Learning Kinematic Constraints in Laparoscopic Surgery

Felix C. Huang, Ferdinando A. Mussa-Ivaldi, Carla M. Pugh, James L. Patton

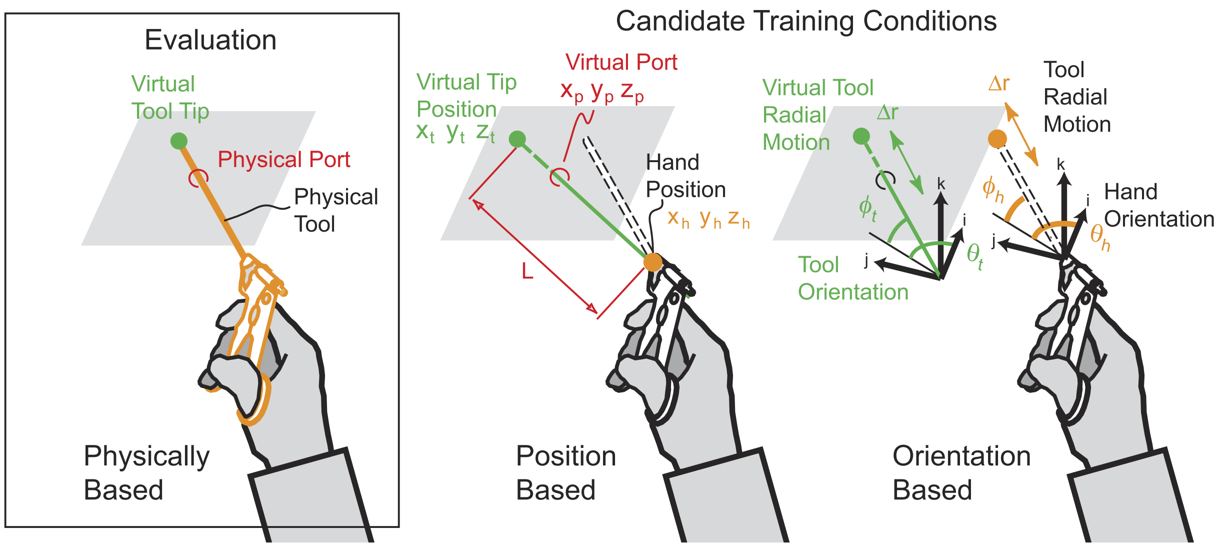
Transactions on Haptics, 5.4:356-364. 2012

Background/Motivation

- Bench top trainers are valuable, but what about them is important?
- What is the importance of haptic feedback in surgical training?
- How does the relationship between the motor system and tool mechanics affect learning?

