Contrôle optimal de trajectoires locomotrices humaines

Quang-Cuong Pham

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Laboratoire de Physiologie de la Perception et de l'Action
Collège de France, Paris, France

Outline

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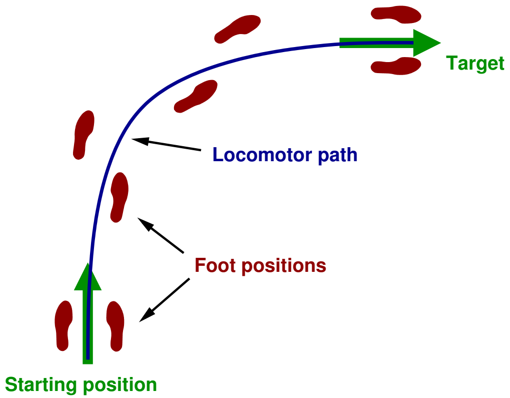
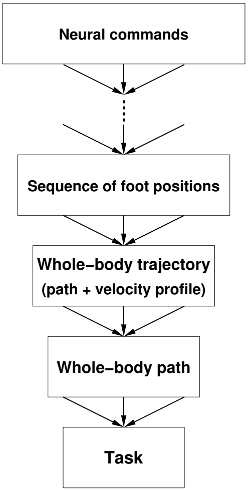
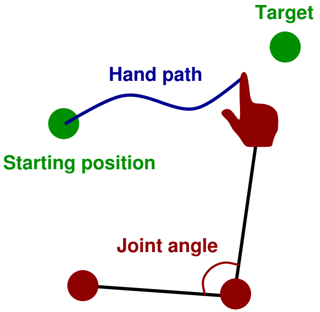
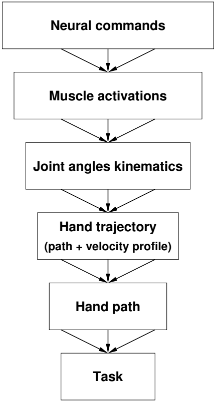
Redundancy in the control of locomotion





Redundancy in the control of arm movements

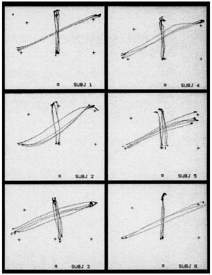




Jordan and Wolpert, in *The Cognitive Neuroscience*, 1999

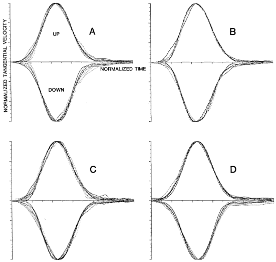
Spatial control of arm movements

Straight hand paths



Morasso, *Exp Brain Res*, 1981

Bell-shaped velocity profiles

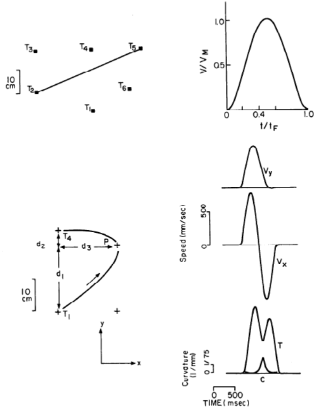


Atkeson and Hollerbach, *J Neurosci*, 1985

- Stereotypy observed only for hand trajectories in Cartesian coordinates
- Control in terms of Cartesian coordinates of the hand, not in terms of e.g. joint angles or muscle activity

Optimal control of arm movements

- Humans may select the hand trajectories that minimize a certain cost
- One popular model is the minimum jerk model developped by Flash and Hogan



$$\min_{x,y} \int_0^1 \left(\left(\frac{\mathrm{d}^3 x}{\mathrm{d}t^3} \right)^2 + \left(\frac{\mathrm{d}^3 y}{\mathrm{d}t^3} \right)^2 \right) \mathrm{d}t$$

Typical features:

- Straight, smooth, hand paths
- Bell-shaped velocity profiles
- Inverse relationship between velocity and curvature (via-points)

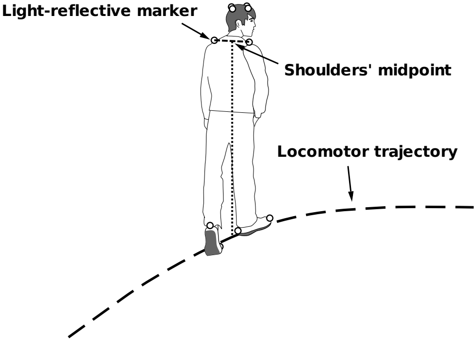
Questions

- Is human locomotion controlled at the level of whole-body trajectories?
- Are locomotor trajectories optimal? According to what criteria?
- What mechanisms underly the formation of locomotor trajectories?

