Open-loop and feedback processes in the formation of trajectories during visual and nonvisual locomotion in humans

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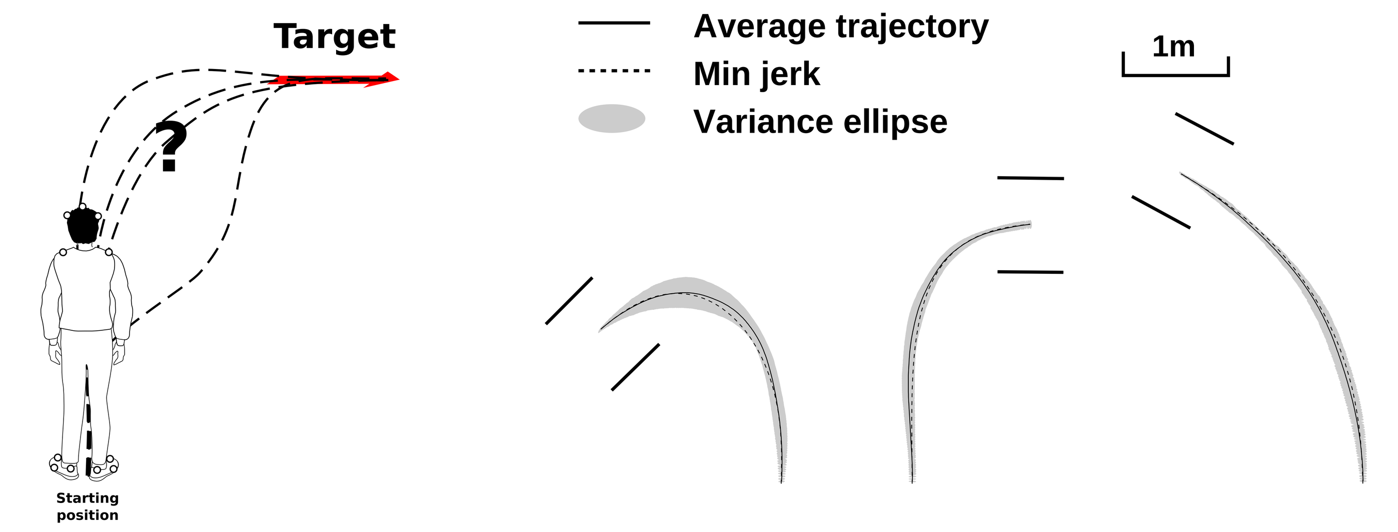
Introduction

We study locomotor trajectories in space
Previously, we showed [Hicheur et al. 2007, Pham et al. 2007]

- these trajectories are stereotyped (in contrast with feet placements)
- these trajectories are well reproduced by a minimum jerk model (as in hand movements [Flash & Hogan 1985])



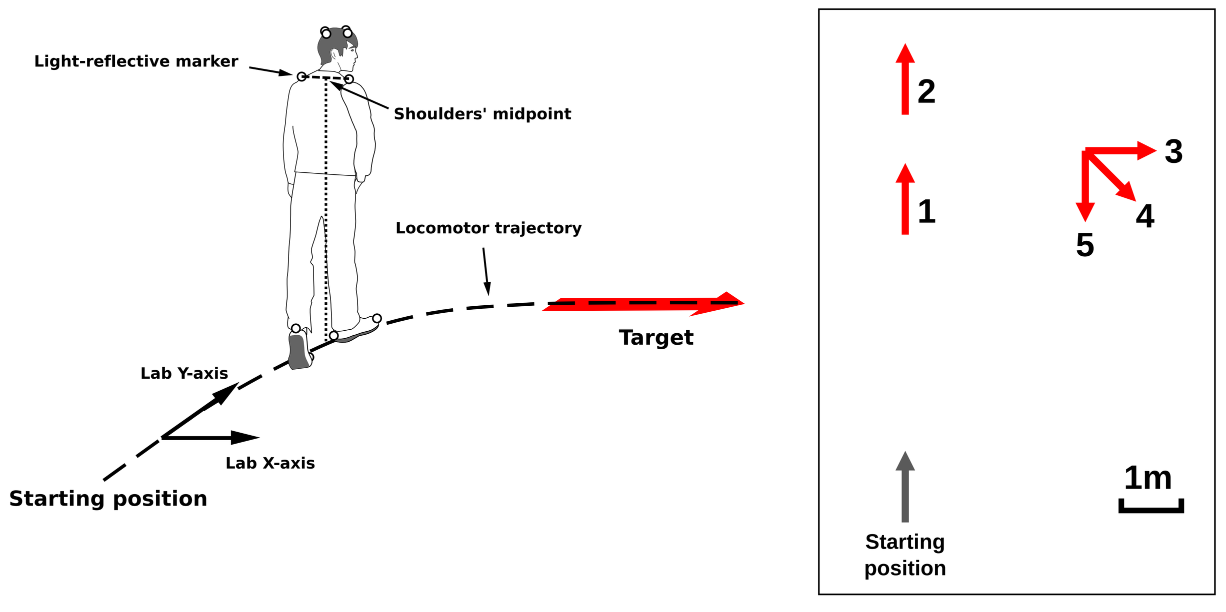
Question: what control mechanisms underly the formation of whole-body trajectories, in visual and nonvisual locomotion?