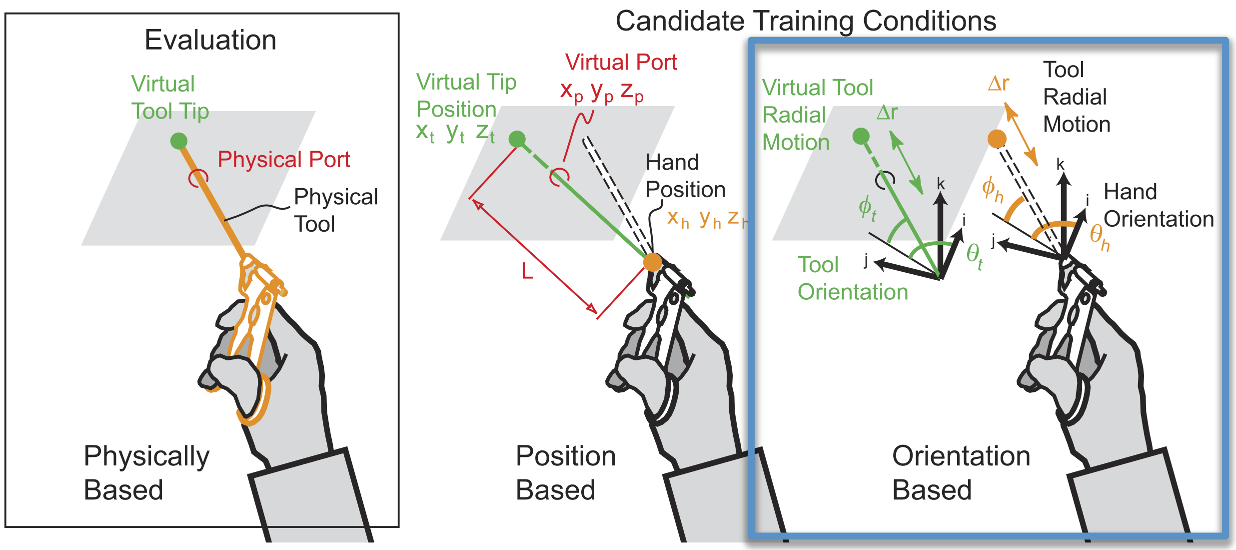
Research Question

- How do kinematic constraints and training sequences affect learning a surgical task?



Research Question

- How do kinematic constraints and training sequences affect learning a surgical task?

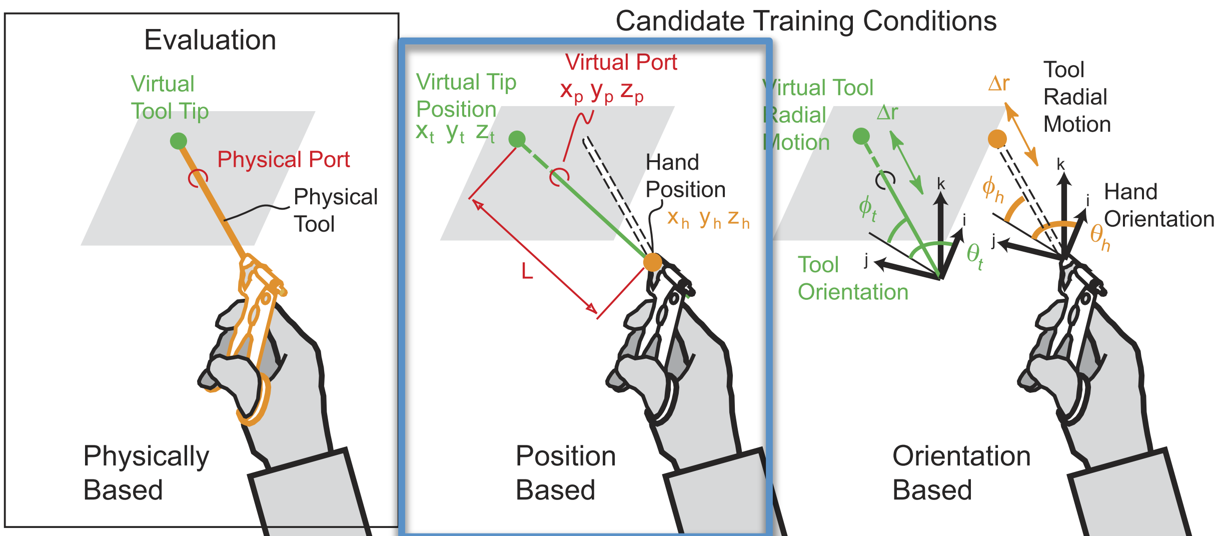


HYPOTHESIS:

(1) Orientation control will be easier to learn due to better mapping with human proprioception.

Research Question

- How do kinematic constraints and training sequences affect learning a surgical task?