Outline

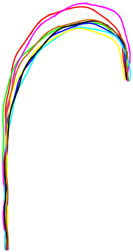
General experimental methods

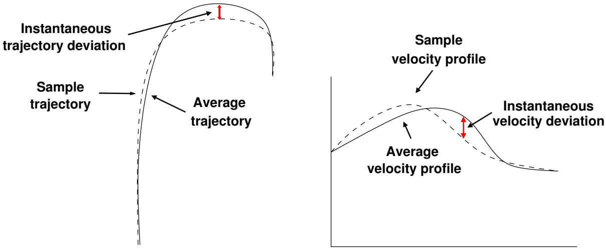
- Motion capture system: infrared cameras + light reflective markers
- Body position defined by shoulders' midpoint



Average trajectories and variabilities

- Time rescaling so that $t_0 = 0$ and $t_1 = 1$
- Definition of average trajectories and variabilities



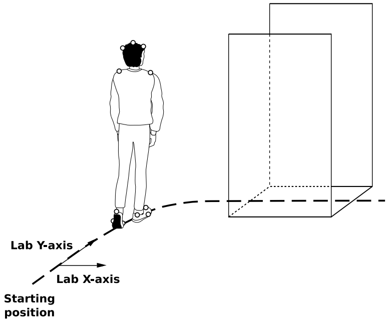


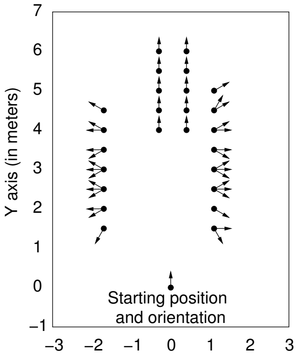
Experiment 1: stereotypy of locomotor trajectories

- Reminder: control of arm movements in terms of Cartesian coordinates of the hand
- What is planned and controlled in goal-oriented locomotion?
  - Step-level: plan and execute sequences of precise foot positions (FP), resulting in a whole-body trajectory
  - Trajectory-level: plan a whole-body trajectory (in Cartesian space) and implement it by appropriate sequences of foot positions
- Variability of the sequences of FP versus variability of whole-body trajectories

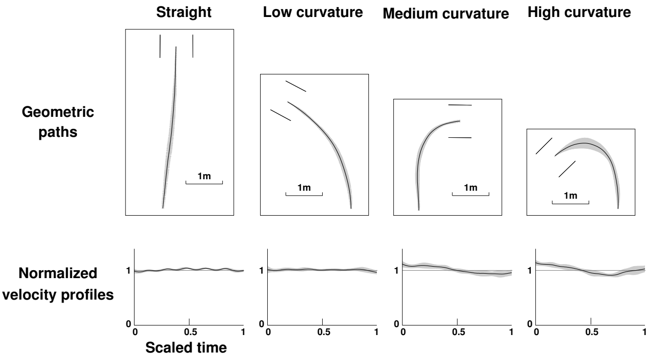
Experiment 1: methods

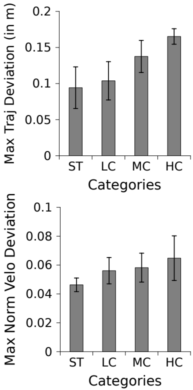
- Protocol: walking towards and through a distant doorway (Arechavaleta et al, 2006)
- Constraints on Initial and final positions and walking directions
- 40 targets (a target = position × orientation)
- 6 subjects × 40 targets × 3 repetitions = 720 trajectories





Experiment 1: results (trajectory stereotypy)