Focus of the present work: analysis of variability profiles and design of an optimal feedback control model

Experiment

A) Methods

- Subjects had to walk from a given position and orientation towards and above 5 distant targets
- Two conditions:
  - with vision (visual: VI)
  - or without vision (nonvisual: NV)
- Motion capture (with Vicon®infra-red cameras)

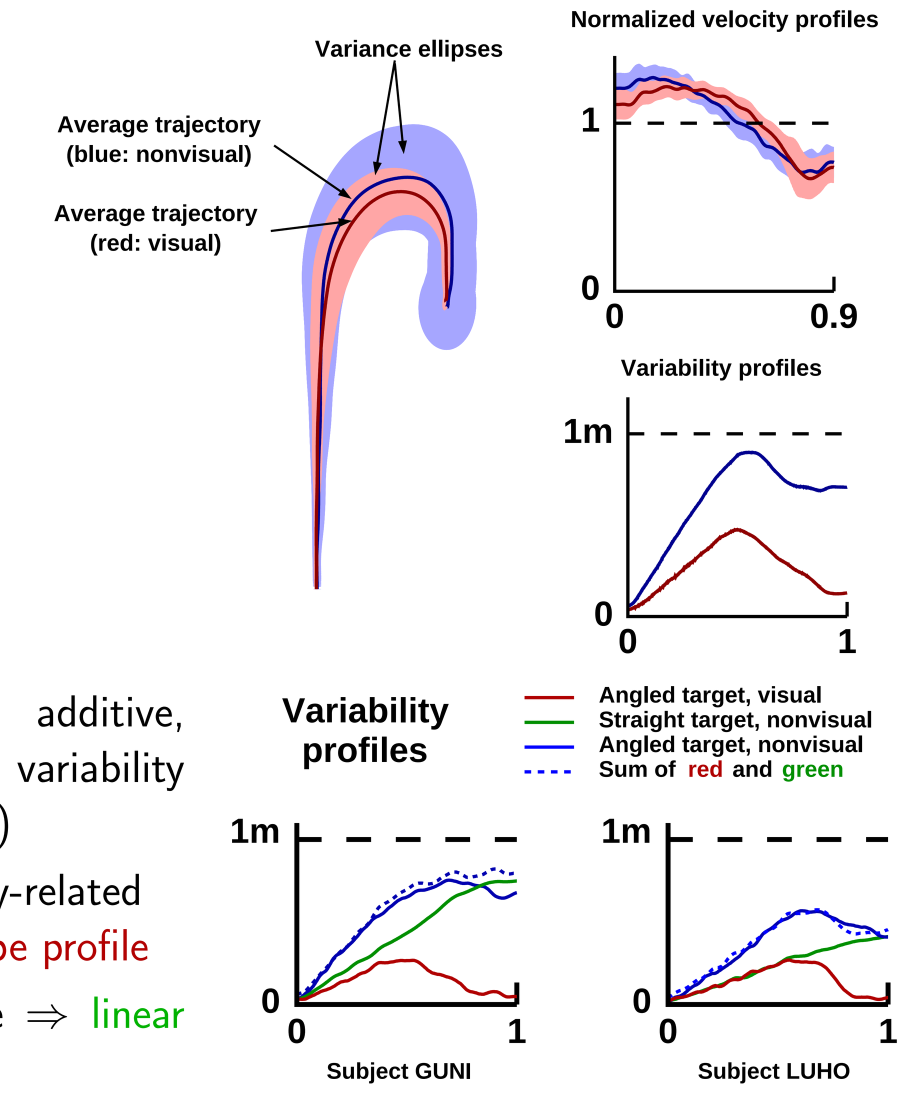


B) Results

- Similar average trajectories and velocity profiles in the VI and NV conditions
- VI: Bump-shape variability profile
- NV: Non-monotonic variability profile

Two independent, additive, sources of trajectory variability (two-source hypothesis)