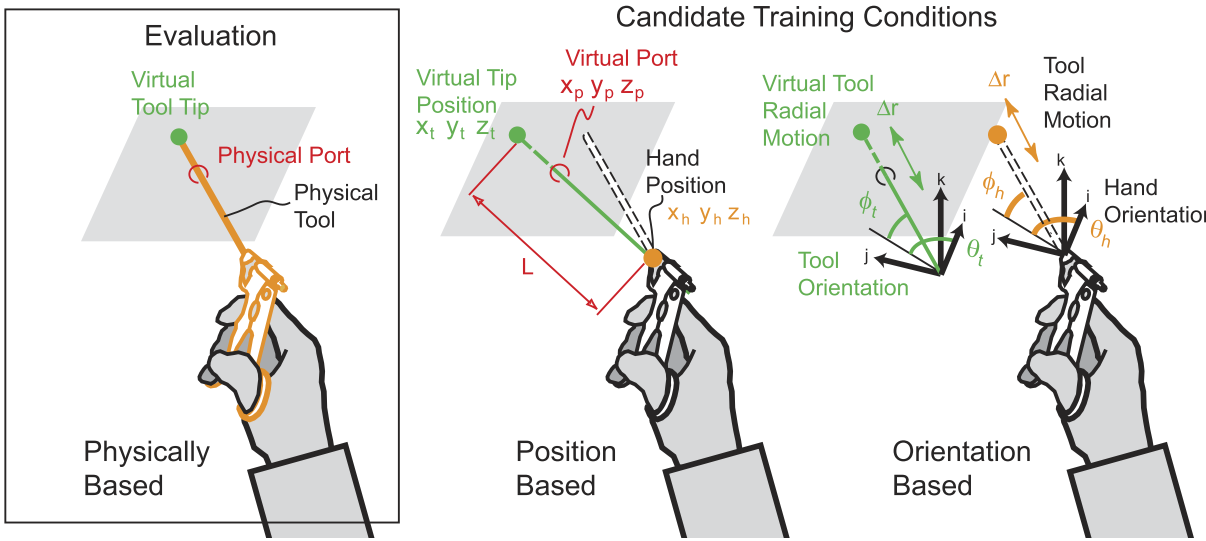


HYPOTHESIS:

(2) Absolute tool representation will be more relevant for operating conditions.

Research Question

- How do kinematic constraints and training sequences affect learning a surgical task?



HYPOTHESIS:

(3) The fulcrum action of the tool will bias learning.

Research Question

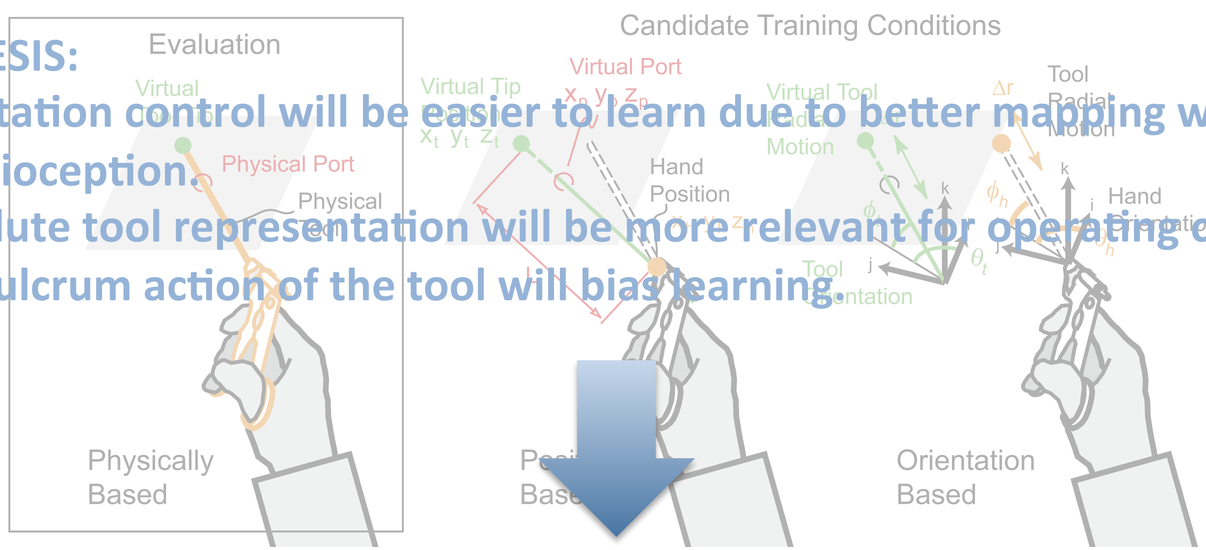
- How do kinematic constraints and training sequences affect learning a surgical task?

HYPOTHESIS:

(1) Orientation control will be easier to learn due to better mapping with human proprioception.

(2) Absolute tool representation will be more relevant for operating conditions.

