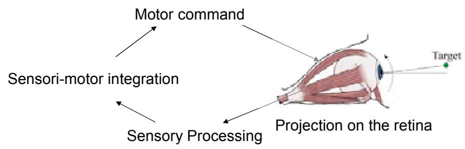
Altered gravity: a key to better understand the neural control of movement

Philippe Lefèvre

CESAME and Lab. Neurophysiol.

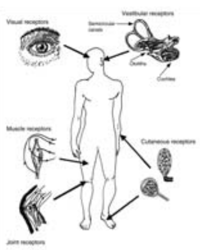
UCL Université catholique de Louvain

Experimental and modeling study of the Neural Control of Movement

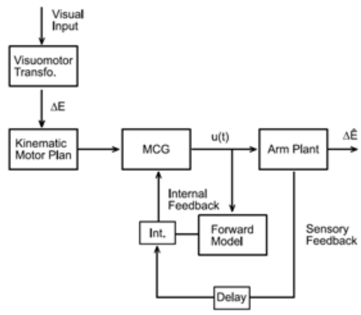


Multisensory integration process

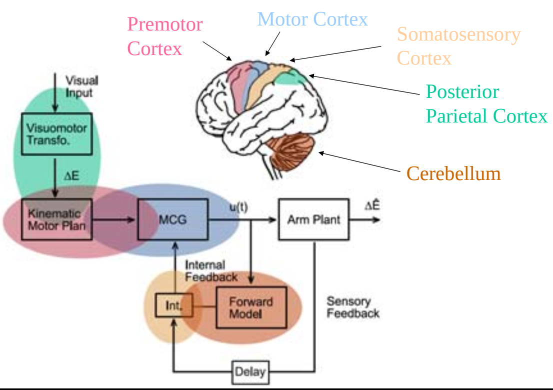
⇒ Multiple sensors and effectors



Modelling limb movements



Neural control of limb movements



Specificity of limb movements

- Gravity plays a major role in the control of limb movements.
- Gravity affects the dynamics of the limb.
- Internal models need to be updated if gravity is altered.

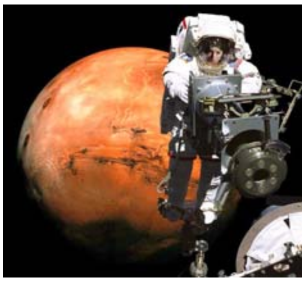
  ⇒ Altered gravity is a good testing bench for investigating adaptation mechanisms

  ⇒ Dexterous manipulation is crucial for astronauts

Context of the research project

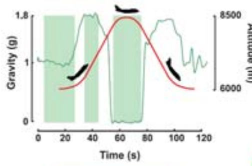
- International Life Sciences Research Announcement (ILSRA-2004) call for projects. Joint selection NASA and ESA.
- Parabolic flights followed by International Space Station (ISS) experiments in 2011.
- Support from ESA and Belspo (IAP and Prodex).

Dexterous manipulation in μ-gravity



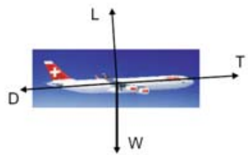
How to alter gravity

Parabolic Flights:
- Reduced cost
- 30 parabolas
- 22 seconds μg
- Hyper-gravity
- Transitions phases
- Short-term learning



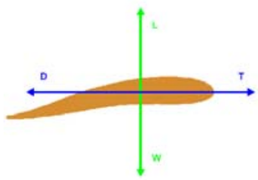
Parabolic flights (1/2)

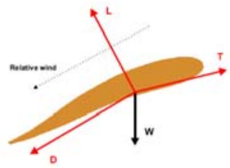
Plane	weight	W		
	thrust	T		
Aerodynamics	drag	D	$=$	$\rho\frac{v^2}{2}AC_D(\alpha)$
	lift	L	$=$	$\rho\frac{v^2}{2}AC_L(\alpha)$



Parabolic flights (2/2)

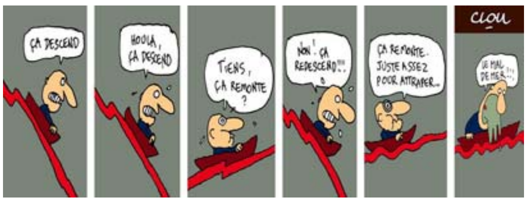
Normal flight | Free fall ⇒ parabola





$$\vec{W}+\vec{L}+\vec{D}+\vec{T}=\vec{0} \qquad \vec{L}+\vec{D}+\vec{T}=\vec{0}$$

A lot of fun?



