Cybernetic Interfaces for the Restoration of Human Movement Through Functional Electrical Stimulation

Eric Perreault, Robert Kirsch, Konrad Kording, Kevin Lynch, Lee Miller, Sandro Mussa-Ivaldi, Matthew Tresch

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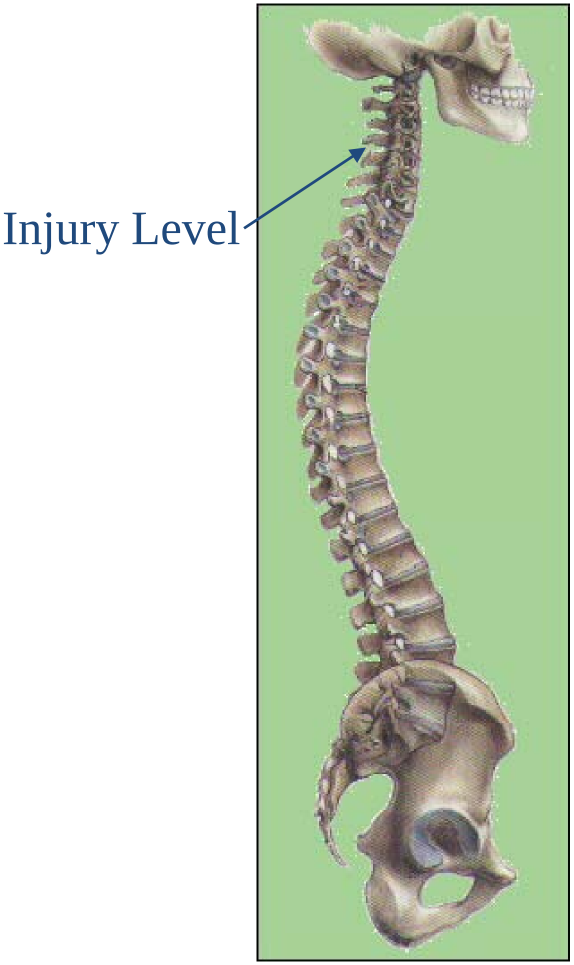
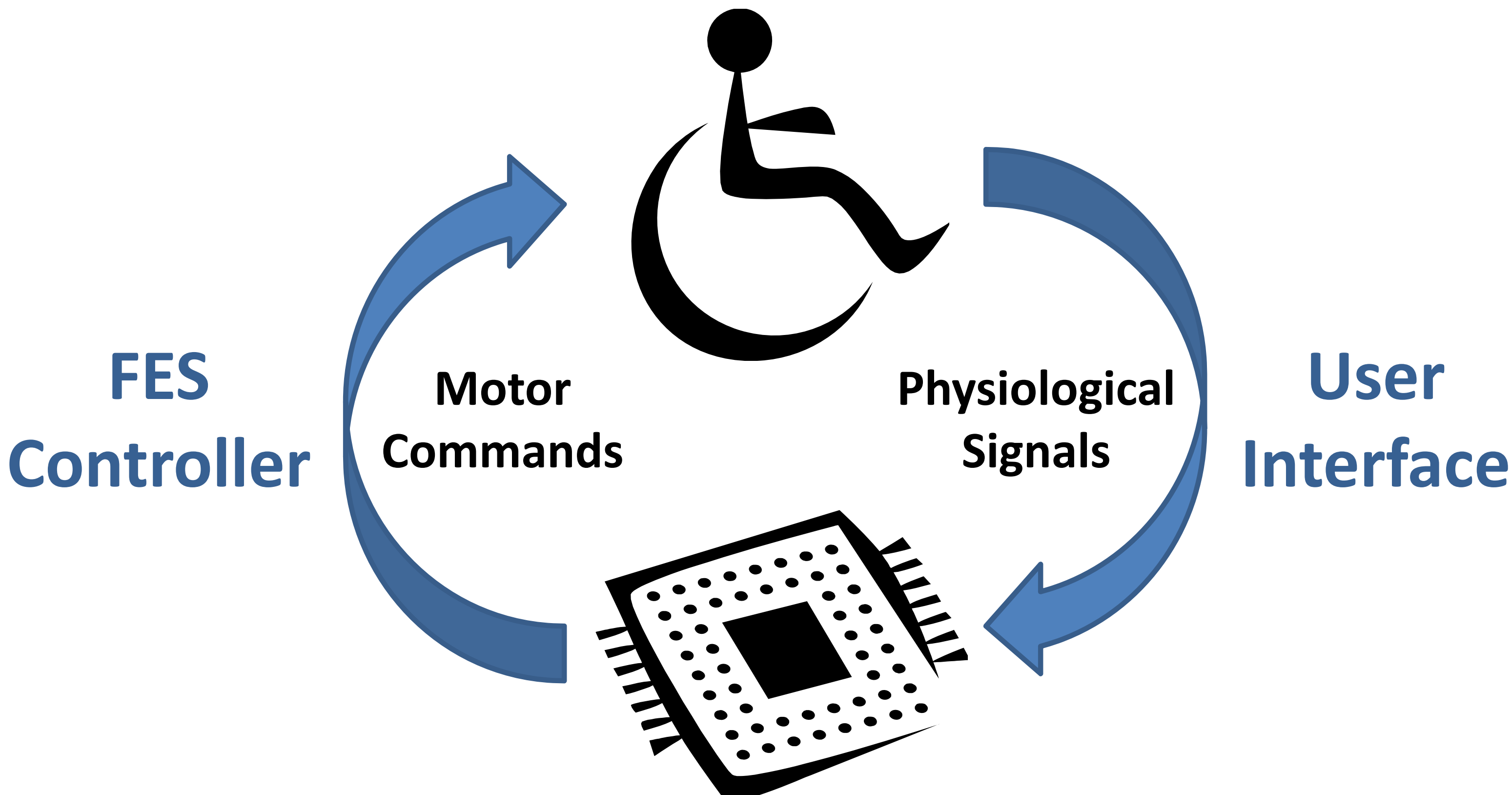
Challenge

