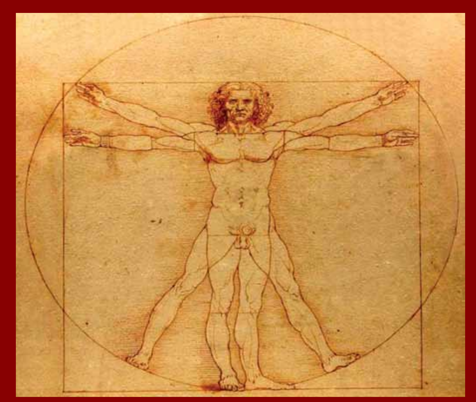
Motor Control Lab



Reconstruction of hand and grip referent trajectories during vertical oscillation of a hand-held object

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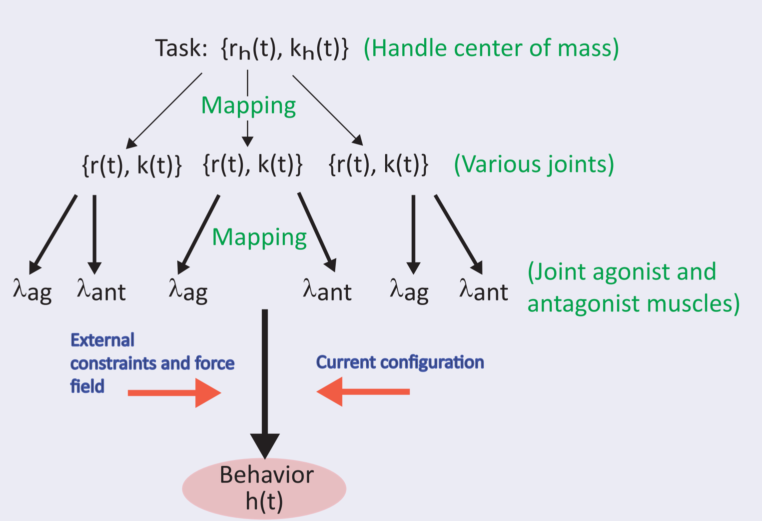
Introduction

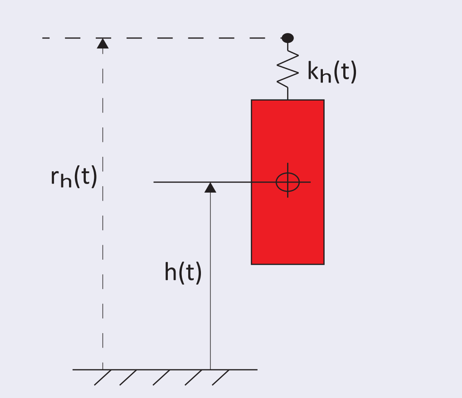
We aim to compute the trajectories of hypothetical neural control signals that the human central nervous system may employ while executing vertical oscillation of a hand-held object. The control signals are deduced for the ***explicit task of vertical oscillation*** and for the ***implicit task of grip-force modulation*** that accompanies vertical object manipulation [1]. Control signals are deduced from
(1) measurements of mechanical motion parameters (forces and movements),
(2) the theoretical framework of the referent configuration hypothesis.

We also investigate how the well-known grip-force-load-force, i.e., F_{GRIP} - F_{HAND} coupling is reflected in the underlying neural control signals.

Referent configuration hypothesis: Neural control of a motor action can be adequately described as referent trajectories for salient task-specific performance variables [2]. For single-muscle control, the **threshold of the tonic stretch reflex** (λ) is considered as the salient referent variable. **Changes in λ lead to movement, active force production, or both depending on external loading conditions.** For multi-muscle actions, a hierarchical control scheme exists with a few referent coordinates for salient variables specified at the highest, i.e. task, level. This is followed by a sequence of few-to-many mappings that yield referent coordinates at lower hierarchical levels all the way down to λs of all involved muscles [3].

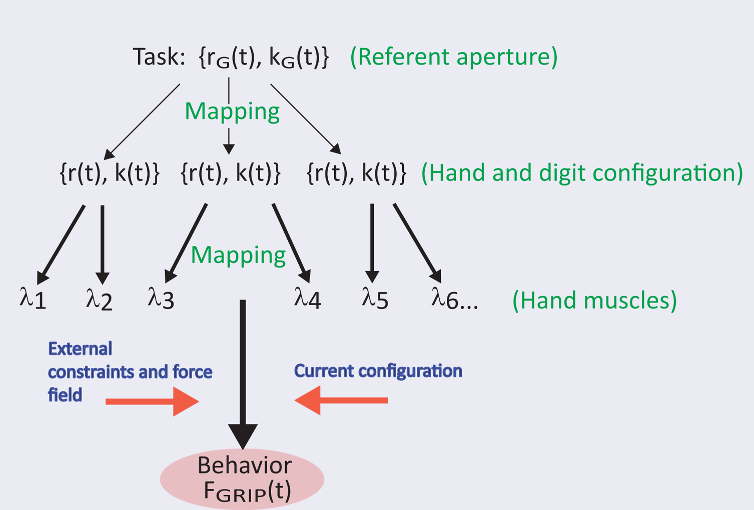
The explicit task: Vertical object movement