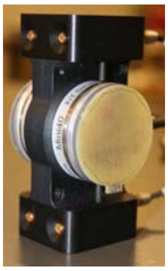
There is always a back-up!

Outline of the results

- Effect of gravity on internal **forward** models: the Grip Force controller
  - Oscillatory movements
  - Discrete point to point movements
- Effect of gravity on internal **inverse** models: the arm movement controller
  - Oscillatory movements
  - Discrete point to point movements

Description of the setup

Equipment (1/3)



Manipulandum

Basic Measures:

- Forces
- Torques
- Acceleration

Additional Measures:

- Moisture
- Position

André T, De Wan M, Lefèvre P, Thonnard JL (2008). Skin Research and Technology, 14, 385–389.
André T, Lefèvre P, Thonnard JL (2009). Journal of Neuroscience Methods, in press.

Equipment (2/3)

Eye Tracker

Basic Measures:

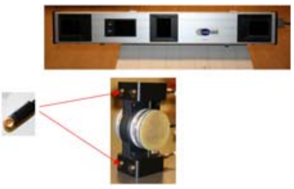
- Eye position in the orbit
- Acceleration

Additional Measures:

- Position signal of the head for gaze reconstruction

Ronsse R, White O, Lefèvre P (2007). Journal of Neuroscience Methods, 159, 158–169.

Equipment (3/3)



3D tracking

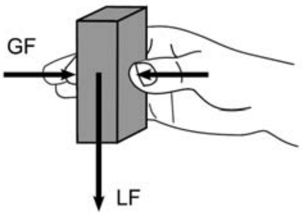
Basic Measures:

- Manipulandum
- Reference frame
- Gaze reconstruction

Additional Measures:

- EMG

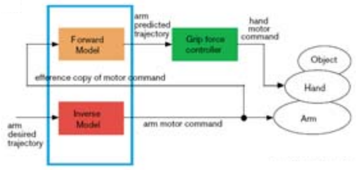
Study 1/2: the Grip Force controller



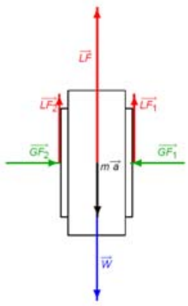
- GF: Grip Force
- LF: Load Force
- GL/LF coupling to avoid slipping
- Coefficient of friction
- Prediction based on internal model

Grip Force controller

Efference copy of motor commands
⇒ Prediction of arm trajectory
⇒ Prediction of Load Force



Grip Force controller

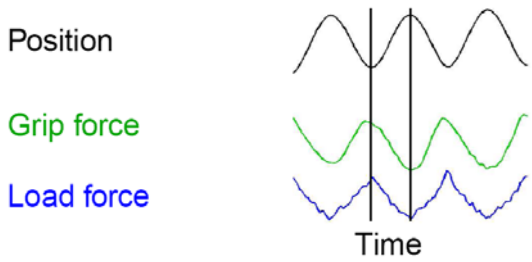


$$\|\vec{LF}\| \le \mu \cdot \|\vec{GF}\|$$
$$\vec{W} = m \cdot \vec{g}$$
$$\vec{LF} = \vec{W} + m \cdot \vec{a}$$

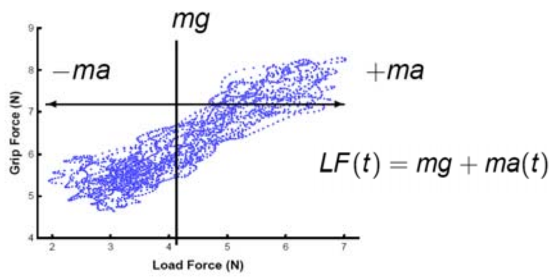
LF = Load Force

GF = Grip Force

Coupling between Grip and Load forces



Phase plot during oscillations

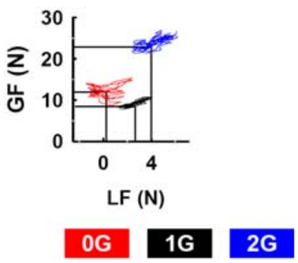


Grip Force controller

- Synchronization between Grip Force and Load Force demonstrates that the Central Nervous System can predict object motion.
- This prediction is based on:
  - An estimation of object trajectory based on motor commands sent to the limb.
  - An estimation of inertial forces based on object trajectory.
  - A combination of gravitational and inertial forces, yielding the total Load Force.