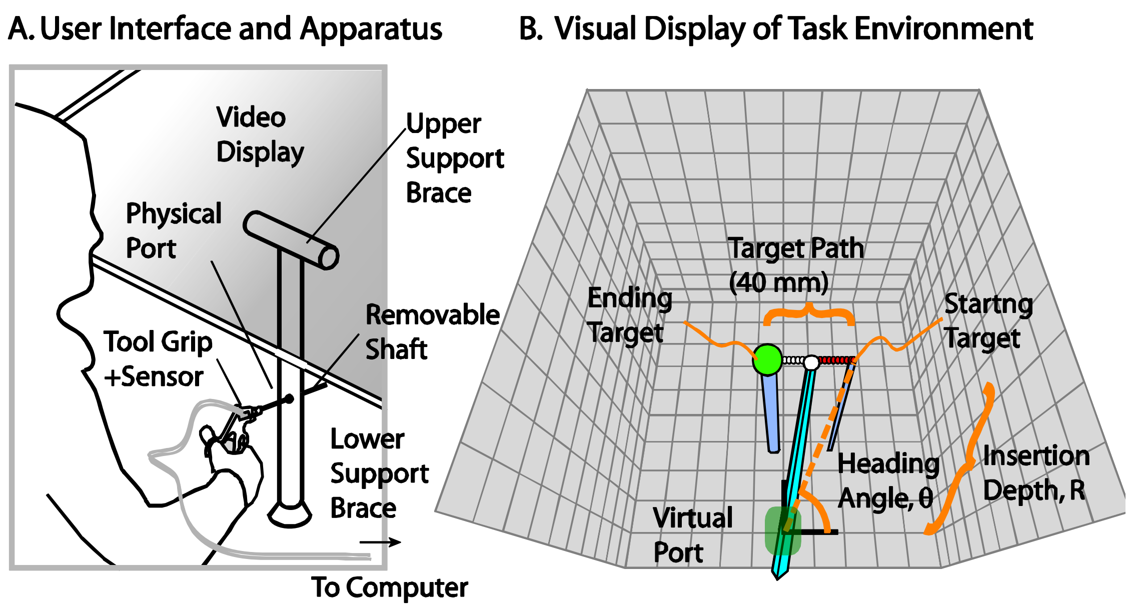
(3) The fulcrum action of the tool will bias learning.



CRITICAL KINEMATIC RELATIONSHIPS FOR NERVIOUS SYSTEM TO ENABLE SUCCESSFUL LAPAROSCOPIC MANUPULATION

Experimental Setup

- Physical and virtual laparoscopy tasks
- 42 human subjects (non-medical)
- 1 control group (physical), 2 test groups (orientation and position control)
- No haptic feedback



Constraint Schemes

Constraint Scheme	Physical Tool Position	Physical Tool Orientation	Virtual Tool Position	Virtual Tool Orientation
Physical	Slide through physical hole	Pivot about hole	Same as physical	Same as physical
Position	Position (x_h,y_h,z_h)	Ignored*	Same (x_h,y_h,z_h)	Determined geometrically (see below)
Orientation	Ignored*	Orientation in space (θ_t,φ_t)	Same as physical (θ_t,φ_t)	Integrated motion of handle projected along tool axis (see below)

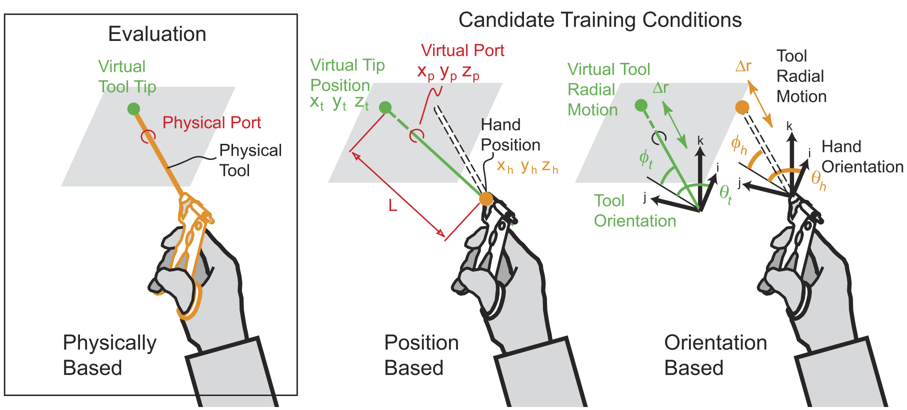
* Meaning, if tool position or orientation are fixed, changes in orientation and position are ignored, respectively.

