Modeling Neural Control of Physically Realistic Movement

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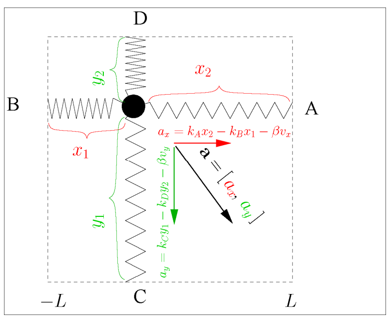
Introduction

- Objective: neural control of artificial motor systems.
- Previous work has focused on kinematic control. This does not take into account physical constraints and may result in unnatural movement artifacts such as jitter.
- Possible solution is to use full biomechanical model of the system, but it is expensive and difficult to control with limited neural bandwidth.
- Our proposal: a computationally simple model with only a few parameters that are directly controlled by the decoded neural signal.

The spring-based model



- Inspired by Hinton & Nair, 2005.
- Represent the hand as a **point mass** m located at the wrist.
- Four virtual **springs**: one end attached to the hand, the other end slides without friction.
- Control of the system is via dynamically **modifying the spring stiffness** coefficients k_A, k_B, k_C and k_D.
- **Viscosity** coefficient β controls damping.
- Impose stiffness constraints $k_A+k_B=k_C+k_D=\kappa$ to maintain non-negative coefficients.

*CAUTION: Investigational device. Limited by Federal (USA) law to investigational use – only being studied in USA.

Methods: Direct decoding of system dynamics

- The controlling signal: firing rates of C units recorded from motor cortex
  - Firing rates estimated in bins of fixed length.
- Let $\tilde{\mathbf{Z}}(t) = [\mathbf{Z}(t-l), \ldots \mathbf{Z}(t)]$ be the *history of firing rates* over l bins.
- We treat the movement decoding as a parametric regression problem:

$$\tilde{\mathbf{Z}}(t) \xrightarrow{f(\cdot;\theta)} \mathbf{K}(t) = [k_A(t), k_B(t), k_C(t), k_D(t)]$$

- **Training paradigm** for the model:
  - Observed data: firing rates $\tilde{\mathbf{Z}}_i(t)$ and hand positions $\mathbf{x}_i(t)$;
  - We estimate instantaneous velocities $\hat{\mathbf{v}}(t)$ and accelerations $\hat{\mathbf{a}}(t)$.
  - From accelerations, we recover the stiffness coefficients, e.g.:

$$\hat{k}_A = \frac{m\hat{a}_x(t) + \hat{v}_x(t) + \kappa(L + x(t))}{2L}$$

  - Given the coupled observed/estimated $\tilde{\mathbf{Z}}(t) \rightarrow k_A(t), k_C(t)$, fit the regression parameters for a chosen regression models.
  - The complementary coefficients (B,D) recovered from stiffness constraint.
  - **Linear regression model:** *linear filter (LF)*

$$k(t) = \mathbf{w}^T \tilde{\mathbf{Z}}(t)$$

where the weight vector $\mathbf{w}$ is learned from data.

  - **Nonlinear regression model:** *Support Vector Machine (SVM)*

$$k(t) = \sum_i \alpha_i h(\tilde{\mathbf{Z}}(t), \tilde{\mathbf{Z}}_i)$$

where h is a kernel function, and α_i are learned from training data.

- **Testing paradigm:**
- Observed firing rates $\tilde{\mathbf{Z}}(t) \xrightarrow{f} \hat{\mathbf{K}}(t) \longrightarrow \hat{\mathbf{a}}(t) \longrightarrow \hat{\mathbf{v}}(t) \longrightarrow \hat{\mathbf{x}}(t+1)$, with $\hat{\mathbf{x}}(t)$ feeding $\hat{\mathbf{a}}(t)$, $\hat{\mathbf{v}}(t-1)$ feeding $\hat{\mathbf{v}}(t)$, and $\hat{\mathbf{x}}(t)$ feeding $\hat{\mathbf{x}}(t+1)$

Methods: Data and Evaluation

All analysis performed on an **offline movement reconstruction** tasks.

- **Monkey data**: behaving animals, moving manipulandum to control cursor.
  - 96-electrode arrays implanted in MI hand/arm area (see Shoham et al., 2005)
  - CL: sequential tracking (piecewise linear movement, discrete target).
  - LA: continuous pursuit (smooth target movement).
- **Human data***: paralyzed subject, instructed to attempt movement
  - A single patient (brain stem stroke); see poster 256.10 for details.
  - Pursuit tracking task (follow cursor manipulated by technician); see 256.11.

Results

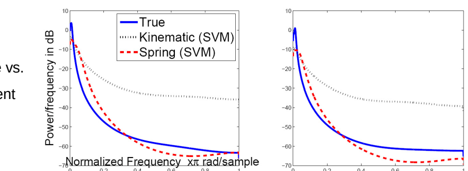
Monkey data; m=400, β=200

	Session	MAE SBM	MAE Kinem	MAE p	CC_x SBM	CC_x Kinem.	CC_y SBM	CC_y Kinem
Linear filter	CL (sequential)	0.29	**0.27**	<0.001	0.61	**0.64**	0.75	**0.79**
	LA (continuous)	0.09	0.09	>0.1	0.76	**0.79**	0.91	**0.92**
SVM	CL (sequential)	0.24	**0.23**	<0.001	0.78	**0.79**	0.84	0.86
	LA (continuous)	0.09	**0.08**	<0.001	0.80	**0.81**	0.92	**0.94**

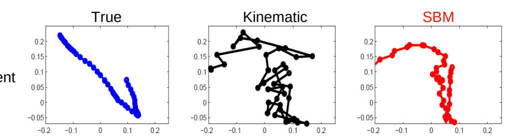
Human data; m=1000, β=250

	Session	MAE SBM	MAE Kinem	MAE p	CC_x SBM	CC_x Kinem.	CC_y SBM	CC_y Kinem
Linear filter	1	**0.33**	0.38	<0.001	**0.56**	0.47	**0.41**	0.32
	2	**0.41**	0.42	0.04	0.30	**0.32**	0.25	0.25
	3	0.57	**0.55**	>0.1	0.08	0.08	**0.21**	0.20
SVM	1	**0.28**	0.29	0.07	**0.66**	0.62	**0.50**	0.46
	2	0.30	0.30	>0.1	**0.58**	0.55	0.38	**0.39**
	3	**0.31**	0.32	<0.001	**0.33**	0.28	**0.45**	0.39

Power spectrum of true vs. reconstructed movement (Session 1)



Example movement paths (Session 3)



Conclusions

- Direct decoding of the parameters of artificial spring-based models allows for movement reconstruction on par with kinematic decoding.
- Introduction of realistic physical constraints yields smoother decoded movement.

References

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