Planning and control of human locomotion
An optimal feedback control model

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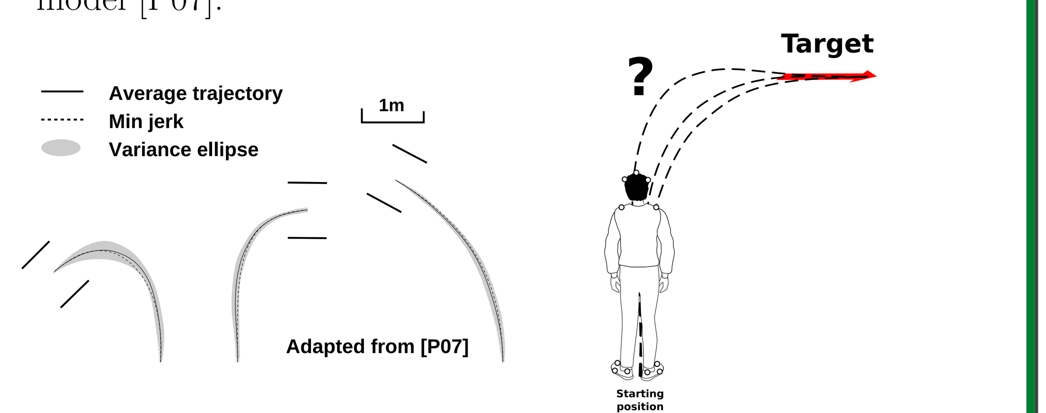
Introduction

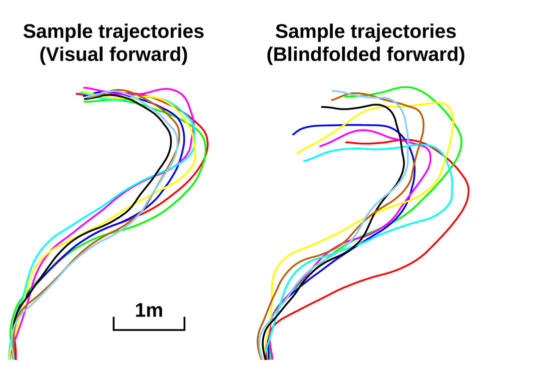
We investigate human locomotion through the study of whole-body trajectories in space.
Previously, we have observed that

- whole-body trajectories are stereotyped, in contrast with foot placements [H07]. This indicated that human locomotion might be planned and controlled at the level of the whole-body trajectory, rather than as a sequence of "foot pointings".
- whole-body trajectories are well reproduced by a minimum jerk model [P07].



Here, we further investigate the relations between the planning/control principles and the sensorimotor implementation of trajectories. For this,

- we study the formation of locomotor trajectories in different sensory (visual vs blindfolded) and motor (forward vs backward walking)



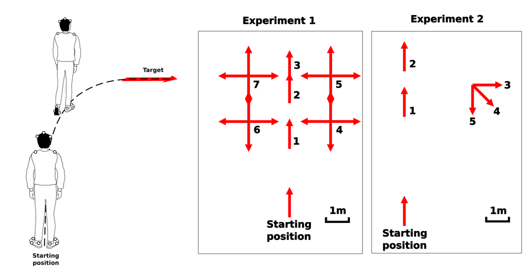
- in addition to the examination of average trajectories, a special focus is put on the analysis of trajectory variability (the variability profile)

Finally, to account for the observed trajectory statistics, we designed a stochastic version of the minimum jerk model, based on a simplified *optimal feedback control* approach.

Experiments

A) Materials and Methods

The subjects were asked to walk from a given initial position and orientation towards a distant target indicated by a 120cm×20cm arrow. To assess the body displacement in space, we used the midpoint between left and right shoulder markers, whose positions were recorded through a motion capture system (Vicon V8).



Experiment 1: We compared the average locomotor trajectories across subjects and repetitions in different sensory (with/without vision) and motor (forward/backward walking) conditions.