Tool orientation from position:

$$\theta_t = \tan^{-1}\frac{y_p - y_h}{x_p - x_h}, \quad \varphi_t = \tan^{-1}\frac{z_p - z_h}{\sqrt{(x_p - x_h)^2 + (y_p - y_h)^2}}$$

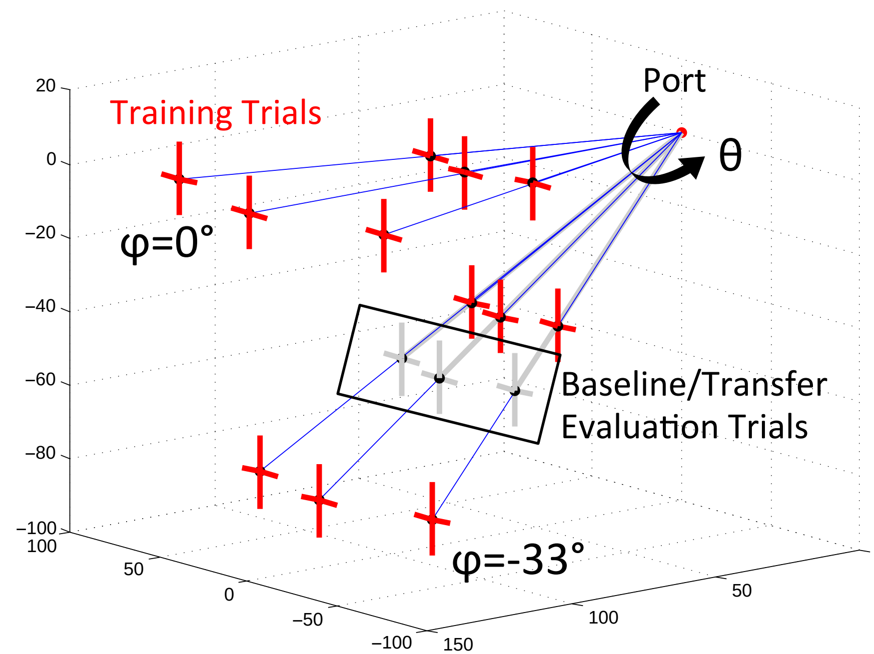
Tool position from orientation:

$$\Delta r_t = \int \dot{r}_h \cdot (\cos\varphi_h \cos\theta_h \hat{i} + \cos\varphi_h \sin\theta_h \hat{j} + \sin\varphi_h \hat{k})\, dt.$$



Experimental Environment

- Subjects were instructed to follow paths displayed on the screen as smoothly and accurately as possible.
- Paths were 40mm long straight lines, facing left, right, up or down, relative to a starting target. 15 starting targets at various locations defined by distance, pitch, and heading.
  - Tool Length: 330 mm
  - Pitch: -33° and 0°
  - Heading: 67.5°, 90°, 112.5°
  - Training & Baseline/Transfer



Experimental Protocol

- Baseline -> Training 1 -> Training 2 -> Transfer
- Group 1: Virtual Position
- Group 2: Virtual Orientation
- Control: Physical
- Training Schedules: Near-Far-Near, Far-Near-Far

		BASELINE	TRAINING 1	TRAINING 2	TRANSFER
Group 1 (n=14)	NFN (n=7)	24	Near x12, Far x96	Near x108	24
(Position Constraint)	FNF (n=7)	24	Far x12, Near x96	Far x108	24
Group 2 (n=14)	NFN (n=7)	24	Near x12, Far x96	Near x108	24
Orientation Constraint	FNF (n=7)	24	Far x12, Near x96	Far x108	24
Control (n=14)	NFN (n=7)	24	Near x12, Far x96	Near x108	24
	FNF (n=7)	24	Far x12, Near x96	Far x108	24

