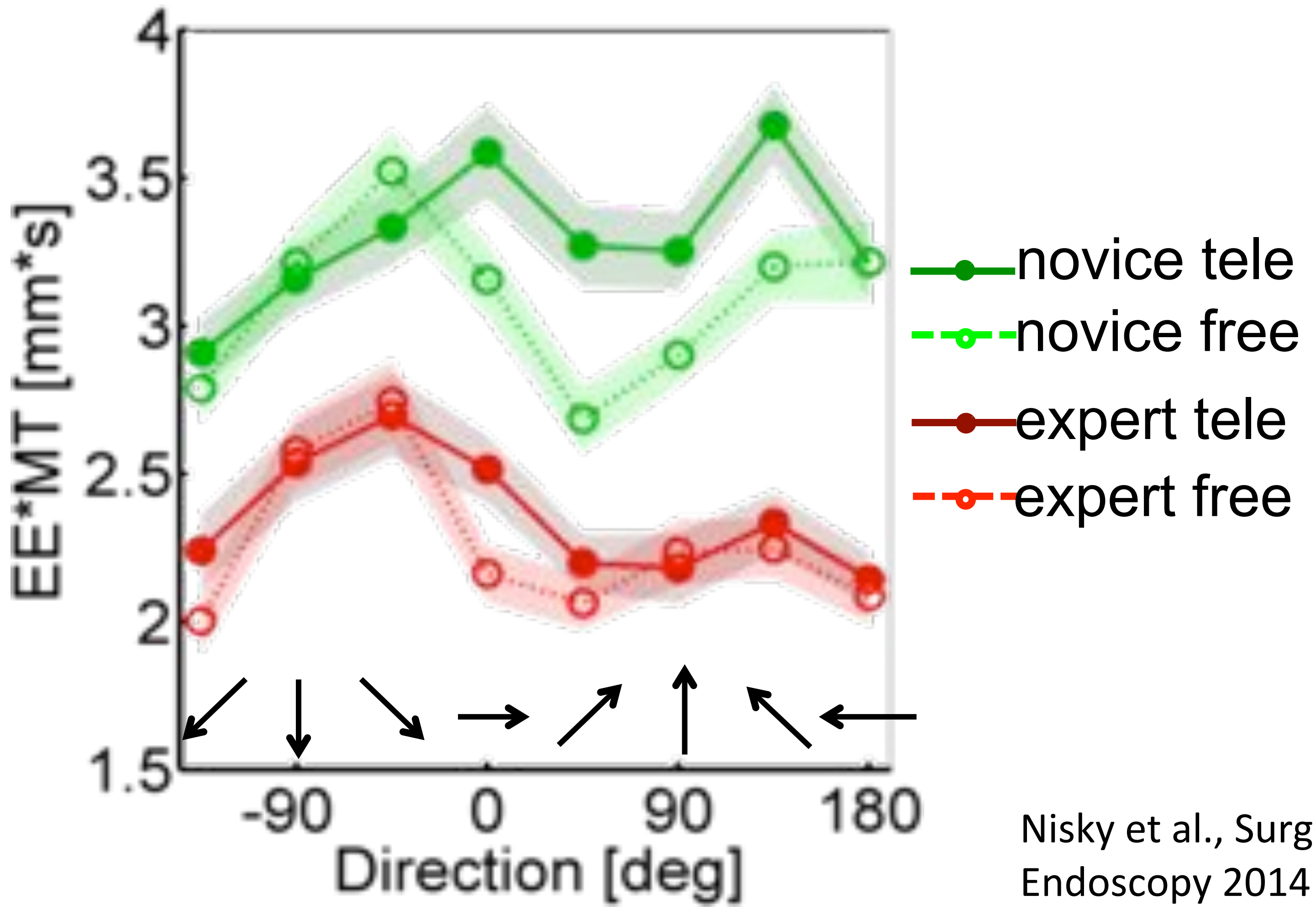




Nisky et al., Surgical Endoscopy 2014

Performance

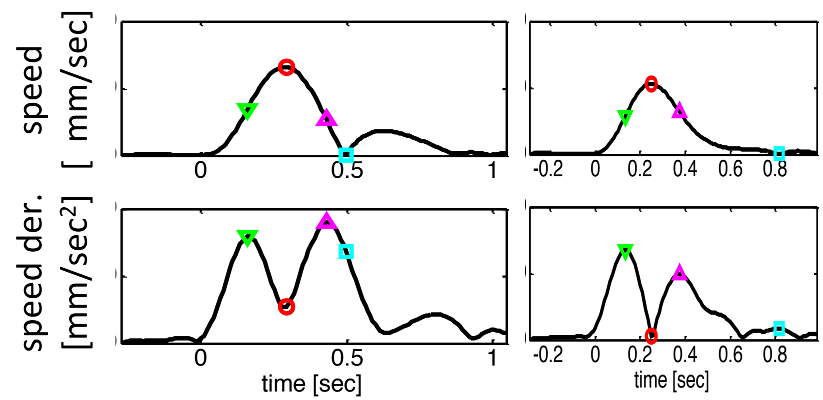
Endpoint Error * Movement Time



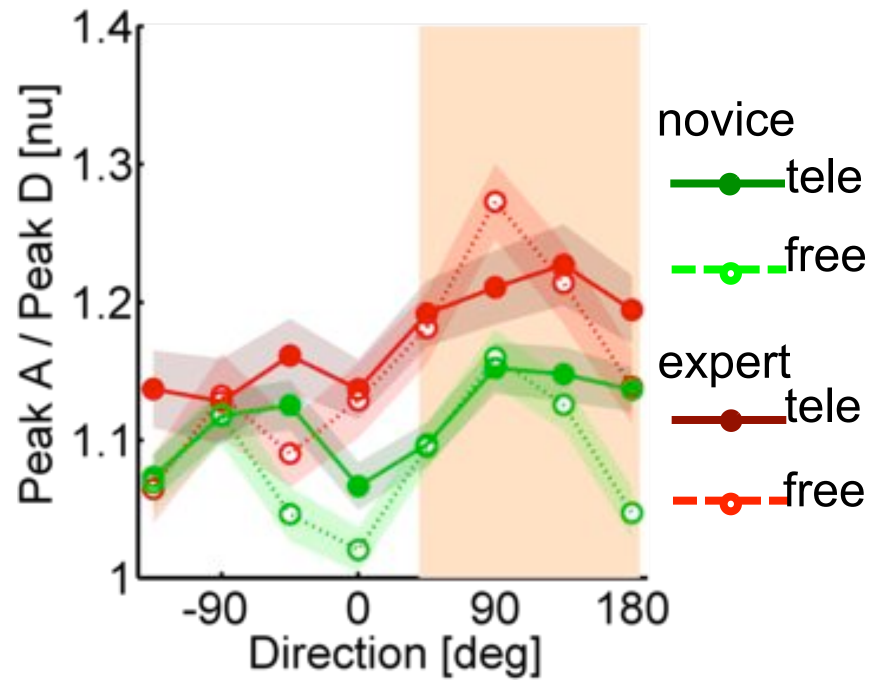
Nisky et al., Surgical Endoscopy 2014

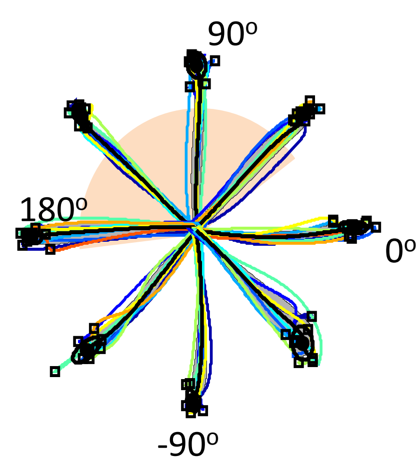
Reach Velocity Skewness

Increased Peak A / Peak D indicates fused corrective movements

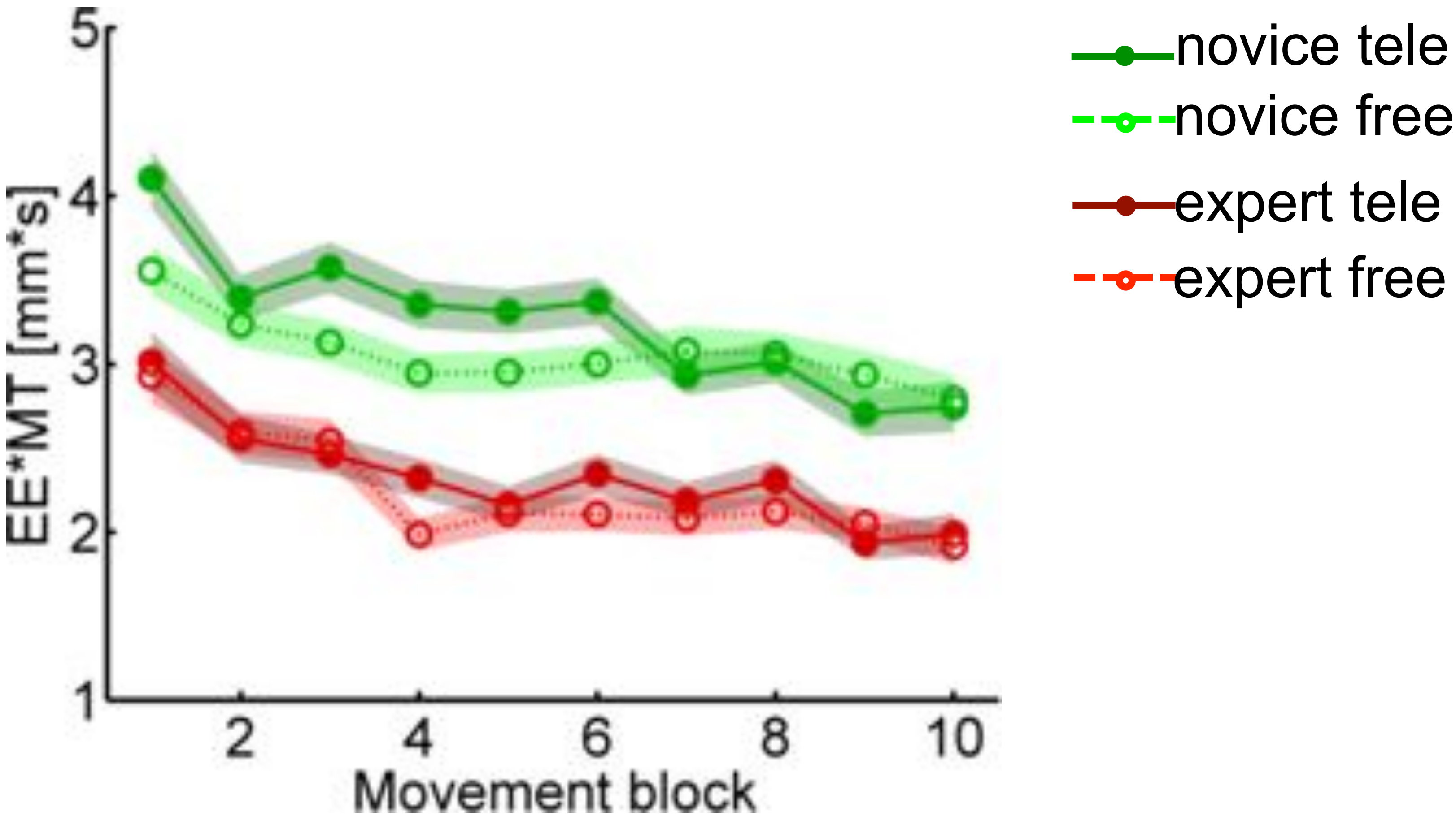


Largest in teleoperated reaches of experts!