Restoration of reaching following high-level spinal cord injury

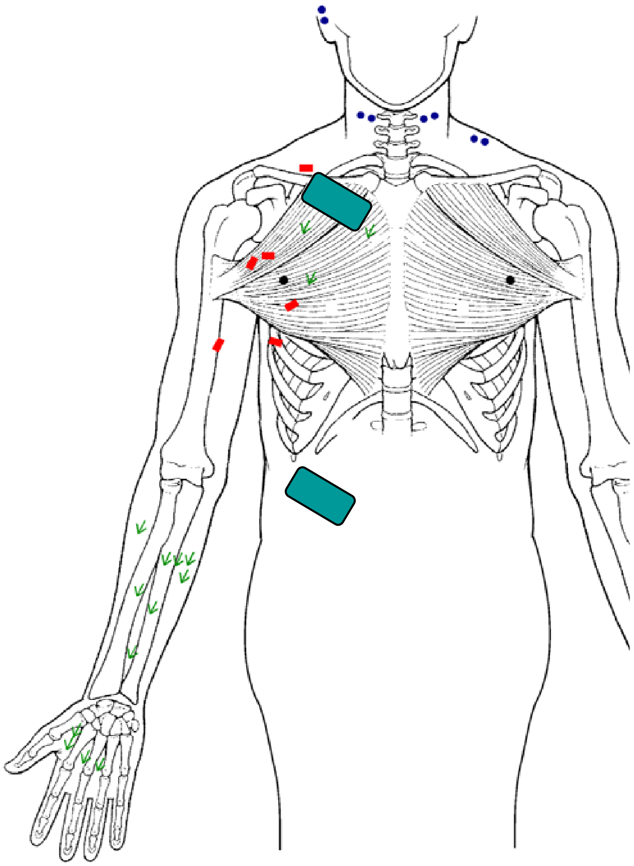


Cyber-Physical Challenges associated with Functional Electrical Stimulation (FES)



- Nonlinear & non-stationary
- ‘Natural ‘ and effortless
- Fault tolerant

Current State of the art in FES



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NIH NINDS contract N01-NS-5-2365

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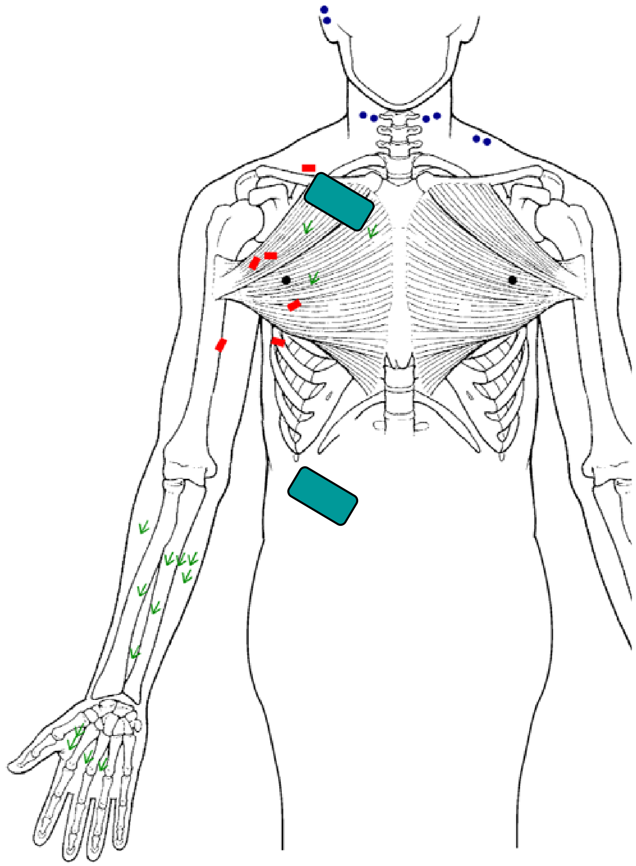

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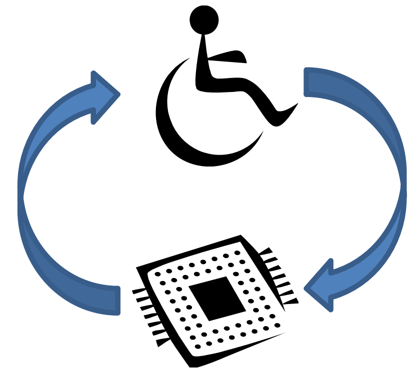
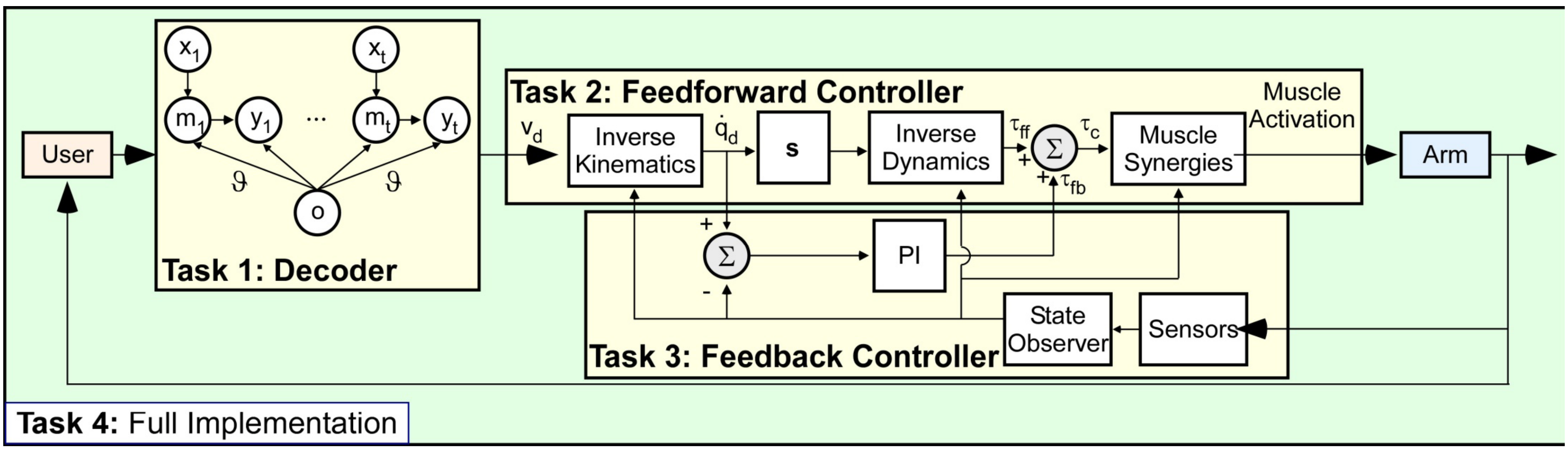
Research Overview