- Trajectory-complexity-related source ⇒ bump-shape profile
- Vision-related source ⇒ linear profile



Models

A) Modified minimum jerk model

Find the trajectory $(x(t), y(t))_{t\in[0,1]}$ that minimizes

$$\int_0^1 \dddot{x}^2 + \dddot{y}^2 + \gamma \left(\frac{d}{dt} \left(\sqrt{\dot{x}^2 + \dot{y}^2} \right) \right)^2 dt$$

subject to the constraints

$$x(0) = x_0,\ \dot{x}(0) = v_0^x,\ \ddot{x}(0) = a_0^x,\ x(1) = x_1,\ \dot{x}(1) = v_1^x,\ \ddot{x}(1) = a_1^x$$

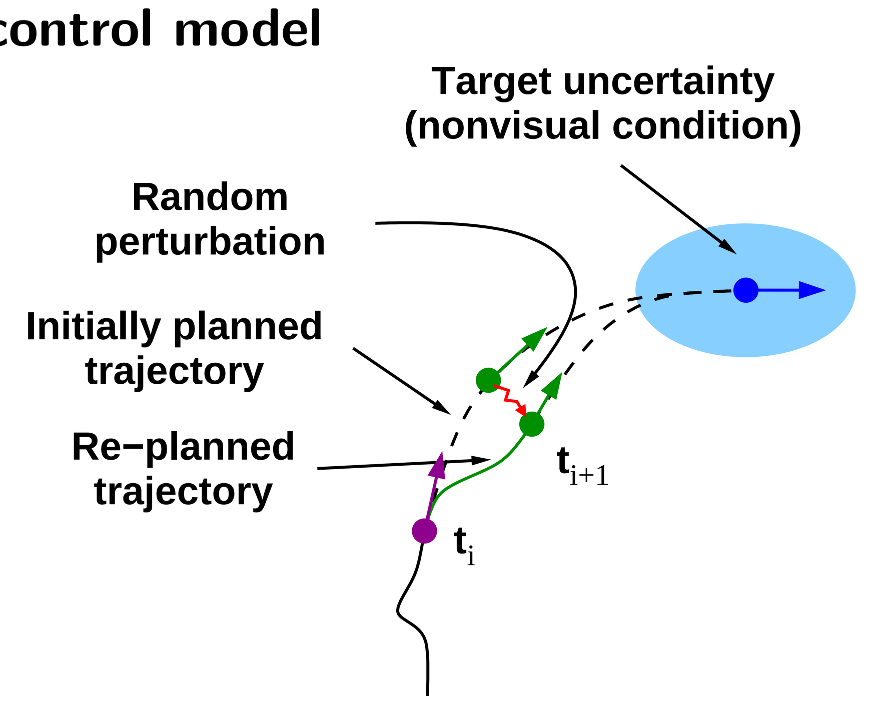
$$y(0) = y_0,\ \dot{y}(0) = v_0^y,\ \ddot{y}(0) = a_0^y,\ y(1) = y_1,\ \dot{y}(1) = v_1^y,\ \ddot{y}(1) = a_1^y$$

where the $x_0, v_0^x, \ldots$ were set to the average experimental values.

