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Modelling 3D saccade generation by feedforward optimal control

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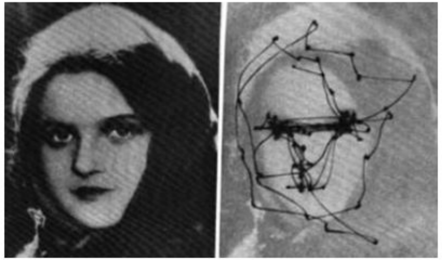
Outline

1. Motivation
2. Human Eye
3. Model
4. Optimal Control
5. Results

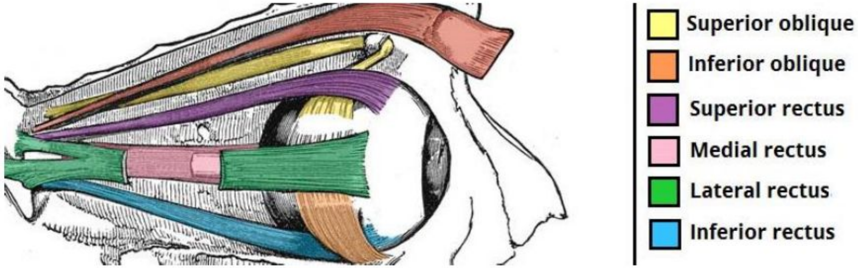
Motivation



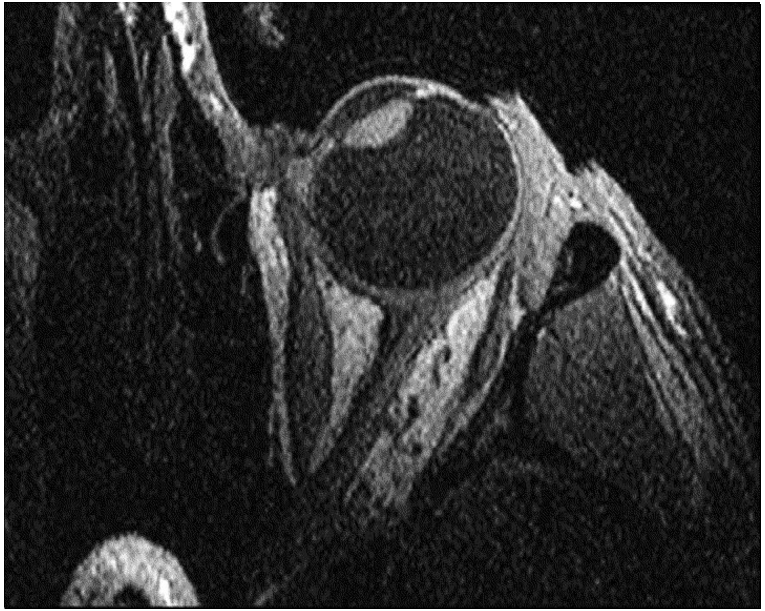
- Saccades (rapid eye movements)
- Extra degrees of freedom
- Existing neurophysiological models seldom work with 3D saccades and rarely consider both kinematic and dynamic properties.
- Trying to explain the kinematics and nonlinear dynamics using open loop optimal control of a simplified 3D biomimetic model.

Extraocular Muscles

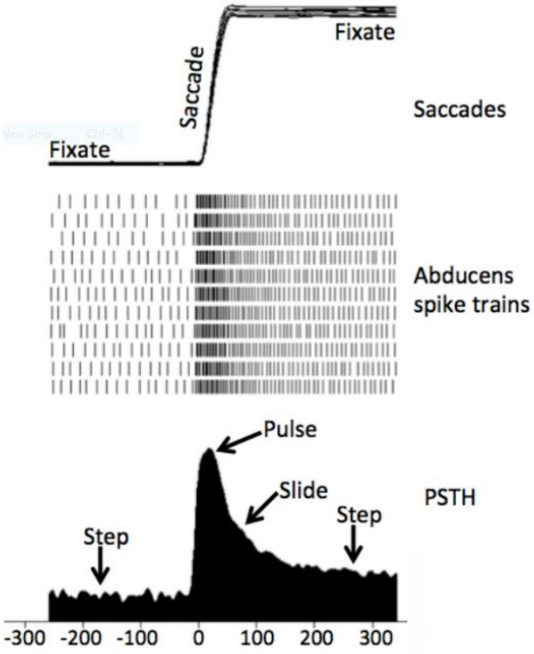
- 6 extraocular muscles (3 agonist-antagonist pairs).
- 5 of the muscles start at the annulus of Zinn. The inferior oblique muscle starts near the nose.
- The muscle actions are coupled.