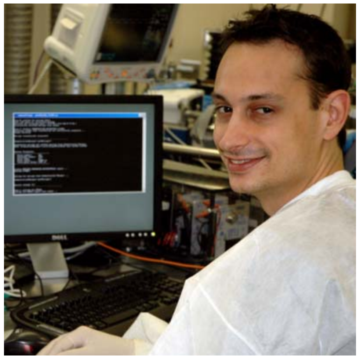


- Noisy measurements from many sensors
- Probabilistic outputs



- High model uncertainties
- Non-stationary
- Noisy sensors
- Robust control

Performance of brain-controlled FES during grasping



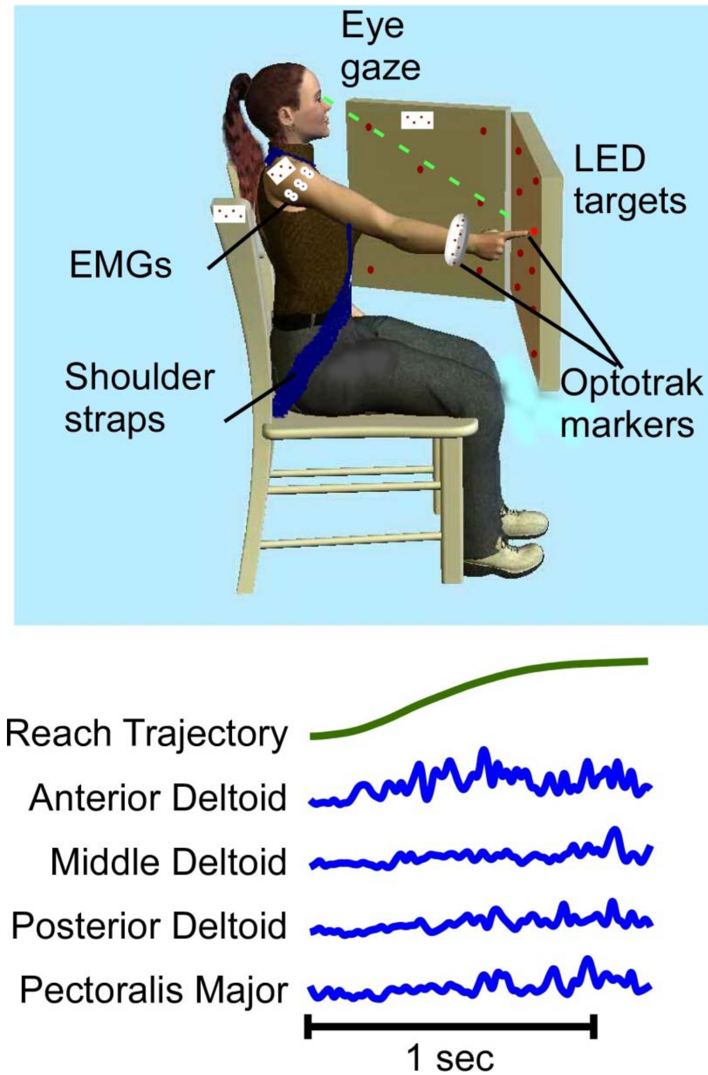
Christian Ethier,
Lee Miller

NIH R01 NS053603

Decoder Design Objectives

- "Natural" control
- Incorporate information from multiple sources
  - Continuous physiological signals
  - Discrete information related to probable targets
- Able to replicate characteristics of natural reaching
  - Arbitrary target locations
  - Arbitrary speeds