Approximated solutions in the subspace of polynomials of degrees ≤ 7.

B) Optimal feedback control model

- stochastic version of the previous modified minimum jerk (MMJ) model
- based on a simplified optimal feedback control scheme [Hoff & Arbib 1993, Todorov & Jordan 2002]



Algorithm 1 1. Discretize the movement into n steps ($10 \leq n \leq 20$ depending on the target)

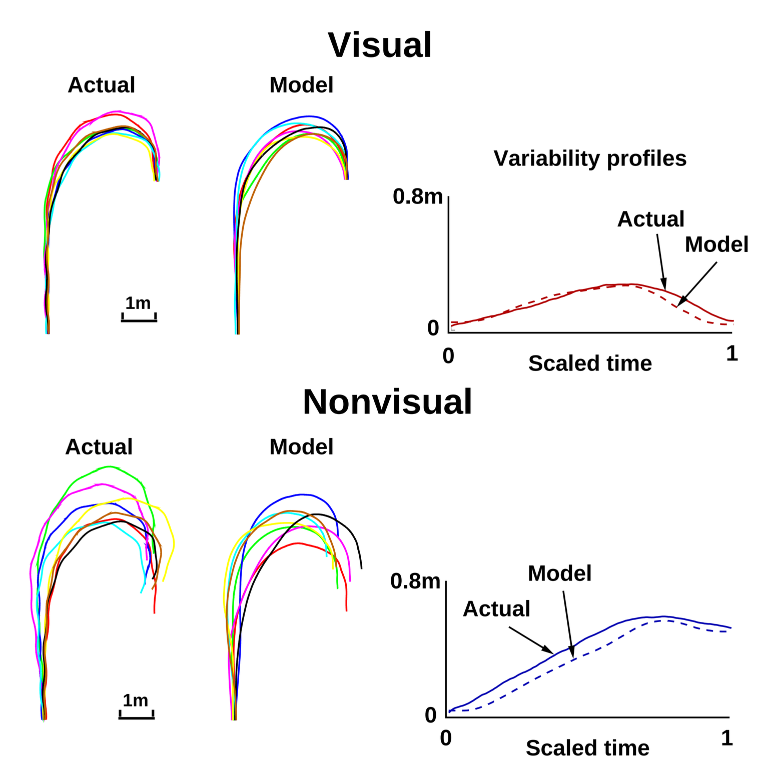
2. At each step i, compute first a MMJ trajectory between the current state $s(i)$ (position, velocity, acceleration at time i) and the final state. This is the "initially planned trajectory"
3. Add a random perturbation to $s'(i+1)$, the state of the "initially planned trajectory" at step $i+1$. This yields the actual state $s(i+1)$. To simulate the "signal dependent noise" effect, the magnitude of the pertubation was set to be an increasing function of the absolute value of the curvature
4. Compute the MMJ between $s(i)$ and $s(i+1)$. This yields the actual trajectory between i and $i+1$
5. Repeat from step 2

Two-source hypothesis ⇒ Add some uncertainty in the position of the target in the NV condition

C) Results

Good reproduction of the typical features of actual trajectories
In particular:

- VI: bump-shaped variability profile
- NV: variability first increases linearly, then decreases near the end



Conclusion

- Similar average trajectories in VI and NV locomotion ⇒ a common open-loop process
- Bump-shape variability profiles in the VI condition ⇒ interplay between execution noise and goal-directed feedback corrections
- Non-monotonic variability profiles in the NV condition. Interpreted as the sum of
  - a bump-shaped profile (caused by the interplay between execution noise and corrections)
  - a linear profile (caused by absence of vision)

  ⇒ goal-directed feedback corrections may also be present in NV locomotion, but the corrections are made towards a uncertain target position
- Modeling results ⇒ optimal feedback control may govern the formation of hand trajectories [Todorov & Jordan 2002] *and* locomotor trajectories

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