Learning effects

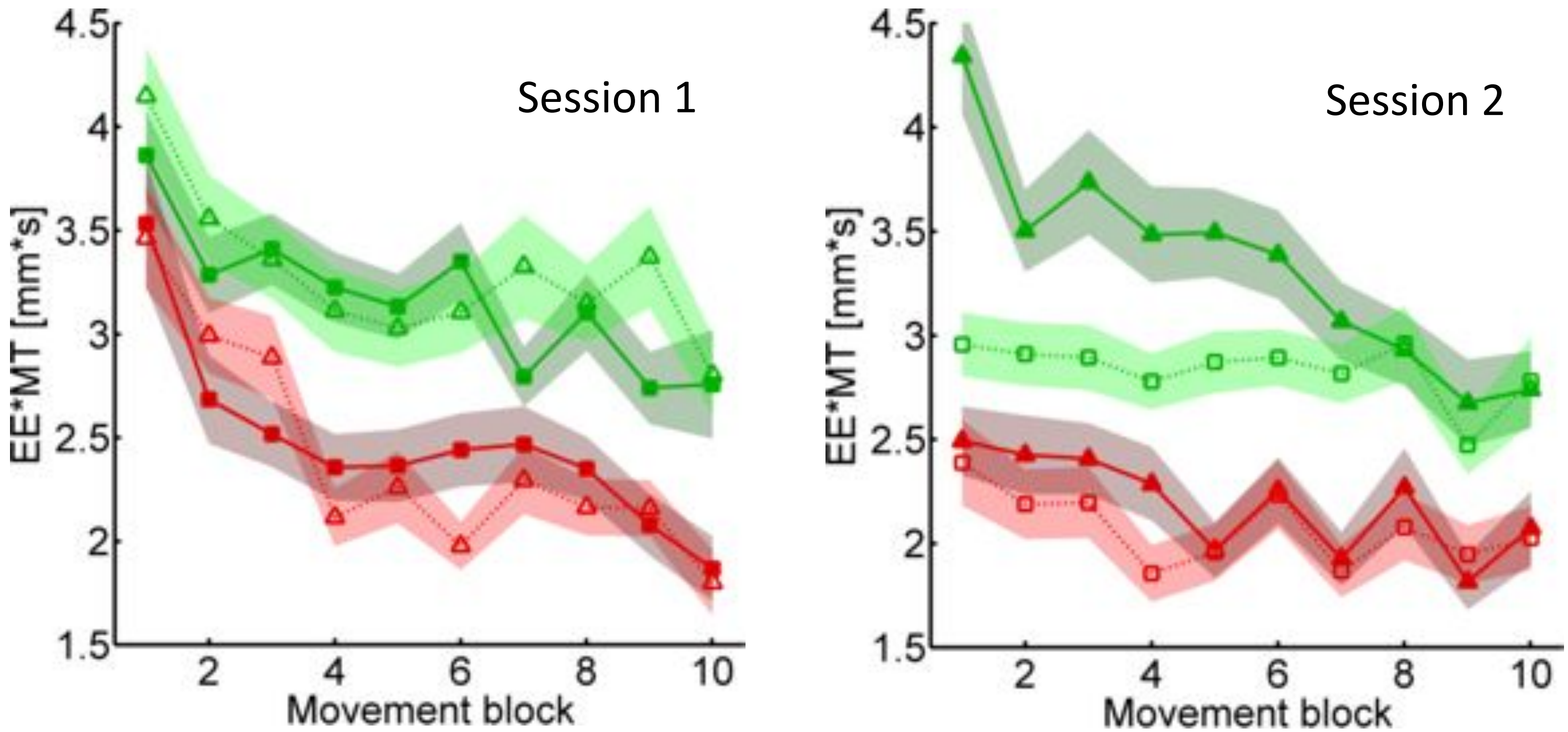


Nisky et al., 2014

Learning effects

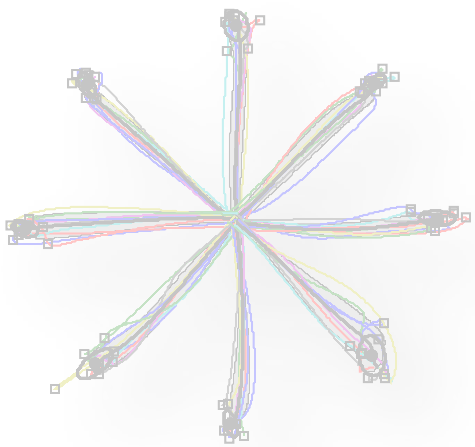
All groups learn the task within 3-4 movement blocks in the first session

Teleoperating novices also learn system dynamics



Nisky et al., 2014

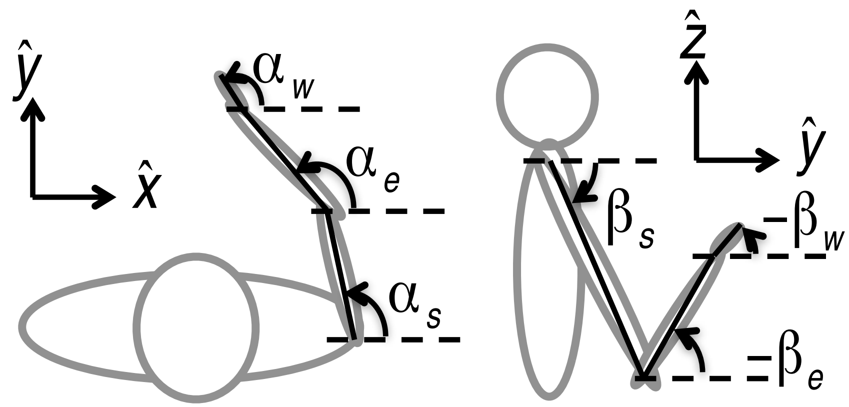
Kinematics



Variability

Redundancy and Variability

Human arm is a **redundant** manipulator

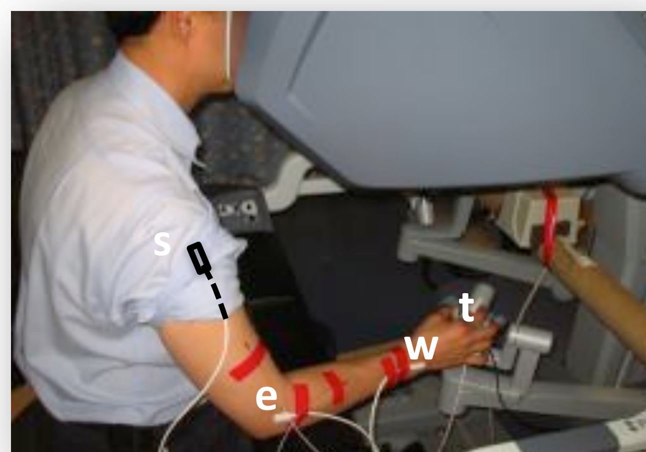


How is redundancy resolved?

- Bernstein, 1967

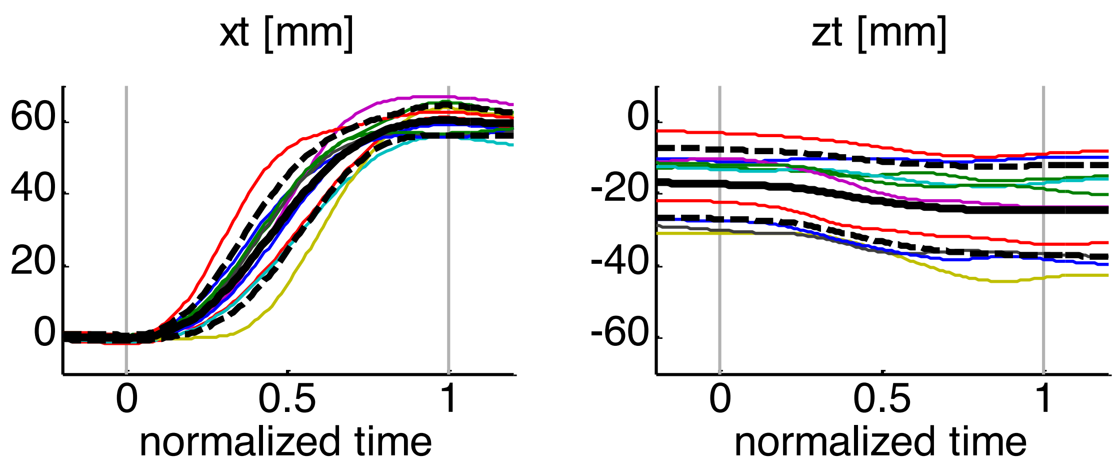
Motor system constrains only task relevant variability

- Uncontrolled Manifold Hypothesis
  Scholtz ans Schoner, 1999
- Minimum intervention principle
  Todorov 2002



Uncontrolled Manifold Hypothesis

Task space



Joint space

2 kinds of trial-to-trial variability in joint angles

- Changes task performance: V_{task}
- Doesn't change task performance: V_{other}