Experimental Setup

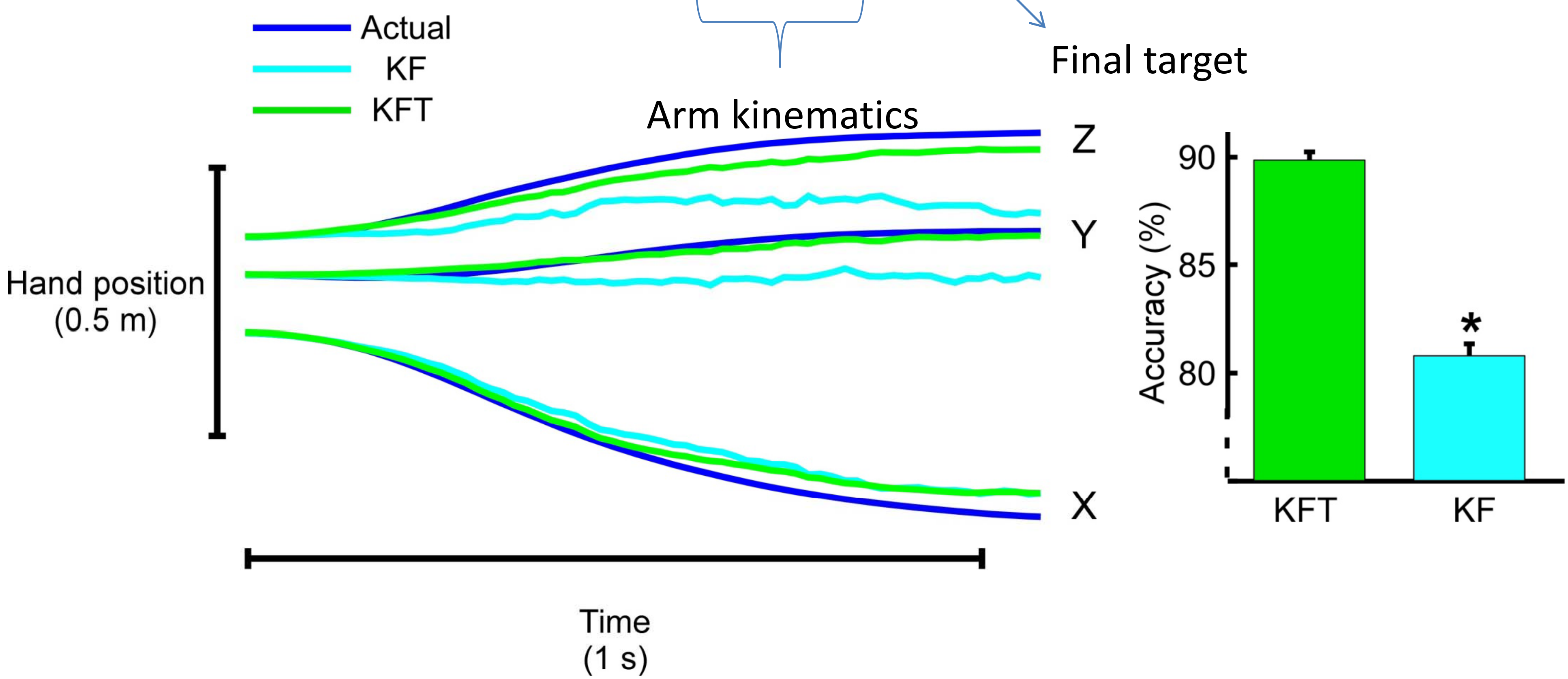


- Protocol
  - Slow, normal and fast reaches
  - 16 targets
  - ~450 trials per subject
- Outputs
  – Endpoint and joint kinematics
- Inputs
  – Electromyograms
  – Gaze direction

Kalman Filter with Target (KFT)

$$\mathrm{x}_t = \Big[\underbrace{x_t, \dot{x}_t, \ddot{x}_t}_{\text{Arm kinematics}}, xT\Big]$$