Sectional View of an Eye Saccade



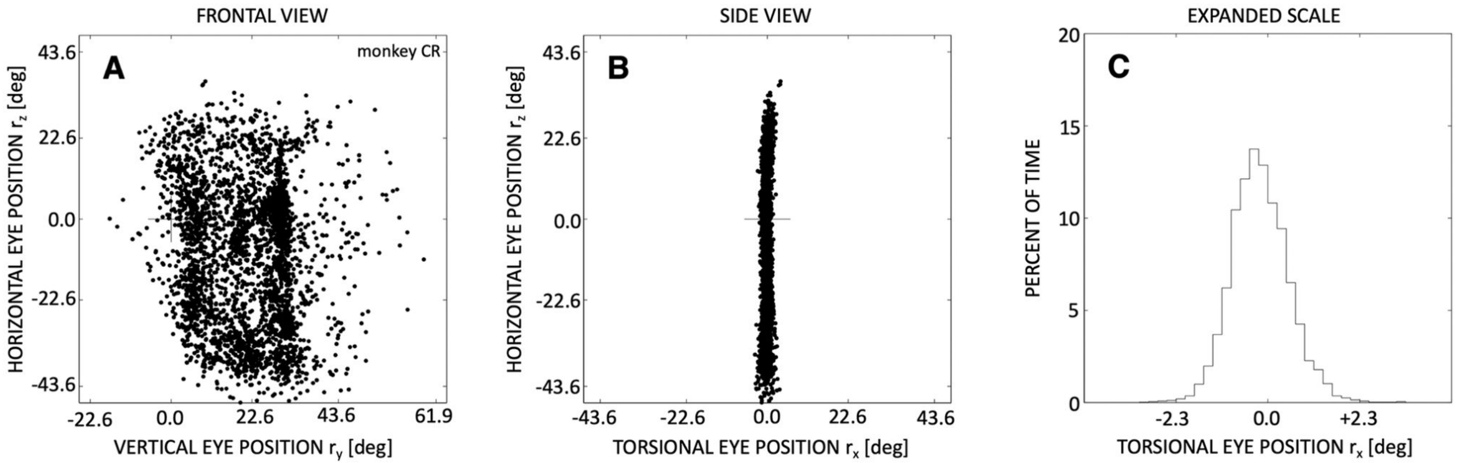
MRI scan of right eye for Saccade from -30 deg to +40 deg
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4981490/



Donders' and Listing's Law

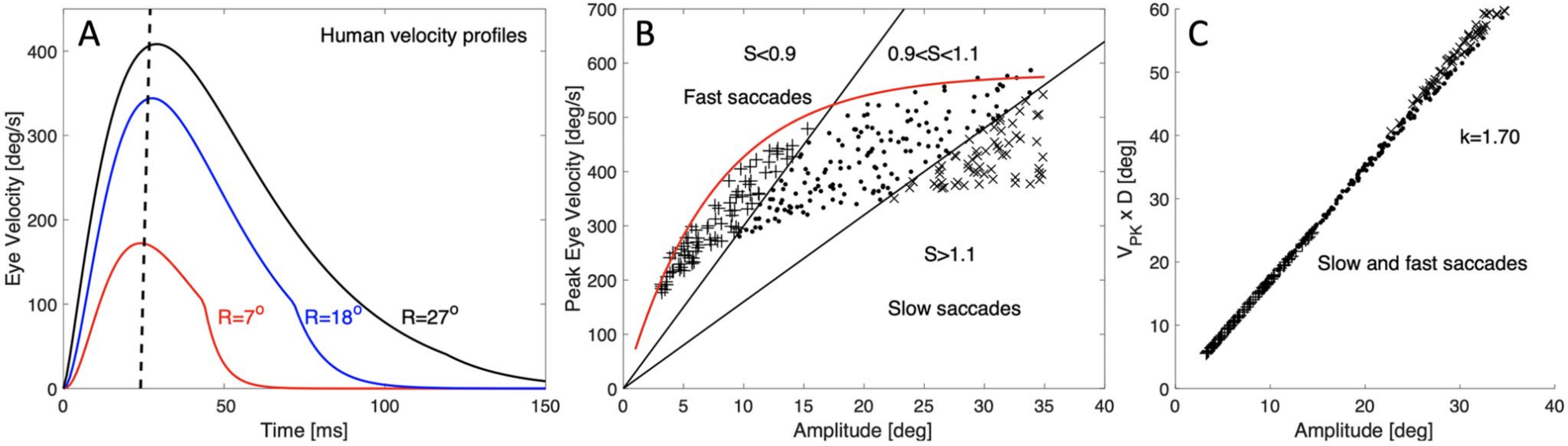
- Donders' Law: The eye's 3D orientation is uniquely determined by its 2D gaze direction and this orientation does not depend on the history of eye motions.