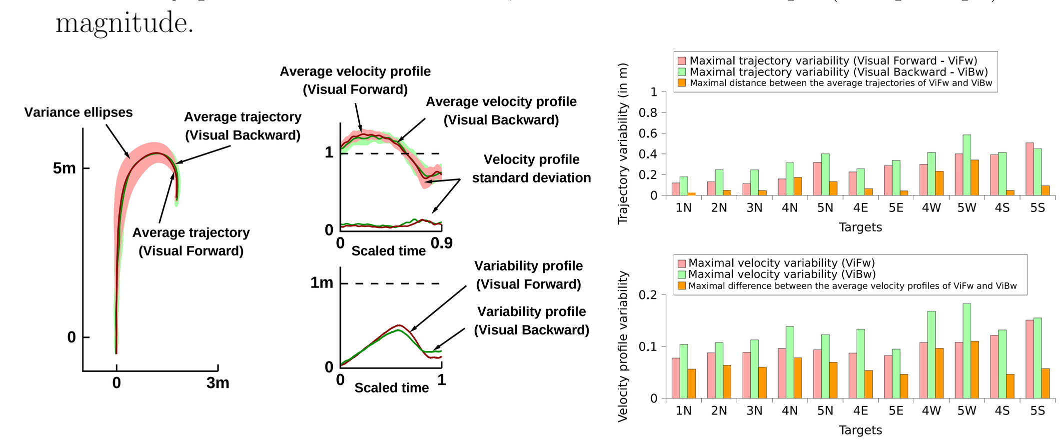
- 4 conditions: Visual Forward, Visual Backward, Blindfolded Forward, Blindfolded Backward (results not shown).
- 4 conditions × 14 subjects × 11 targets × 3 repetitions = 1848 recorded trajectories.

Experiment 2: We studied the intra-subject variability profiles along the trajectories in different conditions. For this, we needed to increase the number of repetitions per subject.

- 4 conditions: Visual Normal speed, Visual Fast speed (results not shown), Blindfolded Normal speed, Blindfolded Fast speed (results not shown for this last condition.
- 2 conditions per subject × 15 subjects × 5 targets × 8 repetitions = 1200 recorded trajectories.

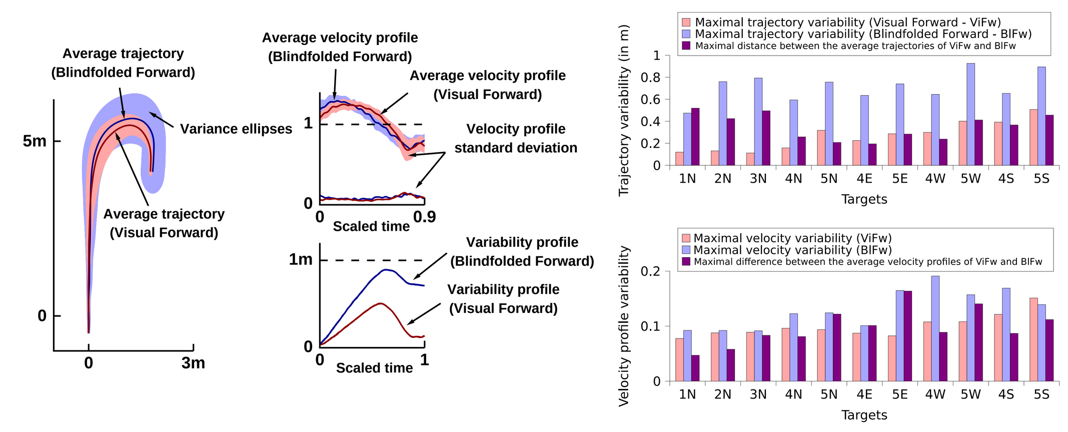
B) Results of experiment 1: Forward vs Backward

- The average trajectories in the Visual Forward and Visual Backward conditions were very similar both at the geometric and the velocity-profile levels.
- Variability profiles were also similar, both in terms of shape (bump-shape) and magnitude.