Final target



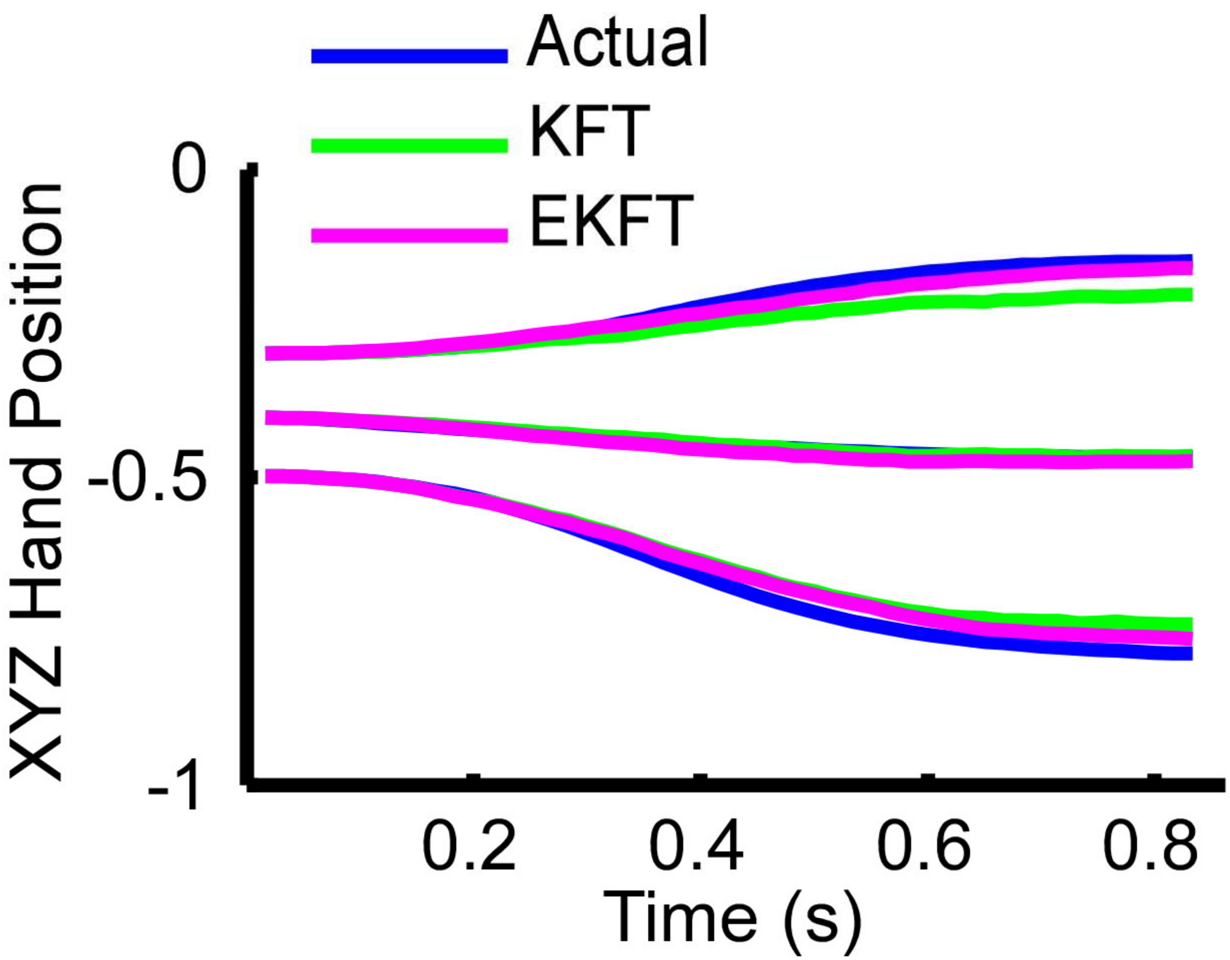
Mulliken, 2008

Time-warping

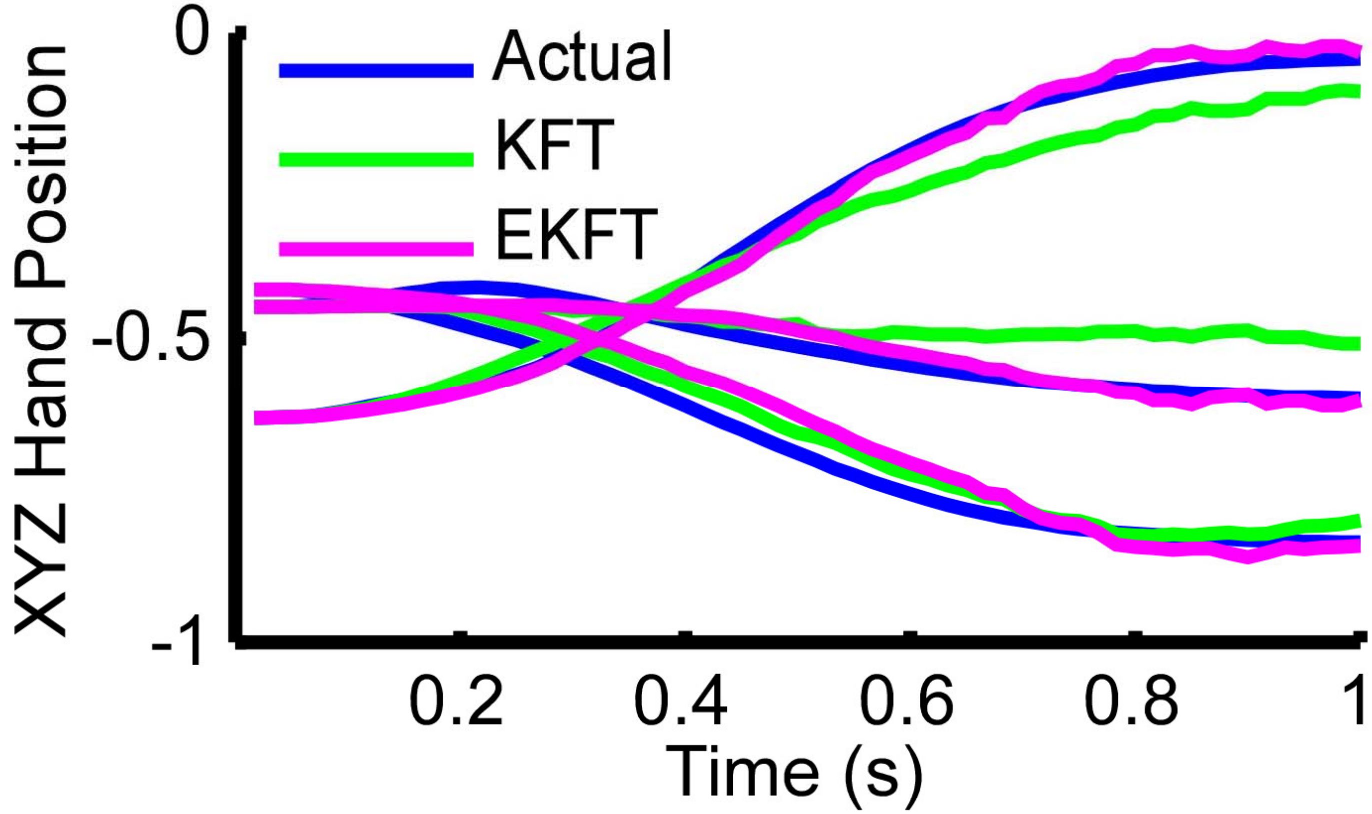
$$\mathbf{x}_\mathrm{t} = [\boldsymbol{x}_t\, \dot{\boldsymbol{x}}_t\, \ddot{\boldsymbol{x}}_t\;\; \boldsymbol{xT}_t\; xs_t]^\mathrm{T} = \; [\boldsymbol{x}_t\, \dot{\boldsymbol{x}}_t\, \ddot{\boldsymbol{x}}_t\;\; \boldsymbol{xT}_t\;\; \log(\mathrm{S_t})]^\mathrm{T}$$

$$\mathbf{x}_\mathrm{t} = \begin{pmatrix} \boldsymbol{x}_t \\ \dot{\boldsymbol{x}}_t \\ \ddot{\boldsymbol{x}}_t \\ \boldsymbol{xT}_t \\ xs_t \end{pmatrix} = \begin{pmatrix} I_p & \Delta t \times I_p & 0_{p\times p} & 0_{p\times p} & 0_{p\times 1} \\ 0_{p\times p} & I_p & \Delta t \times I_p & 0_{p\times p} & 0_{p\times 1} \\ S_{t-1}^2 \alpha_P & S_{t-1}\alpha_V & \alpha_A & S_{t-1}^2 \alpha_T & 0_{p\times 1} \\ 0_{g\times p} & 0_{g\times p} & 0_{g\times p} & I_g & 0_{g\times 1} \\ 0_{1\times p} & 0_{1\times p} & 0_{1\times p} & 0_{1\times p} & 1 \end{pmatrix} \begin{pmatrix} \boldsymbol{x}_{t-1} \\ \dot{\boldsymbol{x}}_{t-1} \\ \ddot{\boldsymbol{x}}_{t-1} \\ \boldsymbol{xT}_{t-1} \\ xs_{t-1} \end{pmatrix} + \boldsymbol{w}_t$$

