Effect of changes in gravity on planning and control of upper limb movements

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Outline

1. Computational problems related to motor control
2. Current model
3. Experimental context: parabolic flights
4. Effect of changing gravity
   1. Inverse models: trajectory planning in hyper and micro gravity
   2. Forward models: control of grip force when moving a weightless object.
5. Summary and Conclusion
Reach to grasp an object

1. Locate the object in space.
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2. Transform from sensors to effectors reference frame.
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3. Select a kinematics plan.
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4. Inverse effectors dynamics to compute joint torques.
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3. Select a kinematics plan.
4. Inverse effectors dynamics to compute joint torques.
5. Set up feedback policy to compensate online for unexpected perturbations.
Current model for motor control

Complications:
1. Signal dependent noise in sensorimotor systems.
2. Sensory feedback is delayed.
Experimental Context: Parabolic Flights
Inverse Models:

Using gravity to move the arm.¹

[¹Crevecoeur et al., proceedings of 4th eMBEC]
Inverse Models: Introduction

How is the action of gravity integrated in the motor plan of vertical movements?

Hypothesis: the motor command is optimized with respect to the action of gravity on the limb.
Inverse Models: Methods

1. 10 healthy subjects, 47\textsuperscript{rd} and 48\textsuperscript{th} ESA PFC.
2. Visually guided pointing with arm straight rotation around the shoulder.
Inverse Models: Optimal Control

Control System:

\[ \ddot{\theta} = f - mg l \cos(\theta) - k_v \dot{\theta}, \]
\[ f' = \frac{1}{\tau}(k_u u - f). \]

Cost:

\[ J(u) = \int_{t_0}^{t_f} |u|^2 dt. \]

Resolution: Direct Multiple Shooting.
Inverse Models: Optimal Control Predictions

**Remark:** optimal control design based on feedback only does not predict this effect.
Inverse Models: Results

Computational Problems
Current Model
Parabolic Flights
Effect of changes in gravity: Inverse Models
Effect of changes in gravity: Forward Models
Conclusion
Inverse Models: Effect on Peak Velocity

Significant effect of movement direction.

Effect of changes in gravity:

Inverse Models

Forward Models

Conclusion
Inverse Models: Conclusion

1. Adaptation to hyper gravity is consistent with the hypothesis that the motor commands are re-optimized in the new gravitational context.

2. Evidence for updating the kinematics motor plan.

3. Effect of movement direction suggests that re-optimization is not the only process for adaptation. (goal of the task ?)
However...

Re-optimization or remapping?
Skewness significantly persists in 0g:
Forward Models:

Adaptive Forward models of inertial loads

In weightlessness.$^2$

[2] Crevecoeur et al., submitted
Forward Models: Introduction

Can we predict the consequences of our actions in weightlessness? Can we adapt the internal representation of arm dynamics?
Forward Models: Methods

1. 8 subjects without prior experience of 0g, 43rd and 44th ESA PFC.
2. Task: align the held load with the current target (random).
3. Variables: Grip Force (GF), Load Force (LF), position.
Forward Models: Results

Decoupling between static and dynamic component of GF.
Forward Models: Results

Decoupling between static and dynamic component of GF.

1. The static component decreases slowly across the blocs.
2. The dynamic component is rapidly correlated with the max/min of LF in both directions.

![Graph showing decoupling between static and dynamic components of GF.](image)
Forward Models: Conclusion

1. Different time scales of adaptation suggest different control processes.

2. Extend previous findings to discrete (point-to-point) and unpredictable movements: evidence for internal prediction of the upcoming LF.

3. Evidence for adaptive internal representation of arm dynamics.
Conclusion

1. The computational problems associated to motor control are efficiently solved despite changes in arm dynamics.
2. Subject’s behaviors provide evidence for existence of feed forward kinematics plan, re-optimized in hyper gravity.
3. The predictions of motor commands consequences are updated when arm dynamics are changed.
Optimal Feedback Control with signal dependent noise

\[ x_{k+1} = Ax_k + Bu_k (1 + \epsilon_k) + \xi_k, \]
\[ y_k = x_k. \]

\[ J_k = x_k^T Q_k x_k + u_k^T R_k u_k. \]
\[ u_k = -L_k x_k. \]
Direct Multiple Shooting

Control system $\dot{x} = f(x, u)$:

\[
\begin{align*}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= -\frac{mgl}{I} \cos(x_1) - \frac{k}{I} x_2 + \frac{x_3}{I}, \\
\dot{x}_3 &= -\frac{1}{r} x_3 + \frac{k_u}{r} u.
\end{align*}
\]

Optimization problem:

\[
\begin{align*}
\min_u J(u) \quad \text{s.t.} \quad & \dot{x} - f(x, u) = 0, \\
& x(0) - x_0 = 0, \\
& x(t_f) - x_f = 0.
\end{align*}
\]

Discretization:

\[
0 = t_0 < t_1 < \cdots < t_n = t_f,
\]

with $u(t) = q_i$, $t \in [t_{i-1}, t_i]$.

Discrete Optimal control problem:

\[
\begin{align*}
\min_{q} \sum_{i=1}^{N} q_i^2 \quad \text{s.t.} \quad & s_{i+1} - \varphi(s_i, q_{i+1}) = 0, \\
& s_0 - x_0 = 0, \\
& s_N - x_f = 0,
\end{align*}
\]

where

\[
\varphi(s_i, q_{i+1}) = s_i + \int_{t_i}^{t_{i+1}} f(x, q_{i+1}) dx.
\]