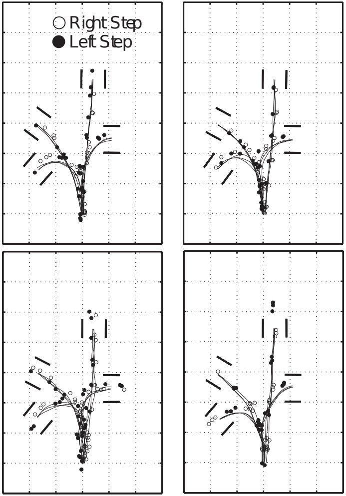


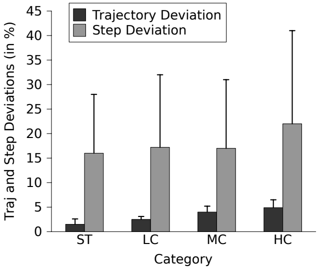


Hicheur, Pham et al, *Eur J Neurosci*, 2007

Even for HC, maximum variability was $\leq$ 17cm

Experiment 1: results (foot positions variability)





- variability of the sequences of FP ($\geq$20% of step length)
- variability of whole-body trajectories ($\leq$5% of trajectory length)

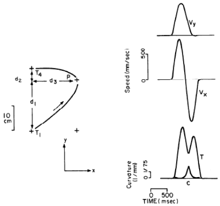
Experiment 1: conclusions

- Goal-oriented locomotion is not planned and controlled as a sequence of precise “foot pointings”
- Rather, it is likely planned and controlled at the level of whole-body trajectories
- This is reminiscent of the concept of spatial control of hand movements (Morasso, *Exp Brain Res*, 1981)

Outline

Context

- Reminder: minimum jerk model for hand trajectories



- Common features of hand and locomotor trajectories:
  - smoothness
  - straightness for locomotor "reaching"
  - inverse relationship between velocity and curvature
- Can the minimum jerk model also simulate locomotor trajectories?

Minimum Square Derivative models

- Minimize

$$\min_{x,y} \int_0^1 \left(\frac{d^n x}{dt^n}\right)^2 + \left(\frac{d^n t}{dt^n}\right)^2 dt$$

for $n = 1, 2, 3, 4$ (min velocity, min acceleration, min jerk, mini snap)

- subject to the constraints (initial and final conditions)

$$\begin{aligned} x(0) &= x_0, & x(1) &= x_1 \\ y(0) &= y_0, & y(1) &= y_1 \\ \dot{x}(0) &= v_0^x, & \dot{y}(0) &= v_0^y \\ \dot{x}(1) &= v_1^x, & \dot{y}(1) &= v_1^y \\ \ddot{x}(0) &= a_0^x, & \ddot{y}(0) &= a_0^y \\ \ddot{x}(1) &= a_1^x, & \ddot{y}(1) &= a_1^y \end{aligned}$$

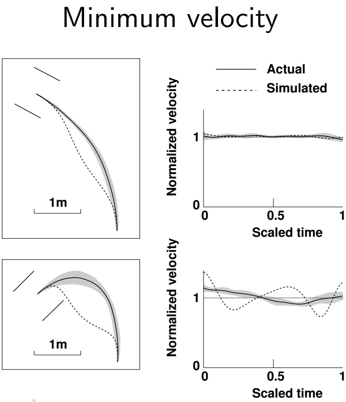
where the x_0, x_1, y_0, $v_0^x, \ldots$ are extracted from the experimental data

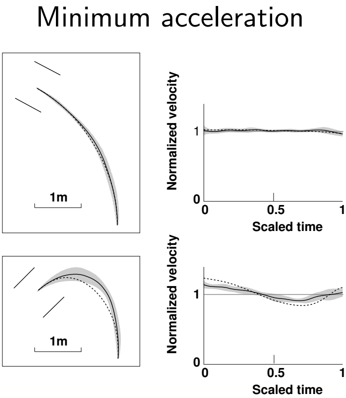
- For $n = 3$ (min jerk), the optimal trajectory is made of 5th-order polynomials