Variability coordination

$R_V = \log(V_{other}/V_{task})$

$R_V > 0$ stabilize

$R_V = 0$ independent

Nisky et al., ICRA 2013

Variability in Joint Space - Uncontrolled Manifold

Forward kinematics

$$\mathbf{x}[t] = F\left(\mathbf{q}[t]\right)$$

Linearize FWD kinematics

$$\mathbf{x}[t] - \overline{\mathbf{x}}[t] = \mathbf{J}(\overline{\mathbf{q}}[t])\left(\mathbf{q}[t] - \overline{\mathbf{q}}[t]\right)$$

Calculate null space

$$\mathbf{J}(\overline{\mathbf{q}}[t]) \cdot \mathbf{e} = 0$$

Project variance onto null and orthogonal spaces

$$\mathbf{q}_{\mathbf{UCM}}[t] = \mathbf{e}\mathbf{e}^T\left(\mathbf{q}[t] - \overline{\mathbf{q}}[t]\right)$$

$$\mathbf{q}_{\mathbf{ORT}}[t] = \left(\mathbf{q}[t] - \overline{\mathbf{q}}[t]\right) - \mathbf{q}_{\mathbf{UCM}}[t]$$

Calculate log of variance ratio

$$\boxed{R_v[t] = \log\left(\frac{\sum_{i=1}^{N}\left(\mathbf{q}_{\mathbf{UCM}}[t]\right)^2 d_{ucm}^{-1} N^{-1}}{\sum_{i=1}^{N}\left(\mathbf{q}_{\mathbf{ORT}}[t]\right)^2 d_{task}^{-1} N^{-1}}\right)}$$

Details in Nisky et al., ICRA 2013,
Nisky et al., IEEE TBME 2014

Variability Predictions

XY movements are stabilized $R_V > 0$

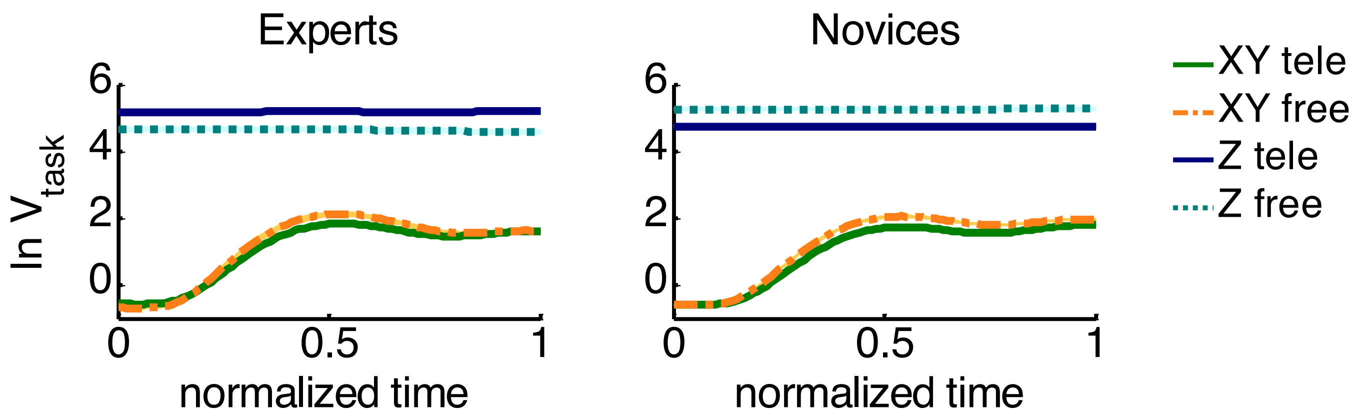
Z movements are not $R_V = 0$

Larger R_V of experts

Skill increases R_V (Muller and Sternad, 2004)