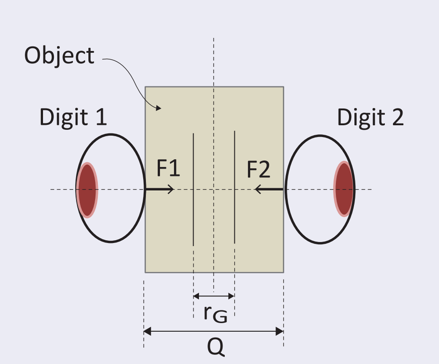




$F_{HAND} = k_h(t)\,[r_h(t) - h(t)]$
k_h:= Apparent hand stiffness

The implicit task: Grip force modulation



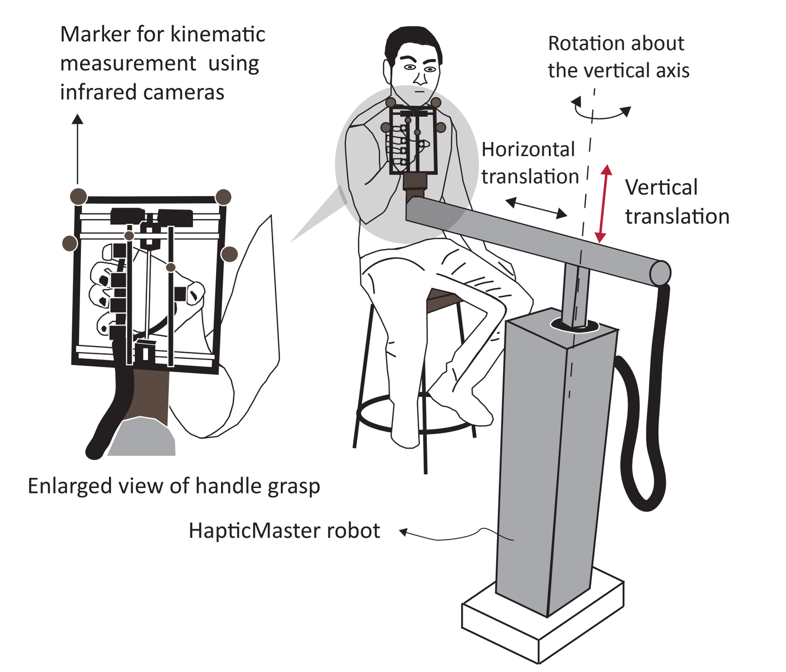


$F_{GRIP} = F1 = F2 = k_G(t)[Q - r_G(t)]$
k_G := Apparent grip stiffness

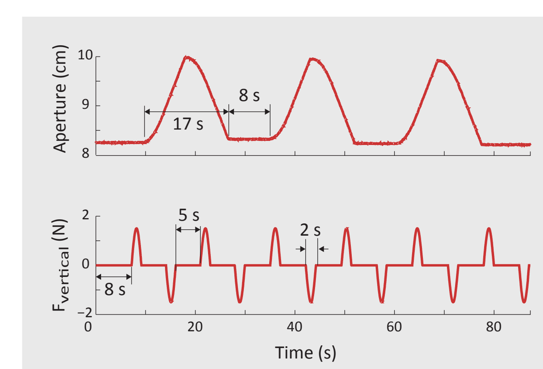
Methods

- Handle held in prismatic grasp; **Sensor under each fingertip measures force**
- Handle attached to HapticMaster robot
- 3 degrees of freedom; **Robot applies small vertical perturbation force to handle**
- Robot compensates for handle weight: Subject effectively accelerates 4 kg inertia
- **Motor-driven mechanism on handle alters actual aperture (Q)**
- Qualisys motion capture system measures handle movement and actual aperture (Q)