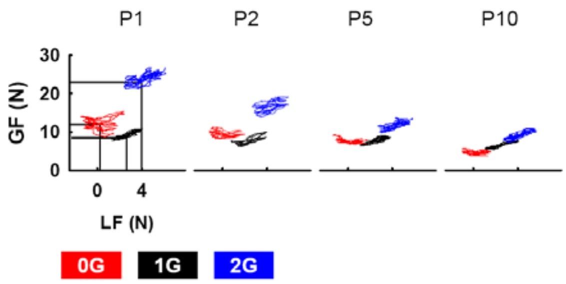
⇒ Evidence for internal models !

Oscillations in parabolic flight



- GF is not scaled to LF
- GF ‘overestimates’ LF in 0G and 2G
- Evidence for the need to adapt internal models
- What happens after repetition of the task?

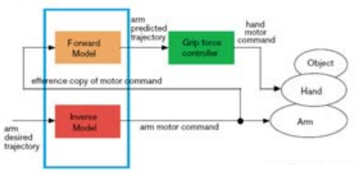
Repetition of oscillations: adaptation



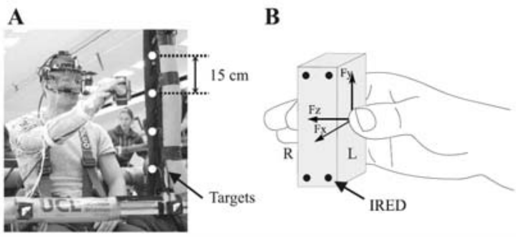
Augurelle AS, Penta M, White O, Thonnard JL (2003). Experimental Brain Research 148: 533–540

Grip Force controller

Evidence for an adaptation to the new environment
⇒ Prediction of arm trajectory
⇒ Updating of the internal model
⇒ Switching strategy based on the context

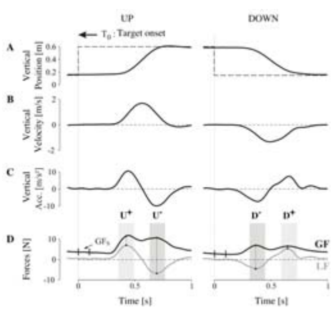


Grip Force during discrete movements



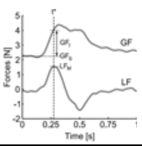
Crevecoeur F, Thonnard JL, Lefèvre P (2009). Neuroscience, 161, 589-598.

Discrete movements



Discrete movements:

- The modulation of GF is scaled to the prediction of LF achieved for each particular movement.
- Scaling is significant for positive LF (acceleration phases) and negative LF (deceleration phase) specific to 0g.



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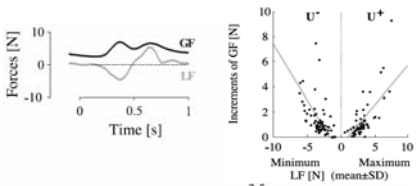
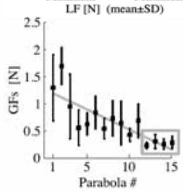
Discrete movements



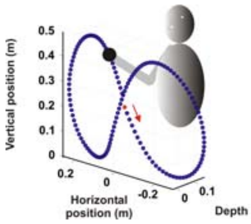
Discrete movements:

- We observe two time scales of learning.
- The ratio GF/LF during the “increment” phase is stable after less than 5 parabolas.
- The GF “static” around which the increments are occurring is stable around the 10th parabola.



Crevecoeur F, Thonnard JL, Lefèvre P (2009). Neuroscience, 161, 589-598.

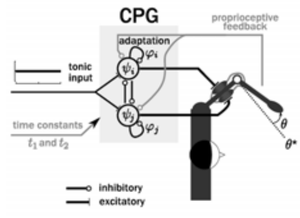
Study 2/2: the arm movement controller



- Many kinds of movements are repetitive in everyday life
- Need for efficient execution of rhythmic activities
- Evidence for the existence of neurons that control rhythmic movements:

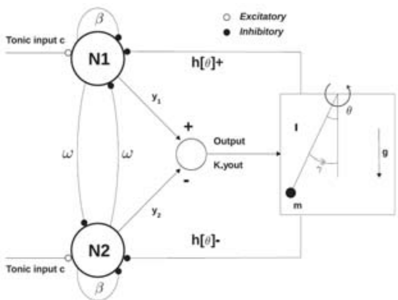
⇒ **Central Pattern Generators** (CPG)

CPG: the Mastuoka oscillator



Ronsse R, Sternad D, Lefèvre P (2009). Neural Computation, 21:5, 1335-1370.

The model: CPG and pendulum



White O, Bleyenheuft Y, Ronsse R, Smith A, Thonnard JL, Lefèvre P (2008). Journal of Neurophysiology, 100, 2819-2824.