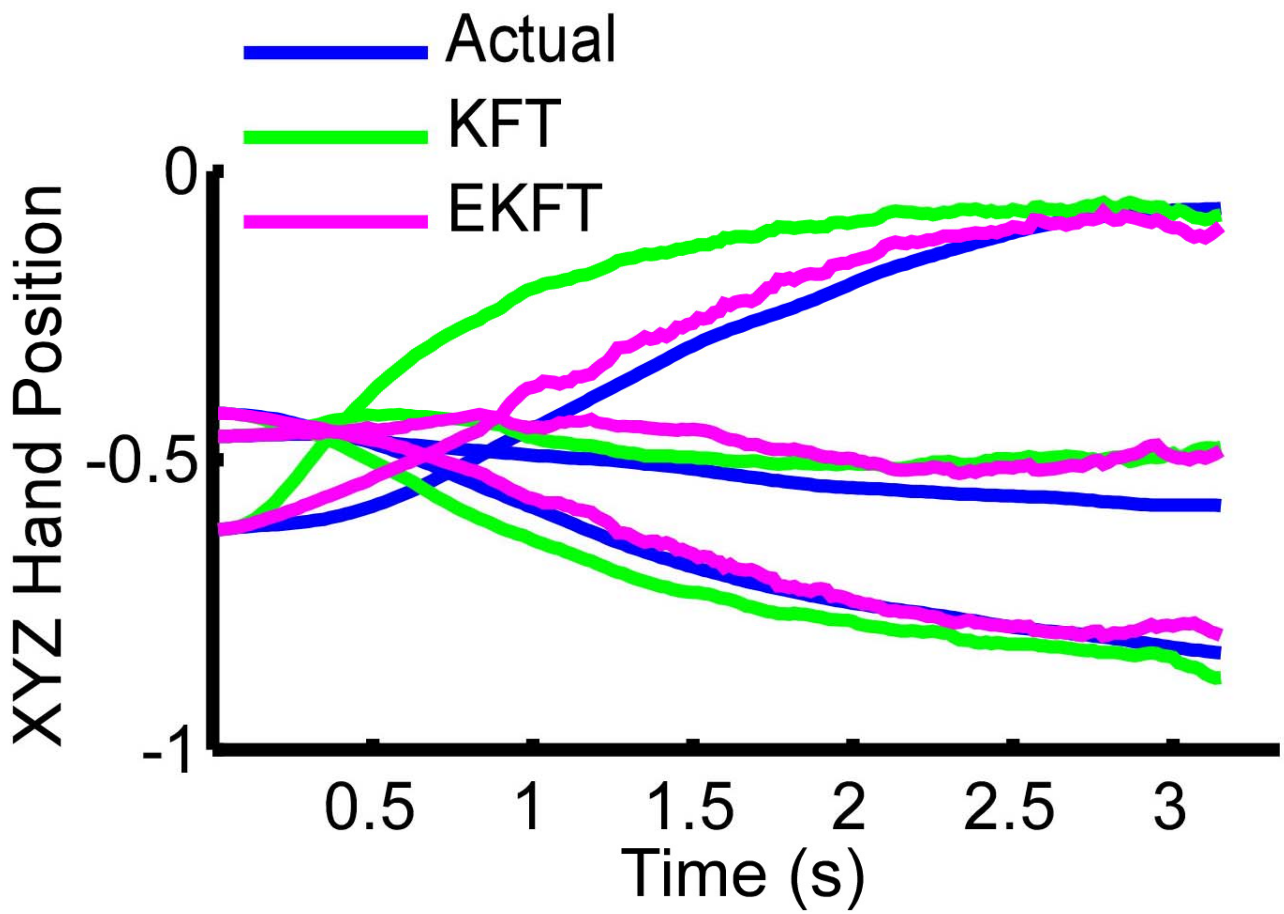
Sample predictions – normal reach



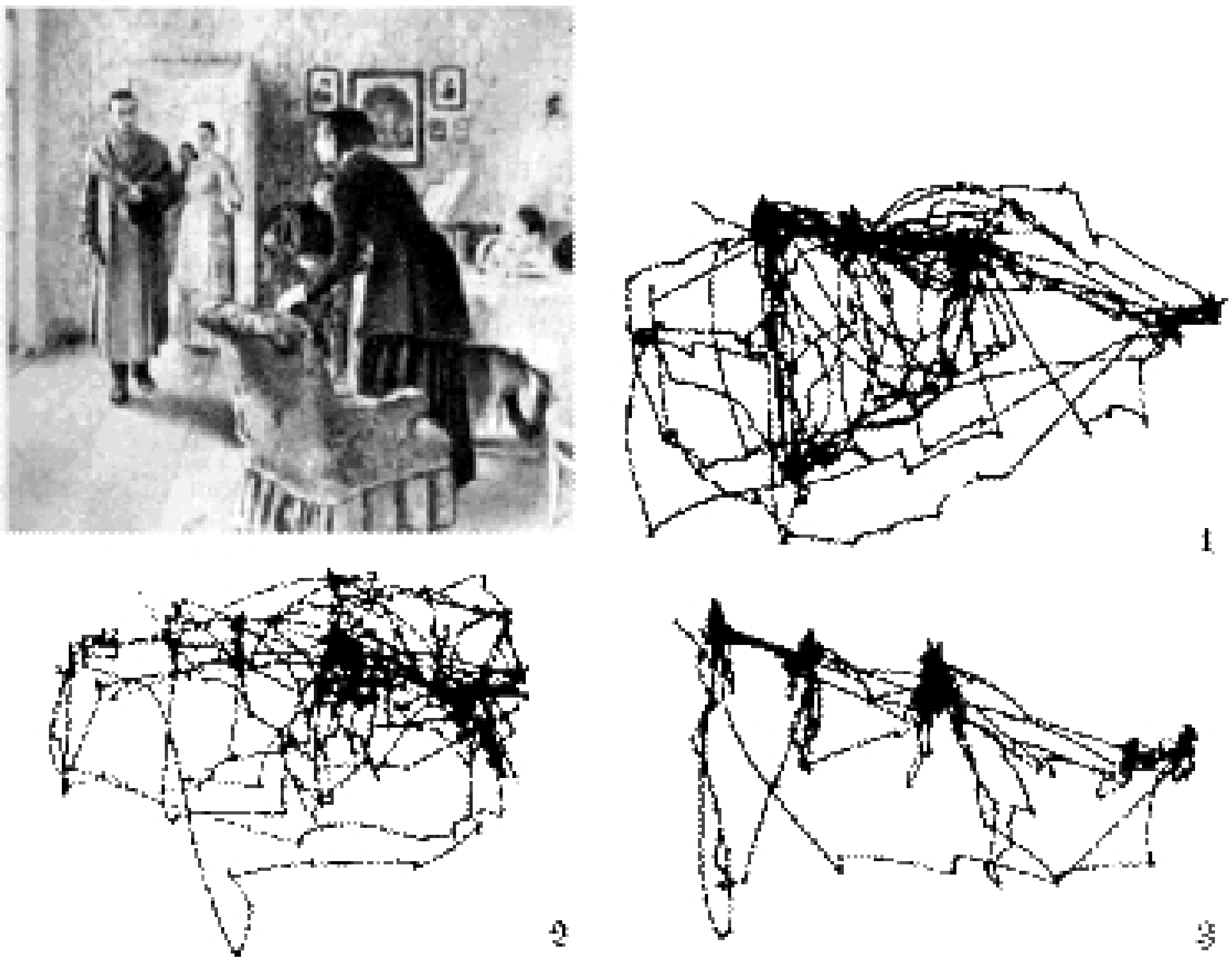
Sample predictions – fast reach



Sample predictions – slow reach



Probabilistic mixtures

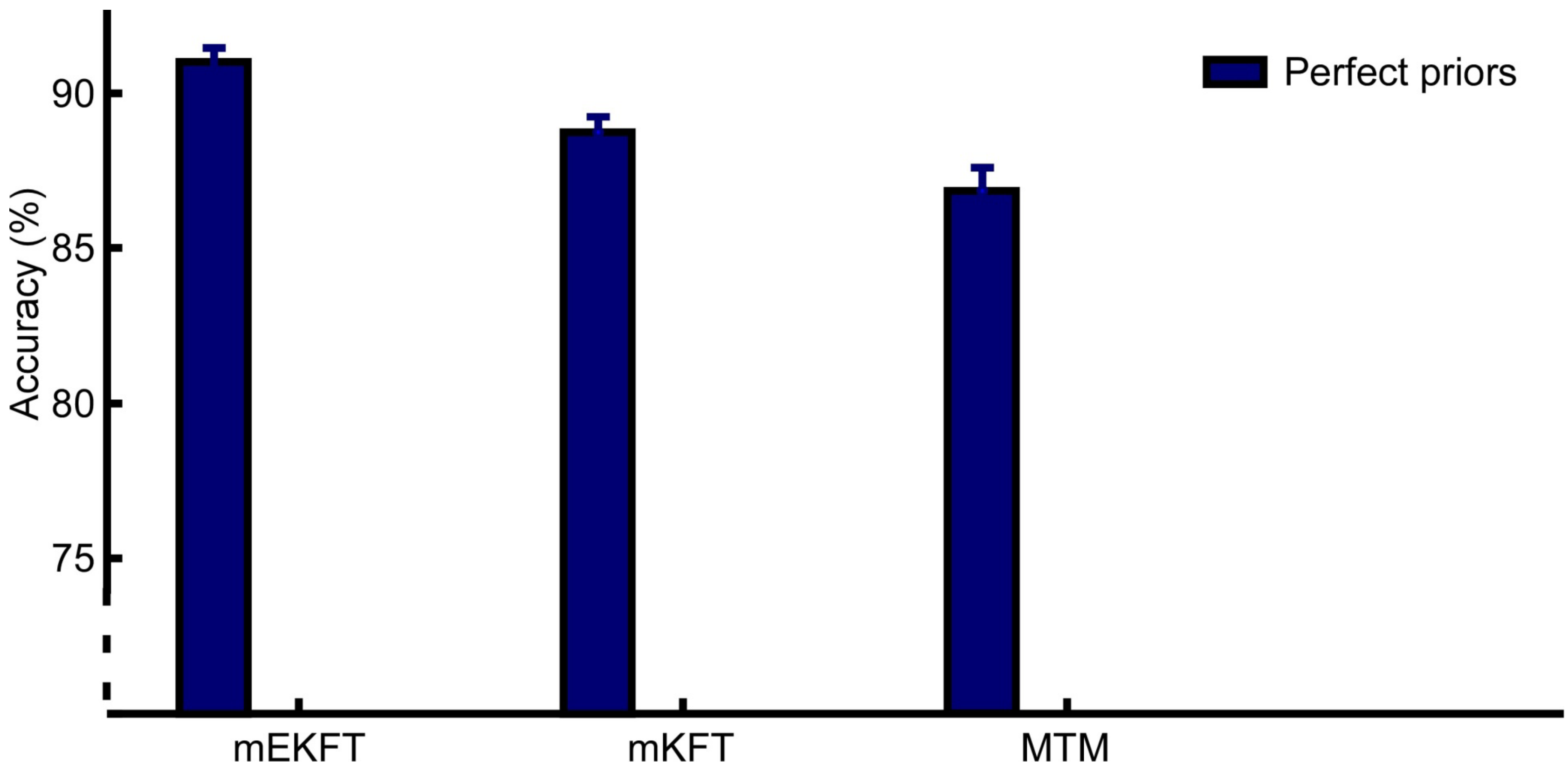


Yarbus, A. L. (1967)