- When eye orientations are represented as single axis ($r = [r_x, r_y, r_z]$) rotations from a primary gaze direction it was observed that this axis lies in a plane of ~0.6 deg thickness.



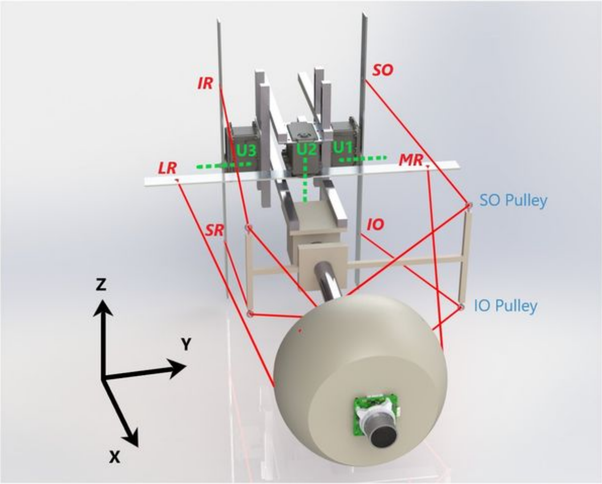
Nonlinear Dynamics

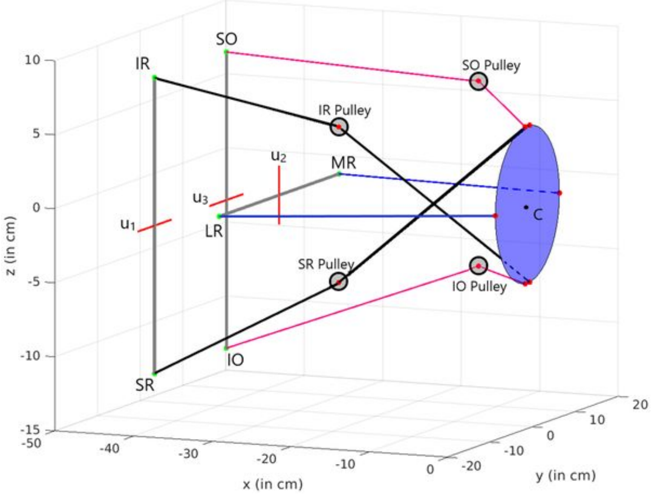
- Skewed velocity profiles
- Saturating peak velocities
- Main sequence



Model

- Only included their most essential features
- Mechanical model with 3 motors.
- Muscle pairs- elastic cables attached to each motor.
- Routing points for cables(pulleys).





Feedforward Optimal Control

- Linearized the system using Matlab system identification
- Feedforward optimal control with the motor rotations U as system input.