$$x(t) = c_5 x^5 + c_4 x^4 + c_3 x^3 + c_2 x^2 + c_1 x + c_0$$

$$y(t) = d_5 y^5 + d_4 y^4 + d_3 y^3 + d_2 y^2 + d_1 y + d_0$$

Results: minimum velocity and minimum acceleration



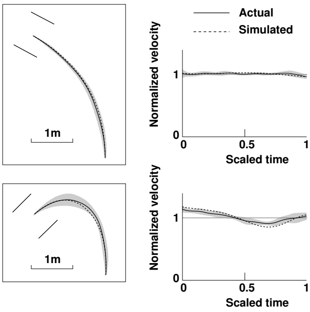


Pham et al, *Eur J Neurosci*, 2007

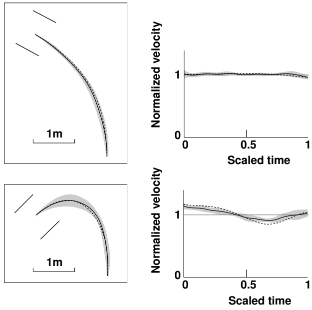
⇒ These models cannot simulate trajectories with large curvature

Results: minimum jerk and minimum snap

Minimum jerk



Minimum snap

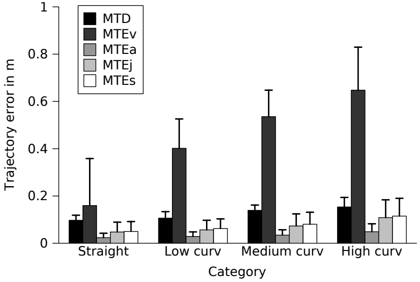


Pham et al, *Eur J Neurosci*, 2007

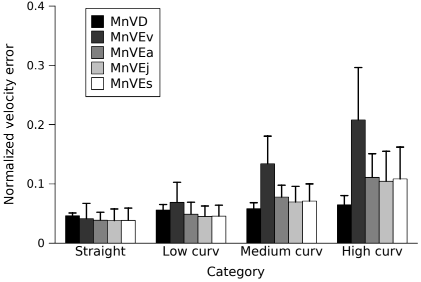
⇒ Good simulations for all categories: the simulated trajectory always lie within the variance ellipses

Results: quantitative comparisons

Max trajectory simulation error



Max velocity profile simulation error



Pham et al, *Eur J Neurosci*, 2007

- Simulation error ≤13cm for min jerk and min snap, that is ≤4% of trajectory length
- This is also smaller than the experimental variability (5%)

Conclusions

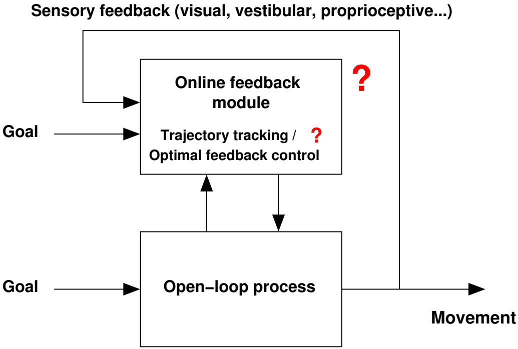
- The minimum jerk model (and also the minimum snap model) can accurately predict the average locomotor trajectories
- The formation of hand and locomotor trajectories thus may obey the same organizing principles
- This strengthens the "motor equivalence principle" hypothesis: "*at the higher levels of the motor system, there may exist kinematic representations of movements that are independent of the nature of the actual effector*" (Bernstein, *The co-ordination and regulation of movement*, 1967)

Outline

Main assumption

Two main issues (indicated by the question marks in the classical diagram)

- Existence of online feedback control in **visual** and **nonvisual** locomotion?
- Nature of the online feedback control?



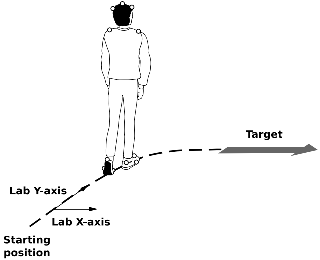
Outline

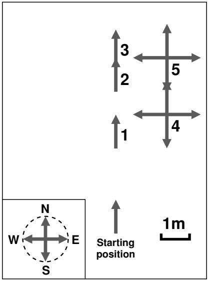
Problem statement

How vision affects the average trajectories?