C) Results of Experiment 1: Visual vs Blindfolded

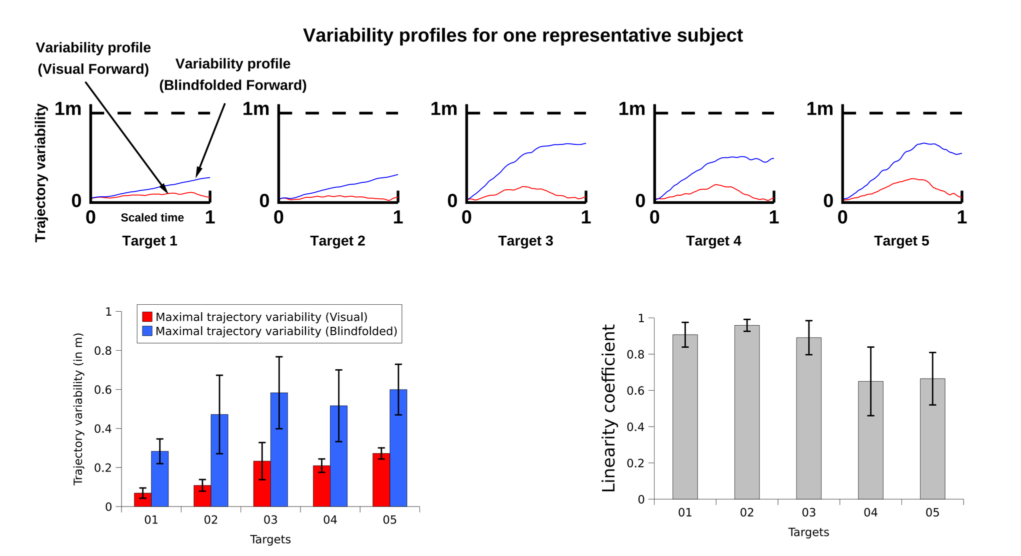
- The average trajectories in the Visual Forward and Blindfolded Forward conditions were also similar.
- The variability is higher in the Blindfolded condition because of the absence of visual feedback. Interestingly, the variability profiles in this condition are *not always increasing*.



D) Results of experiment 2

The intra-subject analysis of variability profiles confirmed our previous observations:

- In the Visual condition, the variability profile is bump-shaped.
- In the Blindfolded condition, the variability does not increase linearly with time for the highly "curved" targets (4 and 5), as shown by the linearity coefficients LC (0 ≤LC≤ 1, with LC=1 for straight lines). Rather, for these targets, the variability even decreases near the end, suggesting that these profiles could result from the *addition of a "bump" profile and a linear profile.*



Models

A) Modified minimum jerk model

In [P07], we presented a minimum jerk model [FH85] that could reproduce with great accuracy locomotor trajectories of moderate curvature. However, we noticed that the minimum jerk model predicted velocity profiles that displayed slightly larger variations than that experimentally observed. For this reason, the simple minimum jerk model failed to predict trajectories recorded in the present experiments, which were highly curved.

To overcome this, we added an extra term that penalizes large variations of the velocity. The influence of this term is weighted by a constant γ that we set to a unique value for all the simulations.

Thus, we looked for 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

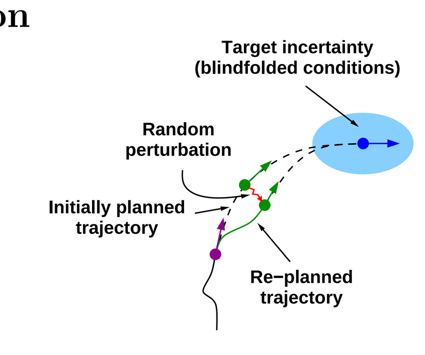
$$x(0)=x_0,\ \dot{x}(0)=v_0^x,\ \ddot{x}(0)=a_0^x,\ x(1)=x_1,\ \dot{x}(1)=v_1^x,\ \ddot{x}(1)=a_1^x$$
$$y(0)=y_0,\ \dot{y}(0)=v_0^y,\ \ddot{y}(0)=a_0^y,\ y(1)=y_1,\ \dot{y}(1)=v_1^y,\ \ddot{y}(1)=a_1^y$$

where the x_0, v_0^x,… were set to the average experimental values.