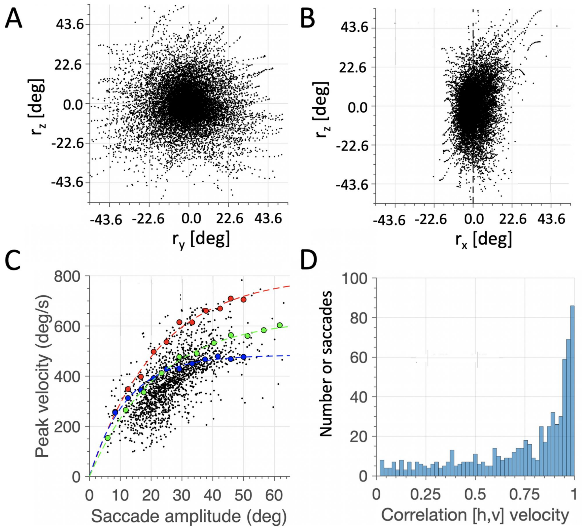
$$\text{minimize}_{\mathbf{U},D} \quad J_{TOT} = \sum_\alpha \lambda_\alpha J_\alpha(\mathbf{U}, D, \mathbf{R})$$

$$\text{subject to :} \quad \mathbf{x}_{t+1} = A\mathbf{x}_t + B\mathbf{u}_t$$

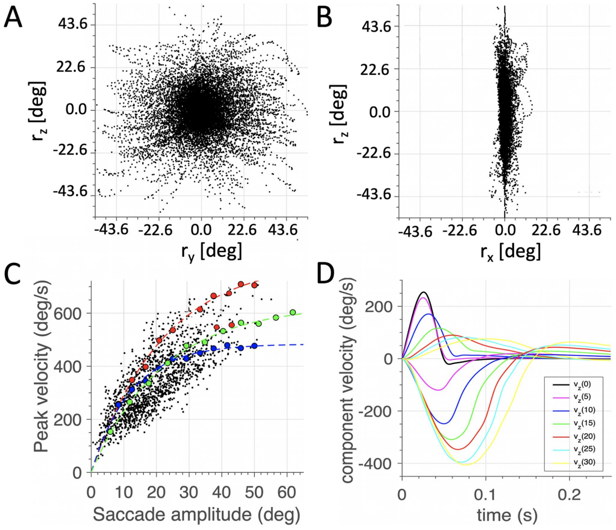
$$\mathbf{r}_t = C\mathbf{x}_t + E\mathbf{u}_t \qquad t = 0, \ldots, D$$

- The costs considered were a combination of:
  - Accuracy cost $J_A(r)$ = $\left(r_{y,D} - \hat{r}_y\right)^2 + \left(r_{z,D} - \hat{r}_z\right)^2$ & $[\dot{r}, \ddot{r}] = 0$
  - Energy cost $J_E(U)$ = $\|\Delta U\|^2$
  - Static force cost $J_F(r)$ = $r_p^T H_F r_p$
  - Duration cost, $J_D(p)$ = $\left(1 - \frac{1}{1+\beta p}\right)$
  - Listing plane cost $J_L(r_x)$ = $\|r_x\|^2$

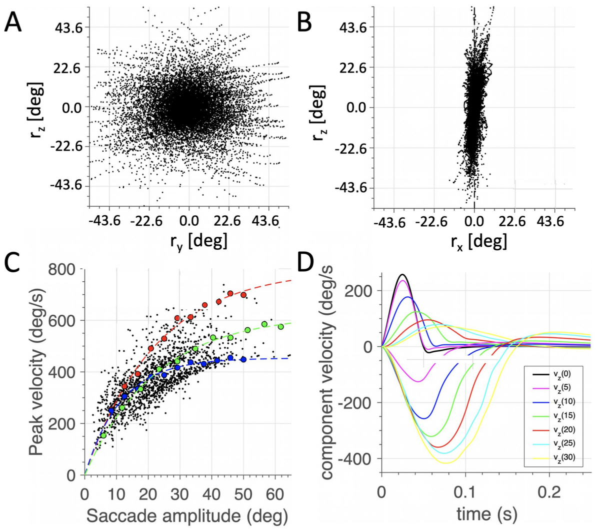
Feedforward Optimal Control



J_{AED}



J_{AEDL}



J_{AEDF}

Results

- Dropping either the penalty on saccade duration (J_D) or energy (J_E) disrupts the main-sequence and cross-coupling properties of the saccades.
- Because of the strong component cross-coupling, saccade trajectories were approximately straight in all directions.
- By including the minimization of static total force on the eye, Listing's law emerged without any additional assumptions regarding the eye's cyclo-torsional state.

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Thank You.
Questions or Suggestions?

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