Experiment 2: methods

- Protocol: same as in Exp 1 with the door replaced by an arrow
- 2 conditions: **Visual (V)** vs **Nonvisual(N)**
- 14 subjects × 2 conditions × 11 targets × 3 repetitions

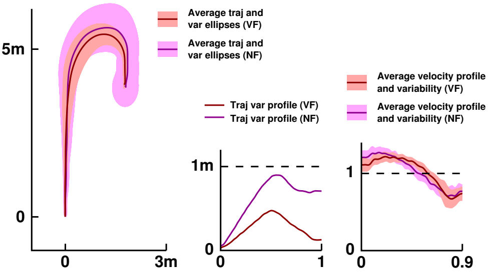


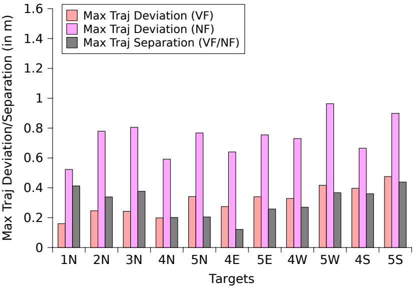


Experiment 2: results

Visual (V) vs **Nonvisual (N)**

- Small differences in average trajectories (Distance between the two trajectories $\leq$ **30cm** on average)
- Large differences in variability profiles (**31cm** for **V** vs **74cm** for **N**)





Pham and Hicheur, *J Neurophysiol*, 2009

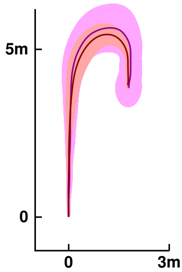
Experiment 2: conclusions

- Vision does not affect the average trajectories
  $\Rightarrow$ Same open-loop processes governing visual and nonvisual locomotion
- Vision affects the variability profiles
  $\Rightarrow$ Existence of vision-dependent feedback processes

Outline

Problem statement

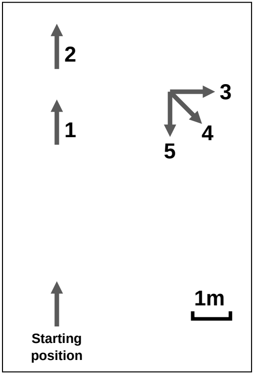
- Reminder: vision does not affect average trajectories



- How vision affects the variability profiles?
- Variability profiles in conditions **V** vs **N**

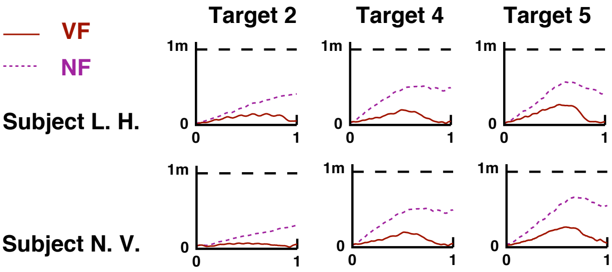
Experiment 3: methods

- Same protocol as in Exp 2
- 5 subjects × 2 conditions (**V**/**N**) × 5 targets × 8 repetitions
- Straight targets: 1, 2 ; Angled targets: 3, 4 , 5
- Intra-subject analysis



Experiment 3: results

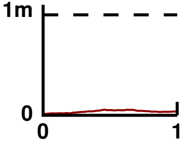
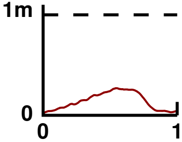
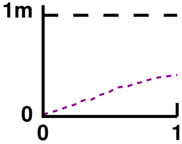
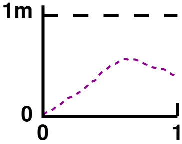
Variability profiles in conditions **V** and **N**



Pham and Hicheur, *J Neurophysiol*, 2009

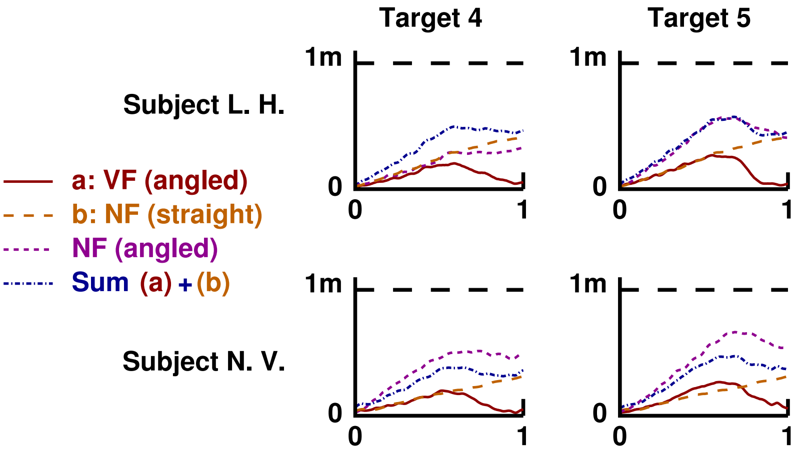
- Larger variability in N than in V
- V: zero variability in straight targets, bump-shape in angled targets
- N: linearly increasing in straight targets, non-monotonic in angled targets

