Equilibrium Points: A unifying abstraction for motor control

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Computing with a physical device
Passive energy storage

Mechanical compliance
F. Gandolfo, F. A. Mussa-Ivaldi*, and E. Bizzi

Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 3843–3846, April 1996
Neurobiology
Directly related ideas
Gunther and Ruder
Biological Cybernetics
89, 89-106 2003
The Model
Motor Simulation: Method

- Use GD on distance error function for kinematics solution.

- Energy consumption optimization with constraints to end effector.
Motor Simulation in Experiments

- Four fastracks are attached to the arm to capture movement data.
- Weights are attached to different segments of the arm to test how the end postures changes.
Simulation comparison with human data

- weights on bicep
- weights on forearm
- weights on hand.
Movement Execution: Theory

• Dynamic skeleton system:

• Springs apply torques to the system

• is spring stiffness and is viscosity. With different and , different trajectories are generated.
Movement Execution: Implementation

- Movement execution
- Use springs in Vortex 2.3, a physics simulation package, to simulate muscles
  - Spring controls extension and flexion
Planar Arm Reaching
Movement Data Comparison (1)

• End effector trajectories fitting

Speed profile along x

Speed profile along y
Movement Data Comparison (2)

Joint profile comparison

Shoulder

Elbow

Wrist
Model Extension of Walking

- Bi-pedal walking:
  - 4 Via points are defined for one cycle of walking
  - Every leg has 3 springs, which control both extension and flexion
Walking
Walking II
Complex Movements Generation

• High DOF system as complicated as human body is hardly tractable
• Human body parts move in relatively independent manners.
• Divide and conquer
  – Motor routines defined for body parts
  – Motor synergies are used to combine complex movements
Motor Synergies

- Two or more tasks can be planned at the same time during motor simulation.
  - Sitting down: hip reaches to destination
  - Balancing: center of mass remains above the feet.
Hand Grasping Routine

• 14 degrees of freedom.
• Grasping is done by setting the EPs inside the objects.
• No high accuracy is required during planning.
Complex Movements II
Proposed Organization

Plan Segment: SMA, Premotor ctx

Execute Segment: Spinal cord
Movement Control Summary

1. Complex Movements Executed in Segments

2. Each Segment: Two phases
   - Offline motor simulation phase
     - End posture for current task
   - Online motion Execution phase
     - Equilibrium point theory
     - Abstract spring-muscle control model

3. Motor synergies
   - Different routines defined for body parts
   - Combination for whole body movements