We found approximated solutions by numerically solving this optimization problem in the subspace of polynomials of degrees ≤ 7.

B) Optimal feedback control version

To account for the observed variability profiles, we derived a stochastic version of the previous modified minimum jerk (MMJ) model by implementing a simplified optimal feedback control scheme [HA93,TJ02].



Algorithm

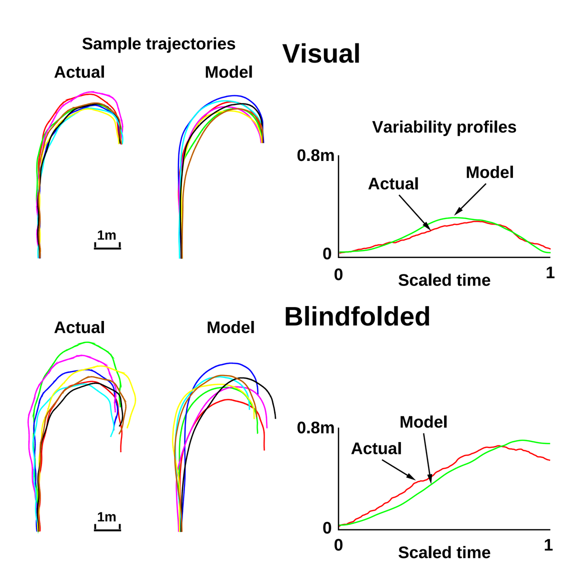
1. Discretize the movement into n steps ($10 \leq n \leq 20$ depending on the target).
2. At each step i, compute first a MMJ trajectory (initially planned trajectory) between the current configuration $C(i)$ (position, velocity, acceleration at time i) and the final configuration.
3. Add a random perturbation (*motor error*) to $C'(i+1)$, the configuration of that trajectory at step $i+1$. This yields the "real" configuration $C(i+1)$. 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 $C(i)$ and $C(i+1)$. This yields the "real" trajectory between i and $i+1$.
5. Repeat from step 2.

In light of our experimental results, we simply modified the above algorithm by adding some uncertainty (*memory or sensory error*) in the position of the target in order to explain the variability profile observed in the Blindfolded condition.

C) Results

The trajectories predicted by our stochastic model are very similar to the experimentally recorded ones, in particular:

- In the Visual condition, the predicted variability profiles are bump-shaped
- In the Blindfolded condition, the predicted variability profiles decrease near the end



Conclusion

We have experimentally shown that:

- The average trajectories are similar across different sensory and motor conditions. This confirmed our hypothesis that whole-body trajectories in these different conditions may be planned and controlled according to a common principle, independent of the precise *sensorimotor implementation.*
- The variability profiles in the visual conditions are bump-shaped. This shape suggests the existence of *goal-directed feedback corrections* [TJ02].
- The variability profiles in the blindfolded conditions can be interpreted as the sum of a bump-shaped profile (similar to the variability profile in the visual conditions) and a linear profile (caused by the target uncertainty in absence of visual feedback). This indicates that goal-directed feedback corrections may also be present, but the *corrections are made towards a remembered target position*, which generally differs from the actual target position.

The model that we designed according to these experimental observations could reproduce with great accuracy both the average trajectories and the variability profiles that were experimentally recorded. This result further confirms the hypothesis that common strategies, such as optimal feedback control theory, may govern the planning and control of very different kind of movements (in this case, hand and whole-body movements).

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Further information

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