Experiment 3: two-sources hypothesis

	Straight (targets 1 and 2)	Angled (targets 4 and 5)
V	0 + 0  	0 + **Bump** 
N	**Line** + 0  	**Line** + **Bump ??** 

- Bump: motor-complexity-dependent, vision-independent
- Line: motor-complexity-independent, vision-dependent

Experiment 3: two-sources hypothesis, verification



Pham and Hicheur, *J Neurophysiol*, 2009

Experiment 3: conclusions

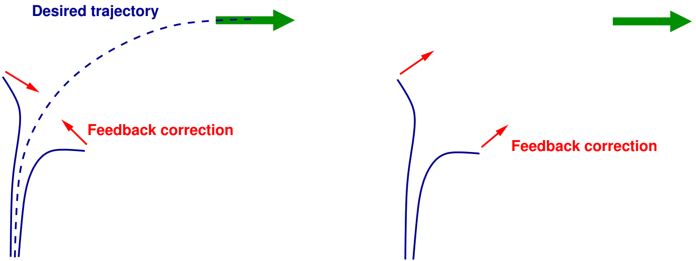
- Non-monotonic profiles ⇒ existence of online feedback control
- Two-sources hypothesis ⇒ the control mechanism in condition **N** can be decomposed into:
  - a vision-independent component (bump)
  - a vision-dependent component (line)
- Bump-shape profile: interplay between execution noise and feedback control

Outline

Problem statement

What is the nature of the online feedback?

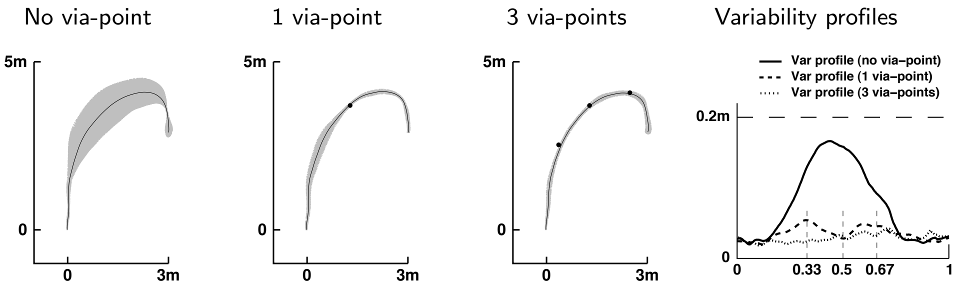
- "Desired-trajectory" tracking operates in two steps
  1. Compute an optimal trajectory according to some cost
  2. Track this trajectory (correct any perturbations back to the desired trajectory)
- Optimal feedback control: no intermediate representation, optimally correct perturbations with respect to the task



Experiment 5: methods

- First session: no via-point
- Second session: 1 via-point placed on the average trajectory
- Third session: 3 via-points placed on the average trajectory

Experiment 5: results



- The simple "desired-trajectory" tracking hypothesis can be rejected
- However, sequentially tracking multiple "desired-trajectories" remains possible
- Optimal feedback control can naturally explain the variability patterns observed

Outline

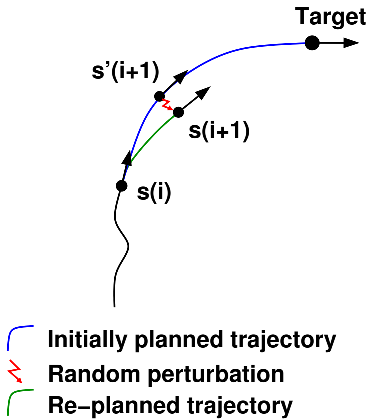
Context

- Deterministic models cannot explain variability profiles
- Here: stochastic models, more precisely some simplified optimal feedback control models (Hoff and Arbib, *J Mot Behav*, 1993; Todorov and Jordan, *Nat Neurosci*, 2002)
- Clarify the relationship between the control mechanisms in visual and nonvisual locomotion