Mixtures of targets and generalization

$$P(\mathbf{x}_t|\boldsymbol{y}_{1...t}) = \sum_{T=T1}^{TN} P(\mathbf{x}_t|\boldsymbol{y}_{1...t}, \boldsymbol{xT}_t)P(\boldsymbol{xT}_t|\boldsymbol{y}_{1...t})$$

Yu, 2007



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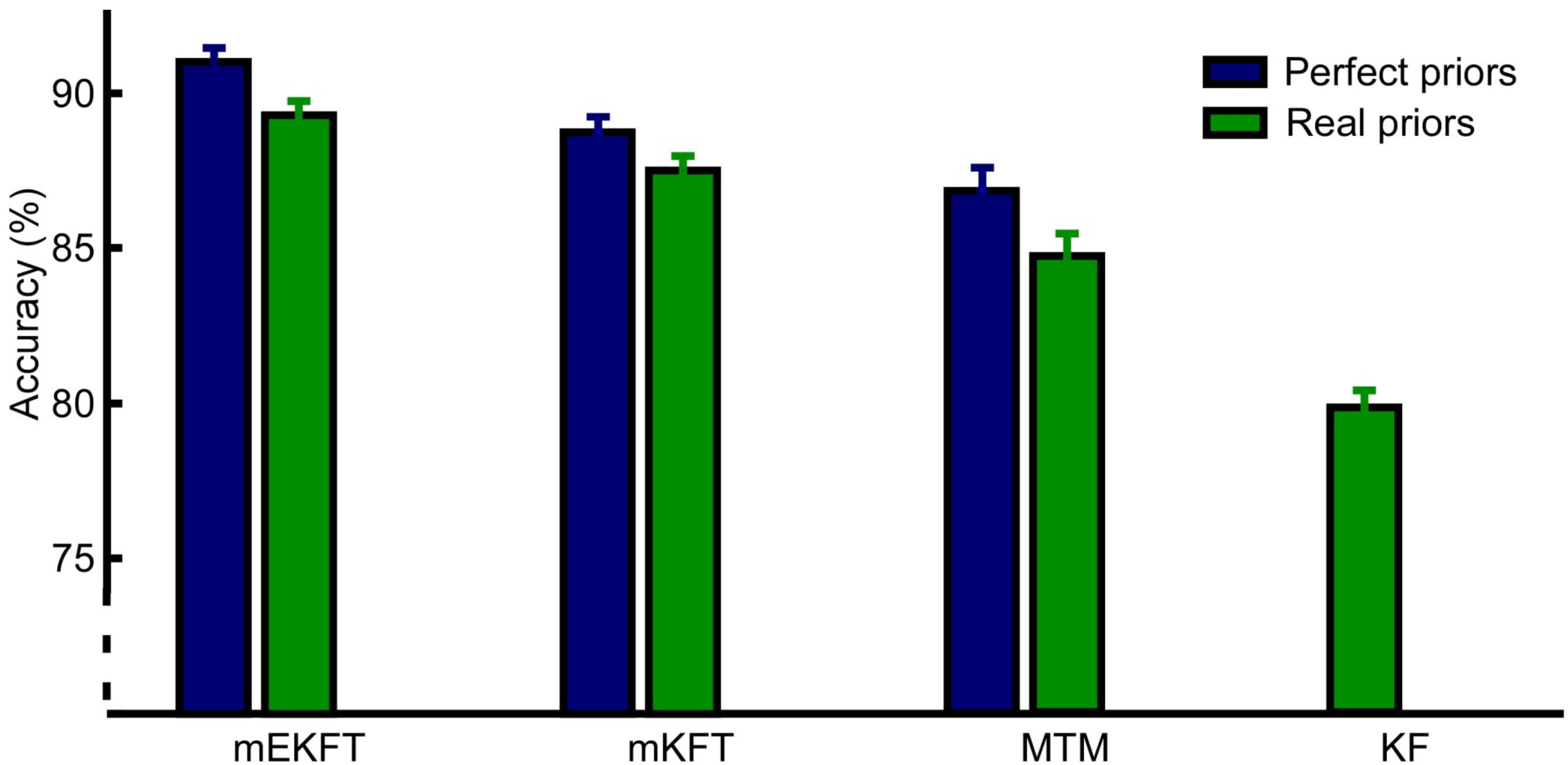