Smaller R_V in teleoperation

Trial-to-trial Variability



Nisky et al.,
IEEE TBME 2014

Coordination of Arm Posture Variability

The task requires only accurate XY movements

XY movements $R_V > 0$

Z movements $R_V = 0$

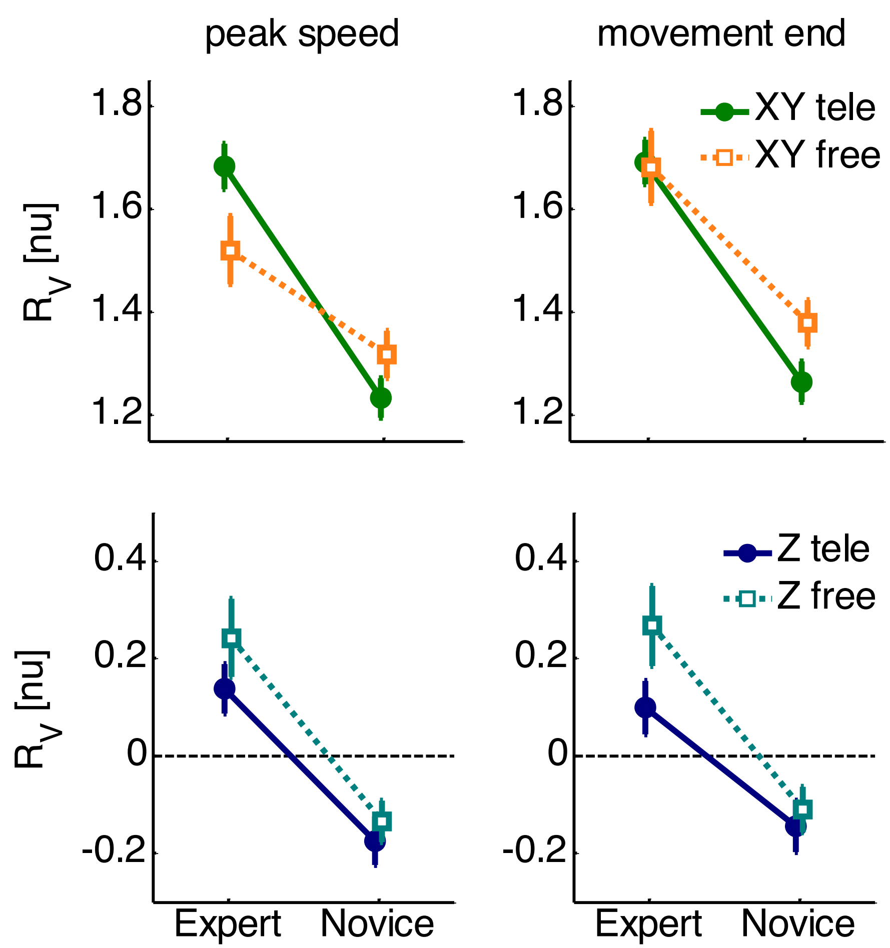
Experience

Larger R_V of experts

Teleoperation

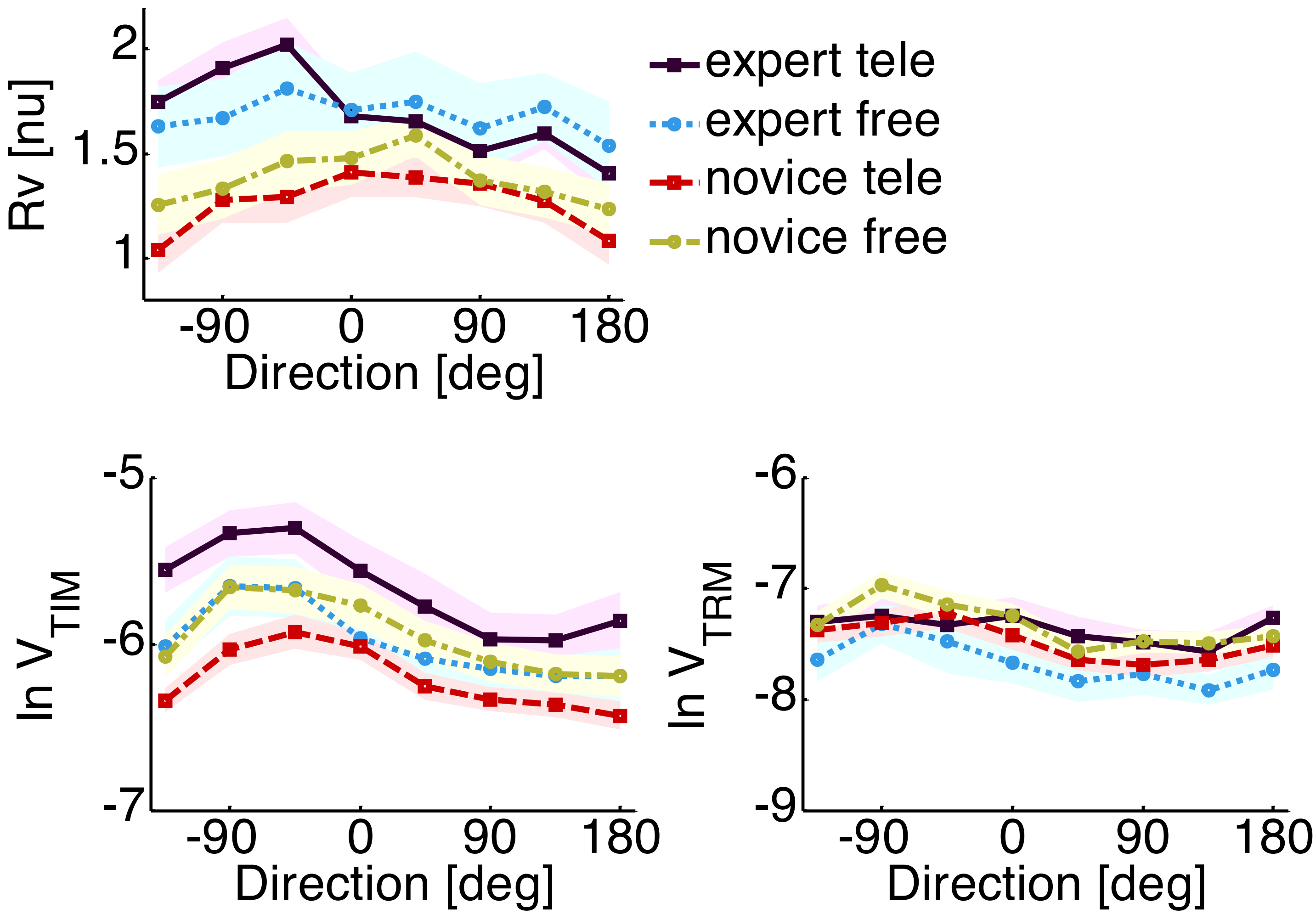
Experts R_V increase

Novices R_V decrease