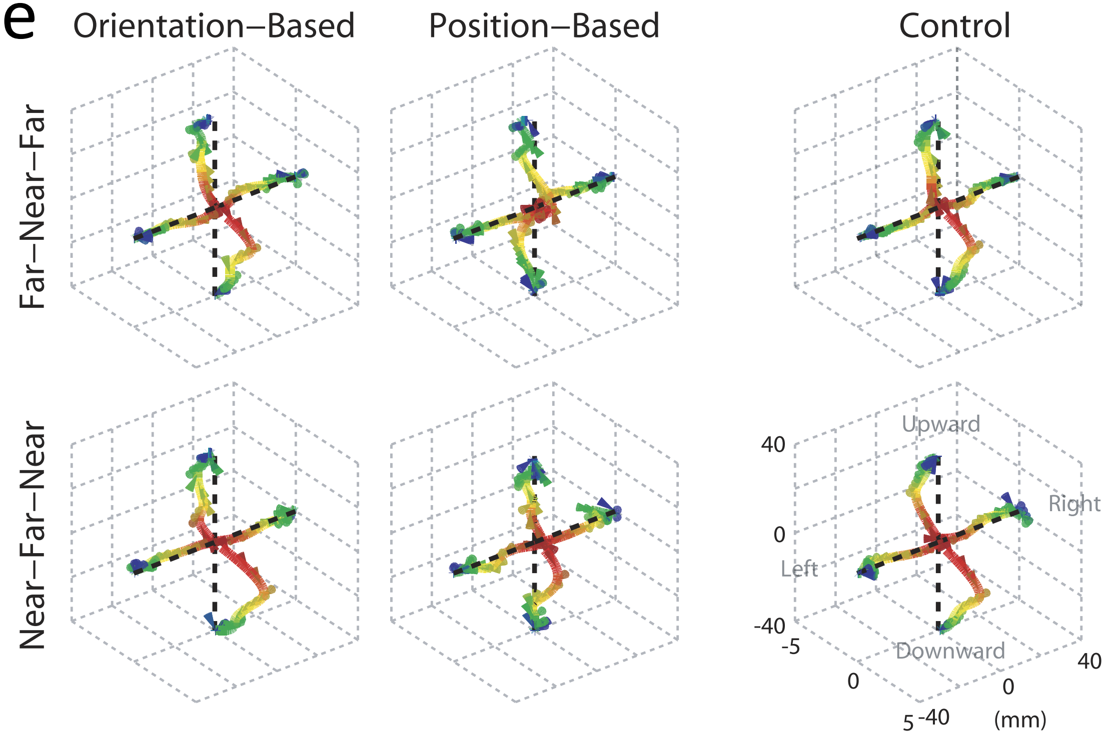
Physical
Postion
Orientation

Evaluation Metrics

- **Movement Error:** Maximum perpendicular deviation from direct path over all time steps for each trial.
- **Movement Time:** Duration of moving between targets.
- Percentage change of each metric was computed for each unique condition
- Schedule Effects were measured by comparing the first 12 blocks for near/far baseline and transfer trials.
- ANOVA analysis was used for comparison (with Tukey's posthoc HSD test)

Results: Systematic Errors

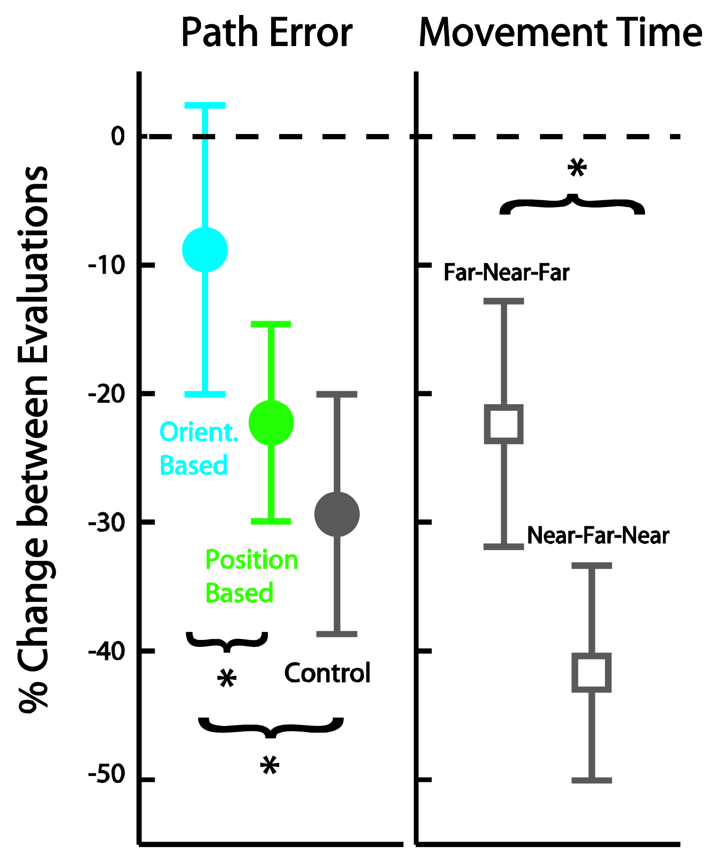
- Most deviation in vertical motions.
- Systematic deviation in evaluation blocks due to failure to compensate for tool direction.
- Varied performance in path direction due to visual occlusions.