Mixtures of targets and generalization

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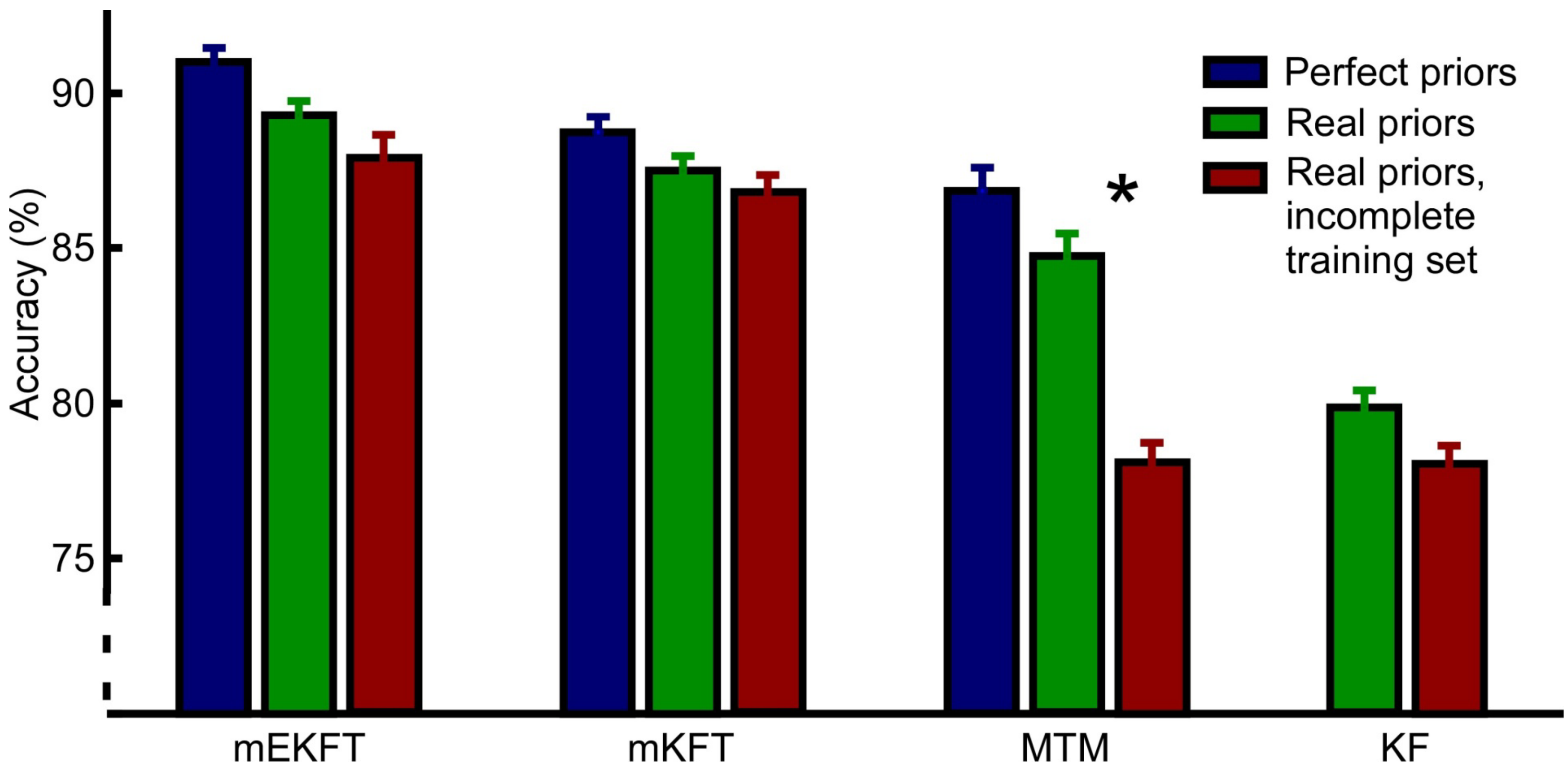

Summary

- CPS Challenges
  - Human in the loop
  - Data fusion
  - Robust control
- Development of a continuous user interface
  - Multiple continuous and discrete noisy sources
  - Arbitrary target locations
  - Arbitrary reach velocities
- Coming soon
  - Evaluation with direct intracortical recordings
  - Controller development

Broader Impacts

- Laboratory outreach program
- Middle school CPS curriculum

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Rehabilitation Institute *of* Chicago

Time-warping improved accuracy