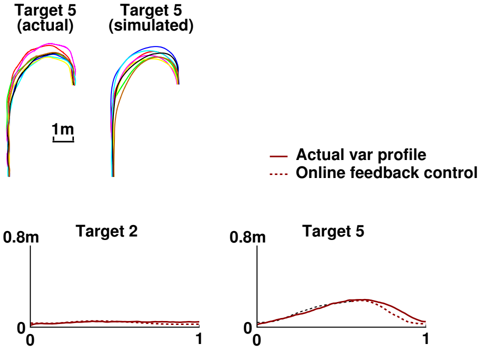
Visual condition: description of the model

Basic idea of optimal feedback control:
"goal-directed corrections"

1. Discretize the movement into n steps
2. At step i, compute first a minimimum jerk trajectory
3. Add some "signal-dependent" random perturbations to the provisional state $s'(i+1)$
4. Smoothly interpolate a new trajectory between the previous state $s(i)$ and the new perturbed state $s(i+1)$



Visual condition: results



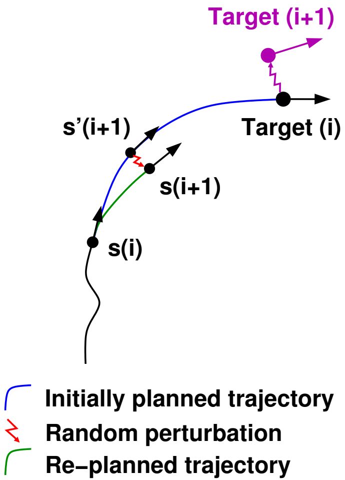
Pham and Hicheur, *J Neurophysiol*, 2009

⇒ This model can simulate both the trajectories and the variability profiles:

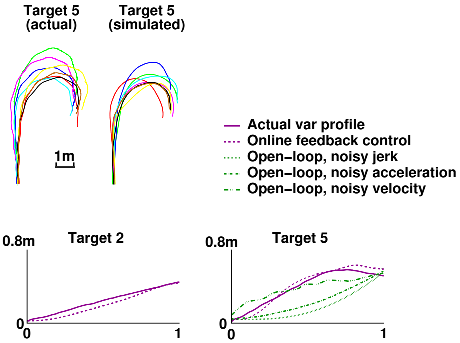
- almost zero in "straight" targets
- bump-shaped in "angled" targets

Nonvisual condition: online feedback model

- "Two-sources" hypothesis
- The first component can be simulated by the same algorithm as in condition **VI**
- The second component is related to state estimation and can be rendered by perturbing the target (can be discussed later)



Nonvisual condition: results



Pham and Hicheur,
J Neurophysiol, 2009

⇒ This model can simulate the variability profiles:

- linearly increasing in "straight" targets
- non-monotonic in "angled" targets

Open-loop models cannot reproduce the non-monotonic behavior

Stochastic models: conclusions

- Existence of online feedback control in **nonvisual locomotion** confirmed
- Two-sources hypothesis confirmed
- In particular: visual and nonvisual locomotion not only share the same open-loop processes but also the same feedback processes
- In nonvisual locomotion, same control mechanisms as in visual, but with respect to a corrupted target position

Outline

Summary of the results

- Locomotor trajectories are stereotyped. Goal-oriented locomotion is likely planned and controlled at the level of whole-body trajectories in space
- Locomotor trajectories are planned and controlled at a high cognitive level and, to some extent, independently of the sensory and motor conditions of locomotion
- Similar principles seem to underlie the formation of locomotor and hand trajectories
- A combination of optimal open-loop and feedback processes governs the formation of locomotor trajectories. The open-loop process is likely based on minimum jerk principle, the feedback process on optimal feedback control

Relations with humanoid robotics?

- Les principes de contrôle des trajectoires locomotrices humaines (contrôle au niveau de la trajectoire, minimum-jerk, optimal feedback) peuvent-ils s'appliquer pour les robots humanoides?
- Quel serait l'intérêt?
  - Robots plus efficients?
  - Robots plus socialement acceptable?