NOTE:
Lower deviations for position-based constraint training and for Far-Near-Far schedule

Results: Training Effects on Systematic Error

- Training improves performance.
- Significant improvement in path error and reduction in movement time for control and position-based training*.



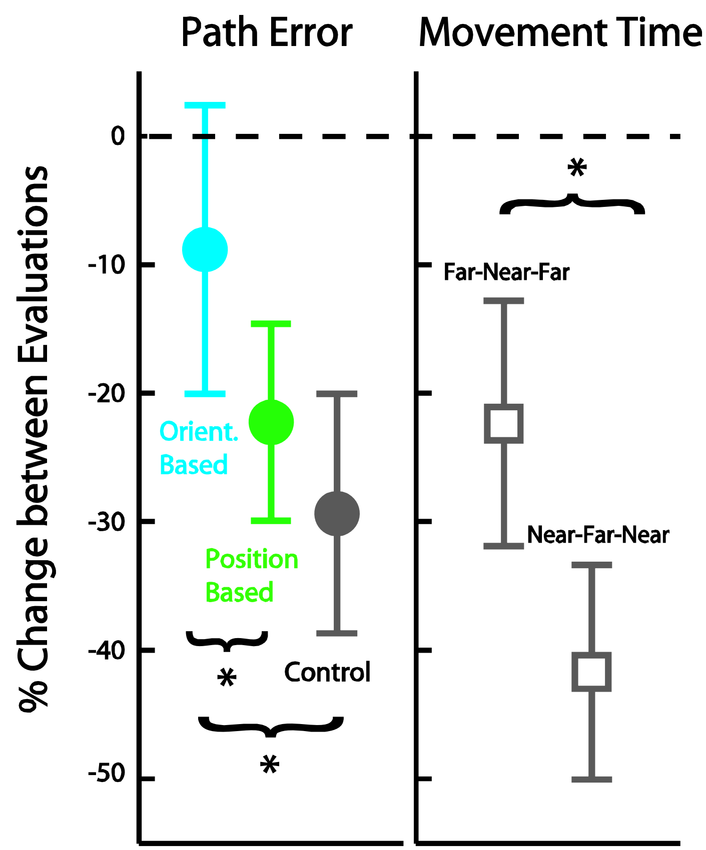
* They say that in general, but doesn't the test only give significance over orientation-based training?

Results: Learning differences due to training

- Checked for differences between training groups.
- **RESULTS:**
  - Position VC and Control have more path error than Orientation VC.
    - *Suggests that orientation VC are easier to learn.*
  - Position VC had greater path error improvements than Orientation VC, similar to Control
    - *suggests similar learning in Postion VC and Control*
  - Position-based training was better for downward movements.
    - *Suggests position-based training is better for difficult movements because downward motion corresponds to the movement with greatest initial evaluation error.*