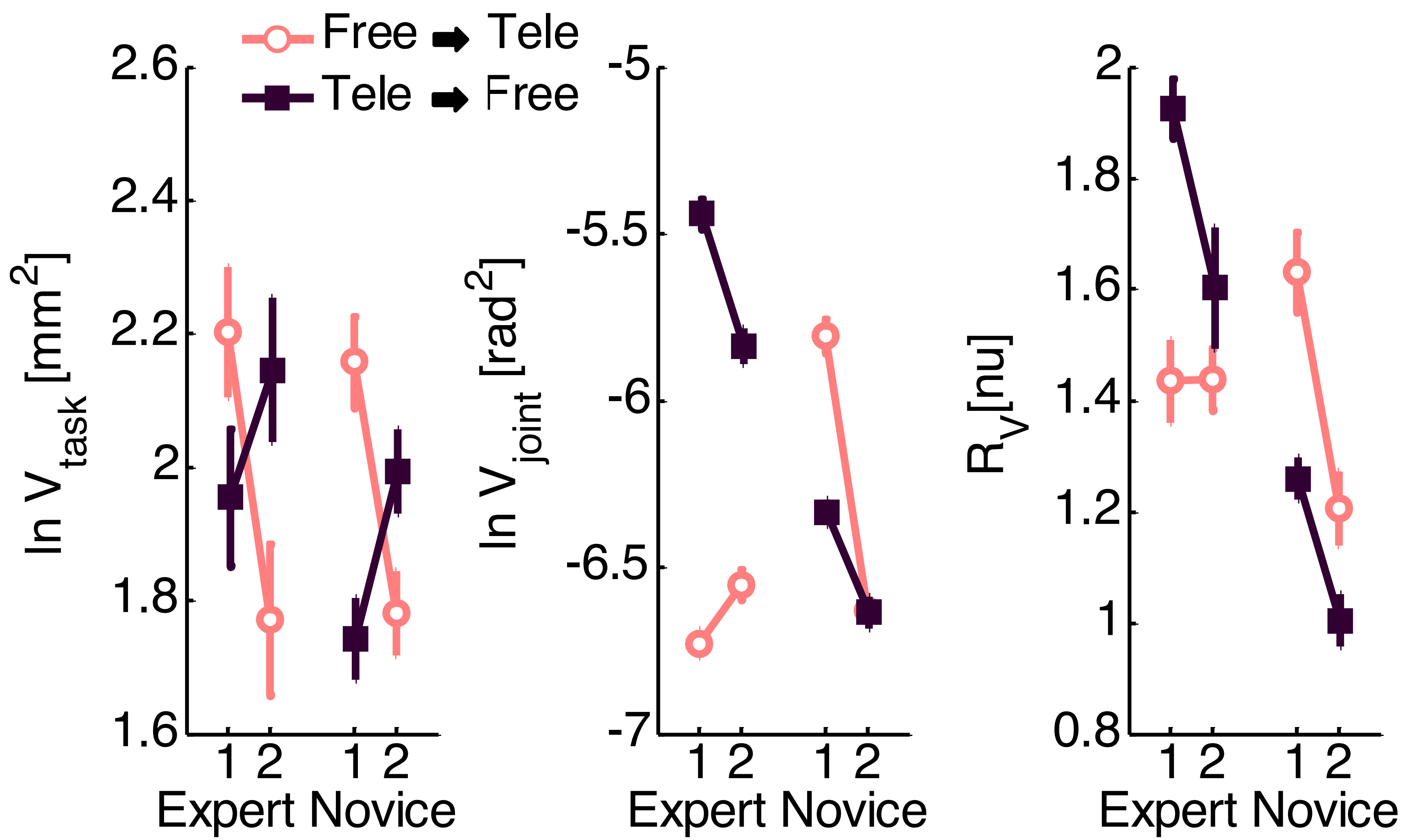
Nisky et al., IEEE TBME 2014

The Effect of Movement Direction



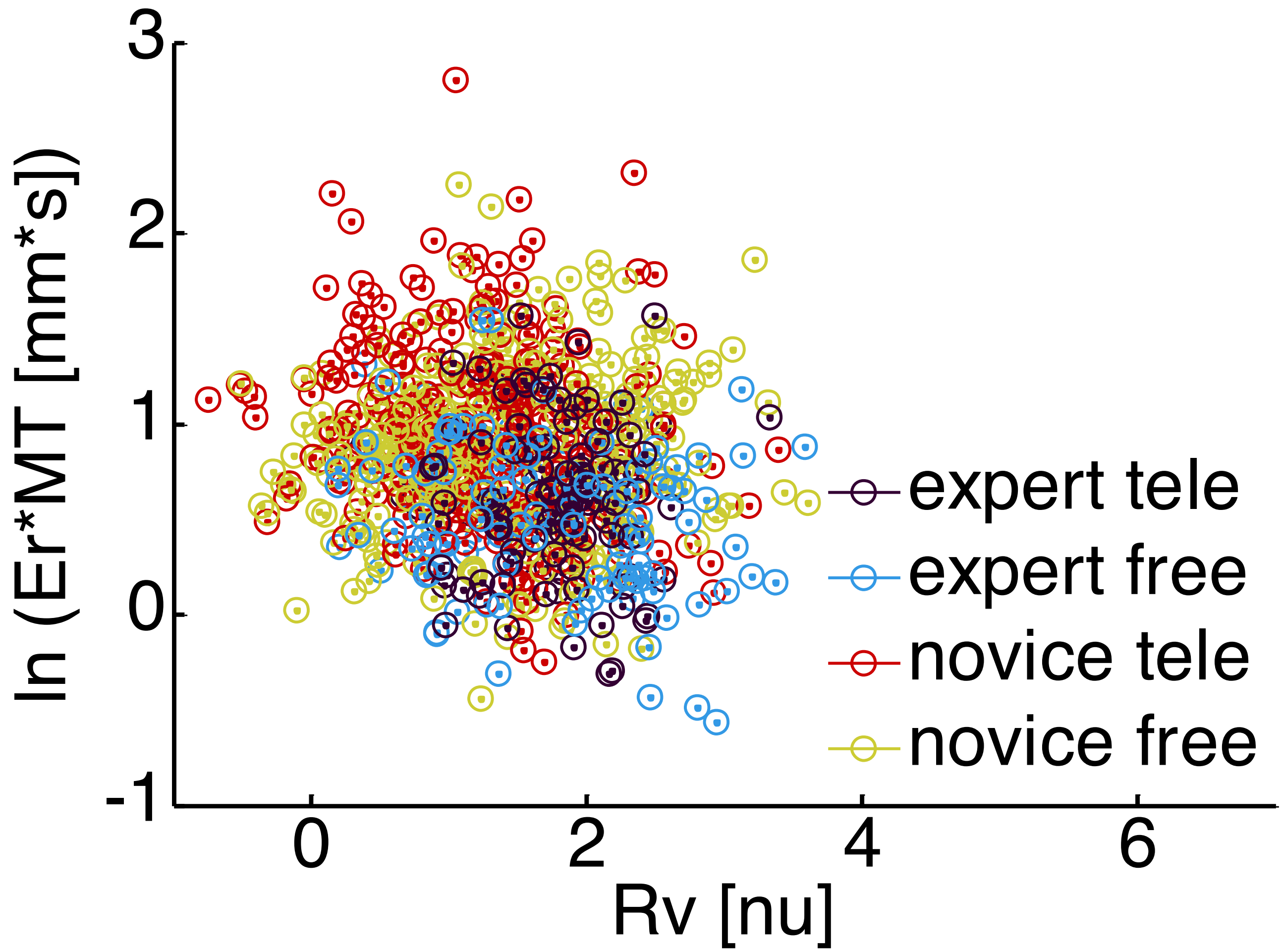
Nisky et al., IEEE TBME 2014

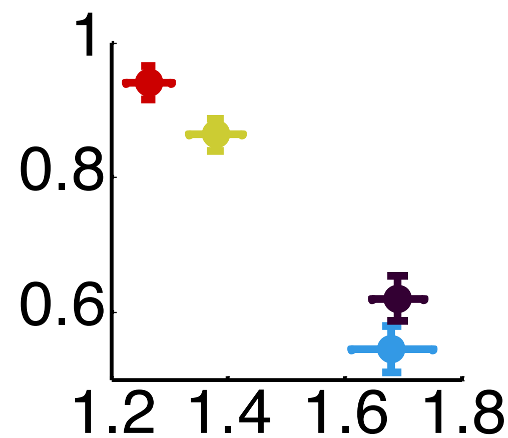
Changes in Variability Between Sessions



Nisky et al., IEEE TBME 2014

Rv and Performance





Nisky et al., IEEE TBME 2014

Realistic Task: Needle driving