Equations of the model

$$\tau_1 \dot{x}_1(t) = -x_1(t) - \beta v_1(t) - \omega[x_2(t)]^+ - h[\theta(t)]^+ + c(t)$$

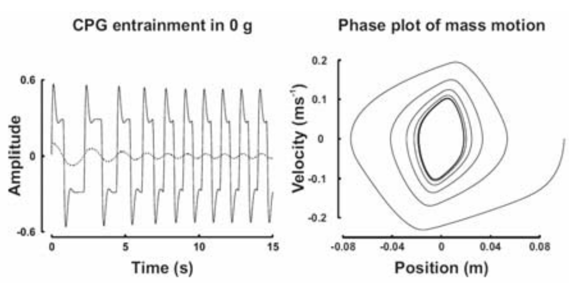
$$\tau_2 \dot{v}_1(t) = -v_1(t) + [x_1(t)]^+$$

$$\tau_1 \dot{x}_2(t) = -x_2(t) - \beta v_2(t) - \omega[x_1(t)]^+ - h[\theta(t)]^- + c(t)$$

$$\tau_2 \dot{v}_2(t) = -v_2(t) + [x_2(t)]^+$$

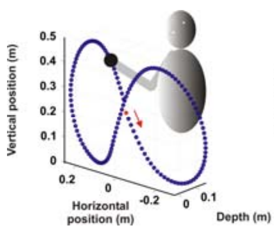
$$\ddot{\theta}(t) + \frac{\gamma}{ml^2}\dot{\theta}(t) + \frac{g}{l}\sin\theta(t) = T_{out}(t) \qquad T = 2\pi\sqrt{\frac{l}{g}}$$

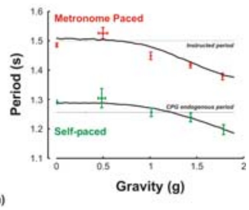
Simulations of the model



Experimental data

Gravity drives the spontaneous movement frequency (resonance phenomenon).
In 0g, subjects must learn appropriate motor commands.

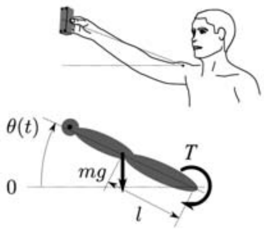




White O, Bleyenheuft Y, Ronsse R, Smith A, Thonnard JL, Lefèvre P (2008). Journal of Neurophysiology, 100, 2819-2824.

The arm controller: discrete movements

Discrete movements: point to point movements in hyper gravity. Model based on minimum control input.



Control system

$$I\ddot{\theta} = T - mgl\cos(\theta) - k_v\dot{\theta},$$

$$\dot{T} = \frac{1}{\tau}(u - T).$$

Cost function

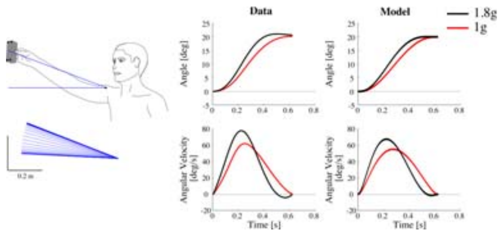
$$J(u) = \int_{t_0}^{t_f} |u|^2 dt.$$

$$(\bar{u}_k, \bar{x}_k).$$

Crevecoeur F, Thonnard JL, Lefèvre P (2009). Journal of Neurophysiology, in press.

The arm controller: discrete movements

Discrete movements: trajectory planning is consistent with minimum motor command input in hyper gravity: optimal control



Crevecoeur F, Thonnard JL, Lefèvre P (2009). Journal of Neurophysiology, in press.

Summary and conclusions

- Synchronization between Grip Force and Load Force demonstrates that the Central Nervous System can predict object motion based on internal forward models.
- When the internal representation of arm and object dynamics are adapted to changes in gravity in the forward model, a good prediction of the Load Force variation is possible for dexterous manipulation.
- Gravity influences the internal representation of arm dynamics and affects the arm trajectories.
- Increase in gravity triggers an optimization process in order to minimize the motor command input.
- Loss of interaction with gravity induces complex changes in arm motor commands.

Acknowledgements

Sponsors: ESA and Belspo (Prodex and IAP)

- Thibaut André (UCLouvain)
- Frédéric Crevecoeur (UCLouvain)
- Renaud Ronsse (ULg -> KULeuven)
- Olivier White (UCL -> ESF)

⇒ Joint project with JL Thonnard (UCLouvain)