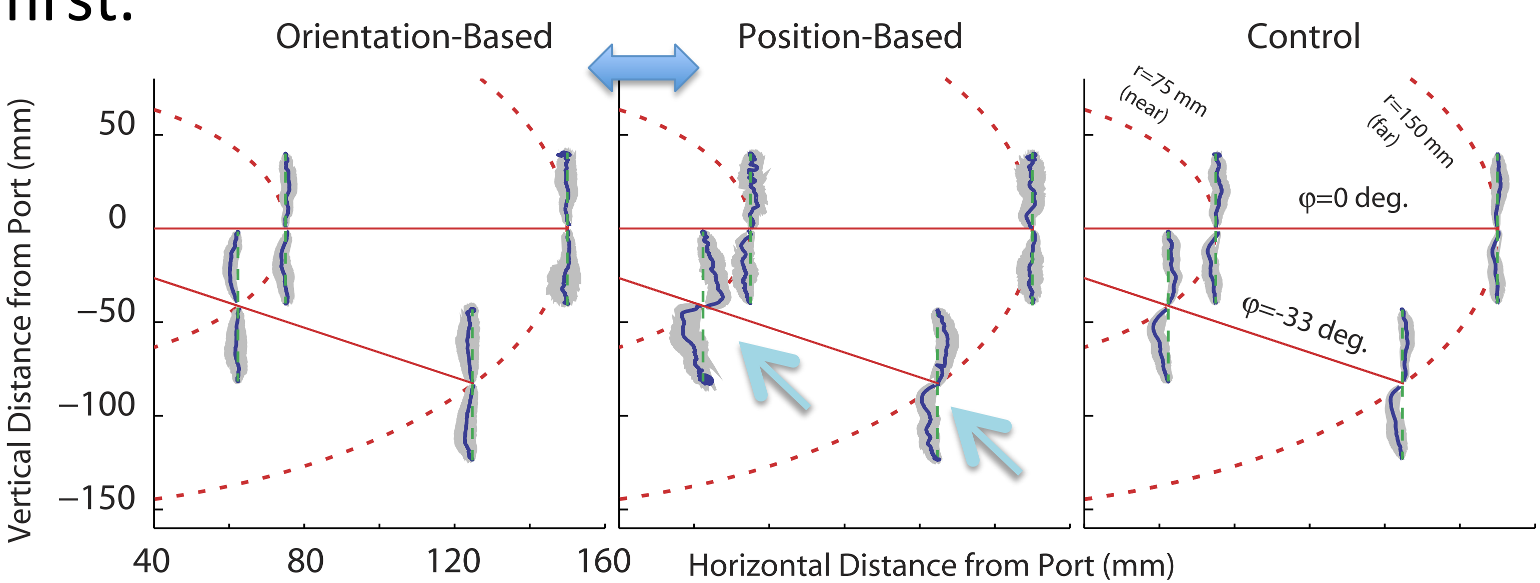
Results: Learning Differences due to Training Schedule

- Near-Far-Near reduced movement time more than Far-Near-Far.
- Possible typo in paper. NFN = 20.5+/-18.9% vs. FNF = 34.0+/-14.8%



Result: Performance During Training

- Training with position-based VC shows greater path error when compared with orientation-based VC.
- Again, see larger errors in downward direction for position-based training and reduction path error for position based training when near targets are trained first.



Discussion

- Position-based training is more beneficial
  - Postion-based training is more challenging to learn
- Training with shallower targets promotes greater reduction in movement time.
  - Due to natural amplification/attenuation effects. Hodgsen et al. show augmented error feedback enhances learning -> increased awareness of tool behavior.
  - Additionally, this is more difficult task with near targets therefore, the subjects must learn more.

$$\delta = L \cdot \left(1 - \sqrt{1 - \frac{d^2}{L^2 \xi^2}}\right)$$

Decreasing fulcrum-target distance results in increased path error

Author Comments

- While no force feedback was used in this study, results suggest it would be helpful for learning skill.
- Investigations of tool use should consider kinematic relationship and their effect on motor performance and haptic perception.
  - *Especially important with faulty kinematic models.*

Recommendations for training

- Focus training on near targets – learning transfers to deep targets.
- Learners should focus on absolute positions relative to the port to minimize errors.
- Use virtual fixtures to decouple fundamental features of a task to identify most critical learning challenges.

Discussion Points

- Difficulty of training -> better improvements
  - But at what point is it too difficult?
- Orientation VC are easier to learn, why not design tools to exploit that?
- Correcting faulty kinematic models with haptic feedback.
- How might this relate to part-whole transfer?