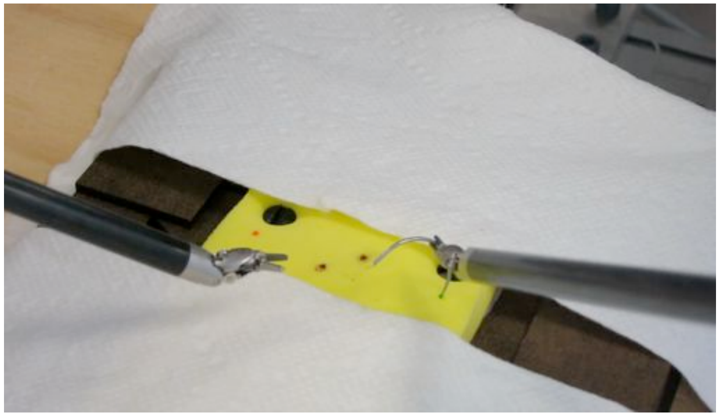
Clinically relevant movement

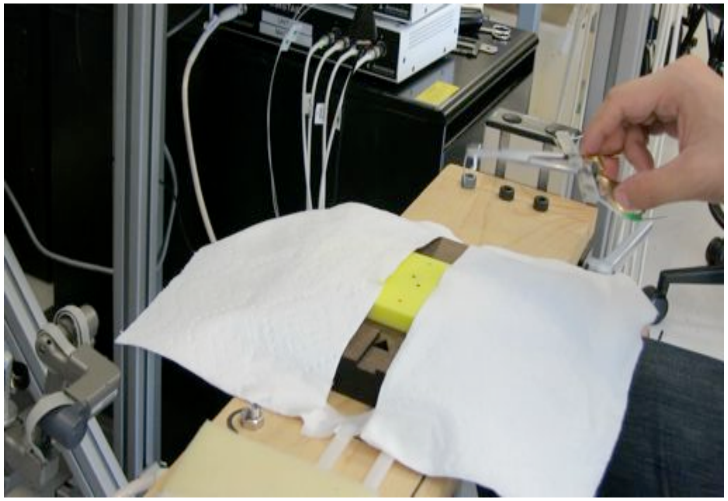
Complexity

- 3D movement
- Tissue interaction
- Orientation is critical

Conditions and participants

- Teleoperated v. open
- Experienced surgeons v. novices

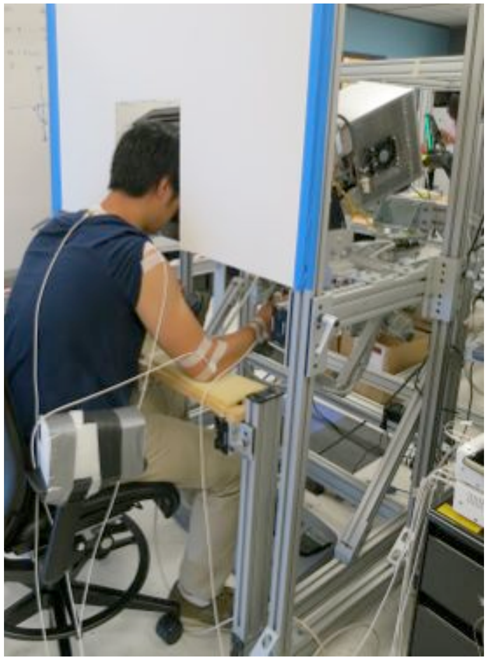




Nisky et al., in preparation

Experimental Setup

Teleoperated - dVRK

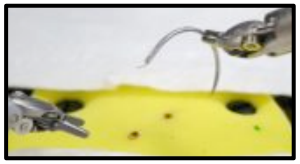


Open – magnetic tracking instrumented needle driver

Needle Driving Task

1

2



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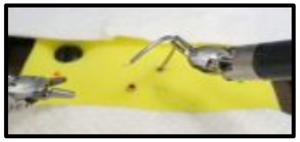

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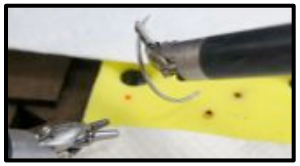
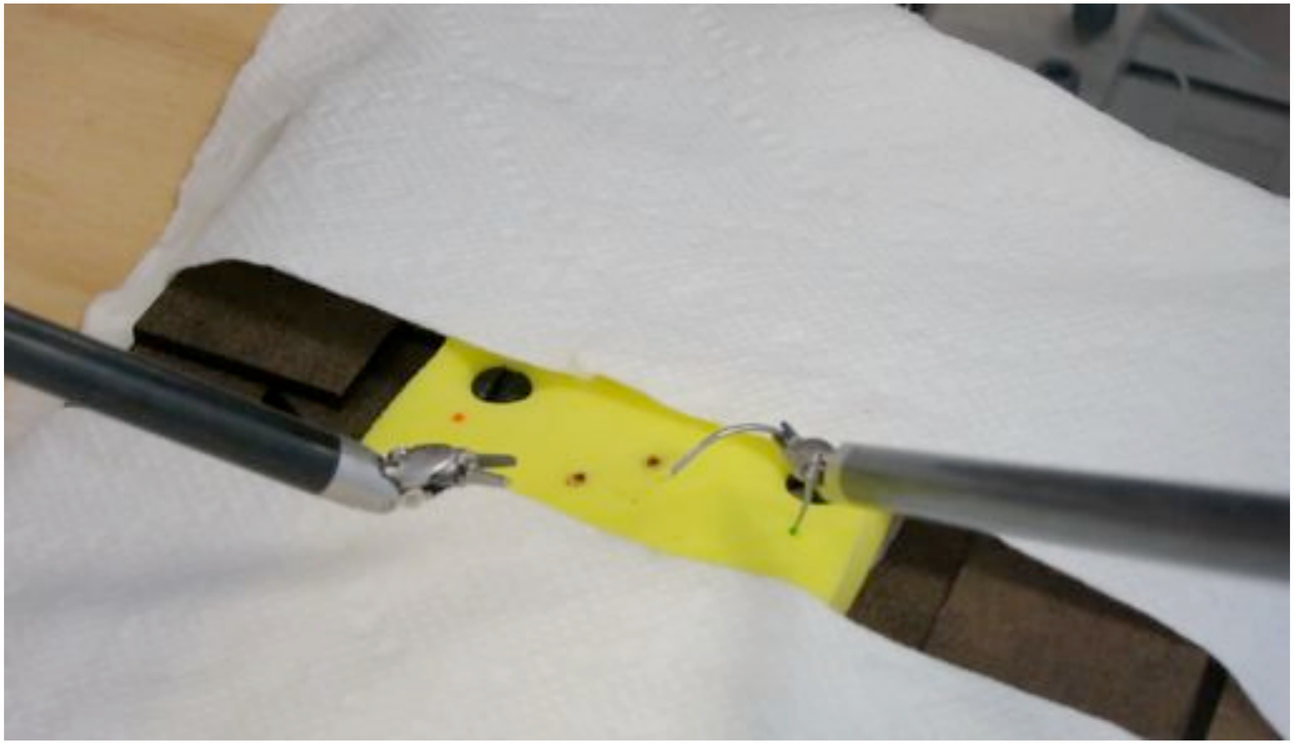
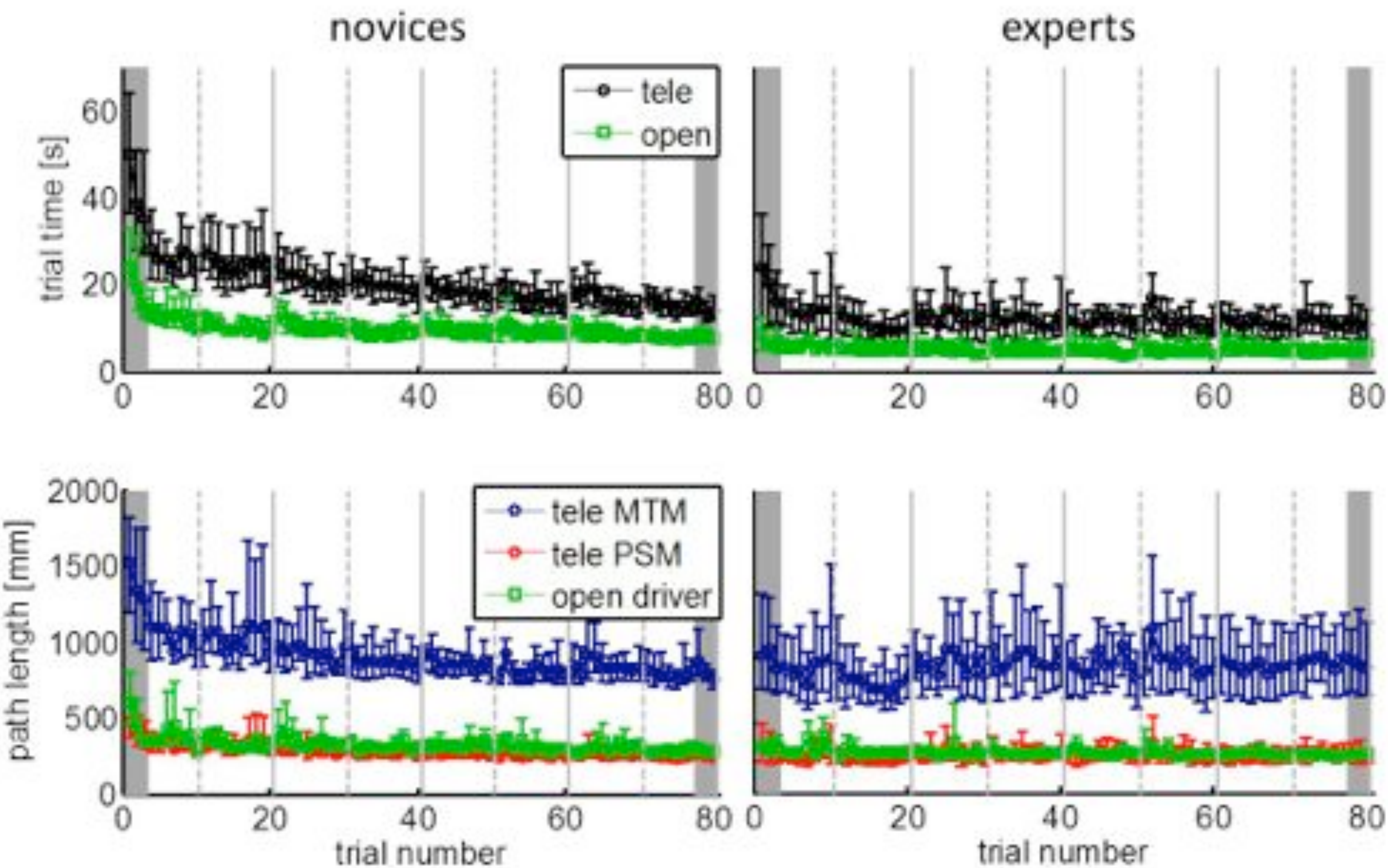


8



Learning Curves

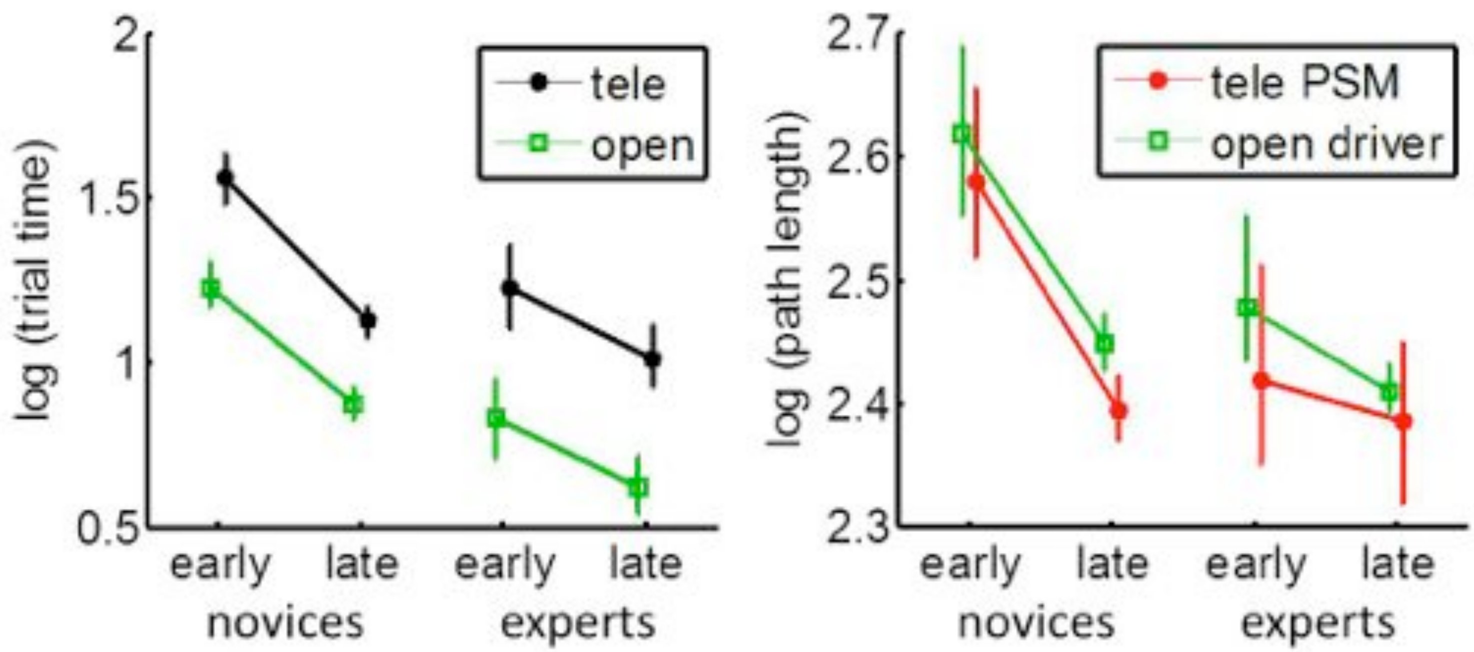


Learning Curves Summary

Open needle driving is faster, but with same needle path length

All participants improve movement time

Only novices improve movement length



Conclusions

The dynamics of the master manipulator matter

Experts have adapted and are better

Experts exploit the redundancy of their arm more than novices

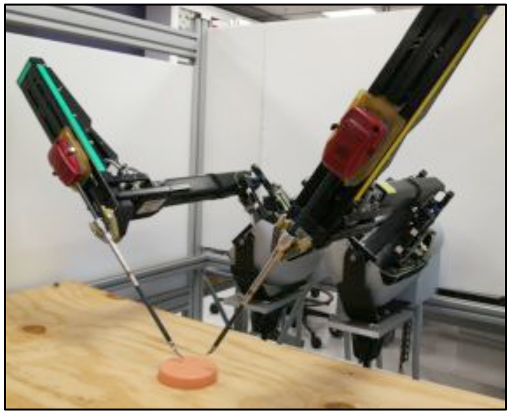
Especially in teleoperation

Future Work

Analysis of interaction forces and **dynamic modeling** of user in teleoperation and freehand

Analysis of redundancy exploitation in needle driving experiment

What is the role of haptic feedback?



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Thank you

Ilana Nisky

Yuhang Che

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Matthew Weber

Sangram Patil

Taru Roy

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Intuitive Surgical Technology Research Grant

Questions?