Experimental setup



Perturbations



Experiment

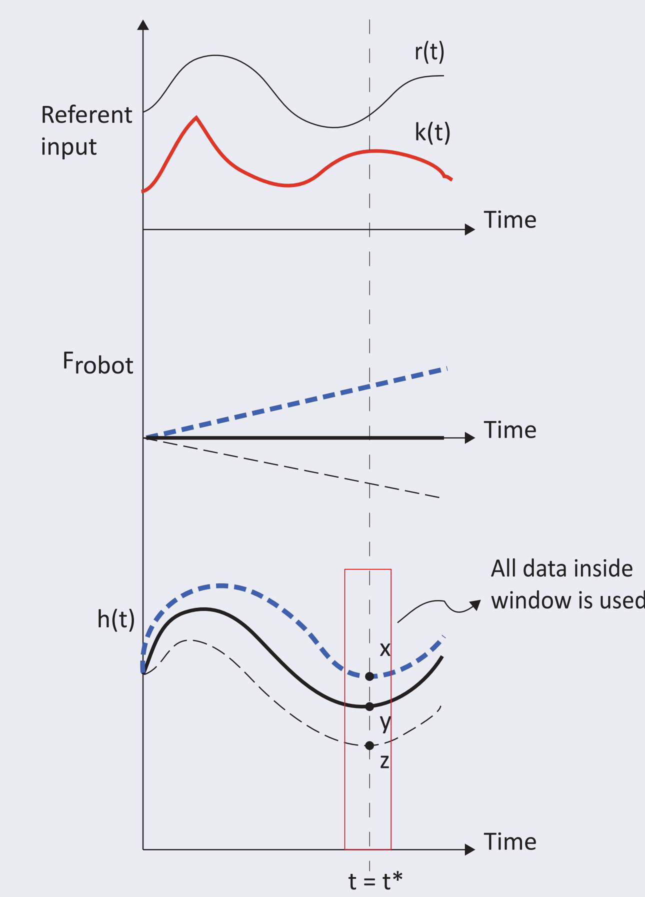
- 11 Subjects (~ 29 yrs) :
- **Oscillate hand-held handle in vertical direction** (Amplitude ~ 20 cm)
- **Five metronome-specified frequencies around the preferred frequency fn** (~ 1 Hz): **{fn - 0.2, fn - 0.1, fn, fn + 0.1, fn + 0.2} Hz**
- Specified initial aperture width (8.25 cm)
- Actual aperture opens by ~2 cm & returns to initial width
- Mean speed of handle-mounted motor ~ 1.8 mm/s
- 'Do not intervene' - ignore all perturbations

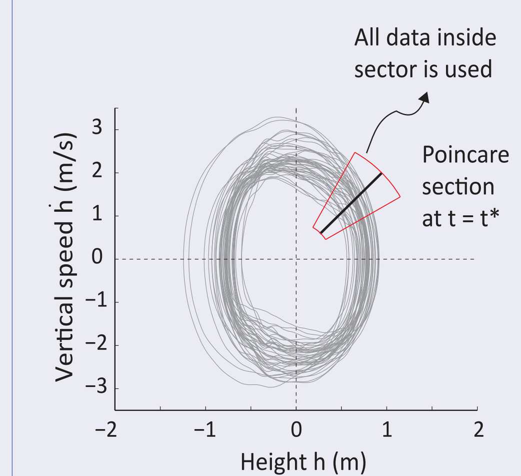
Assumptions

- The central nervous system specfies **{$r_h(t)$; $k_h(t)$}** and **{$r_G(t)$; $k_G(t)$}**
- These cyclic trajectories remain invariant over the task duration
- **External perturbations along with the invariant central control trajectories generate variation in the mechanical variables, viz, handle height and grip force**
- **Contribution of damping is negligible in both the explicit and the implicit task** (Including damping term yielded inconsistent and erratic results)
- Second-order, lumped parameter model describes dynamics
- Ignore time delays in various loops contributing to muscle force - length relation

Computation

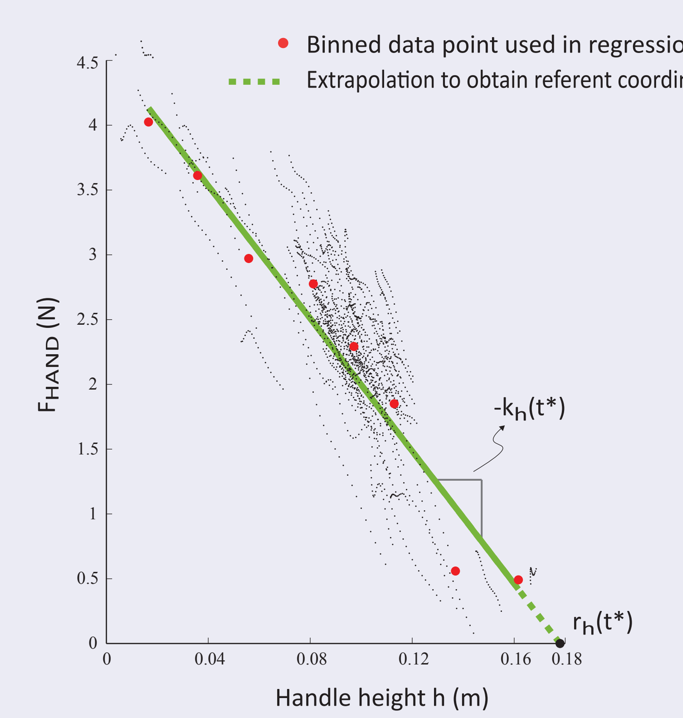
Computational procedure





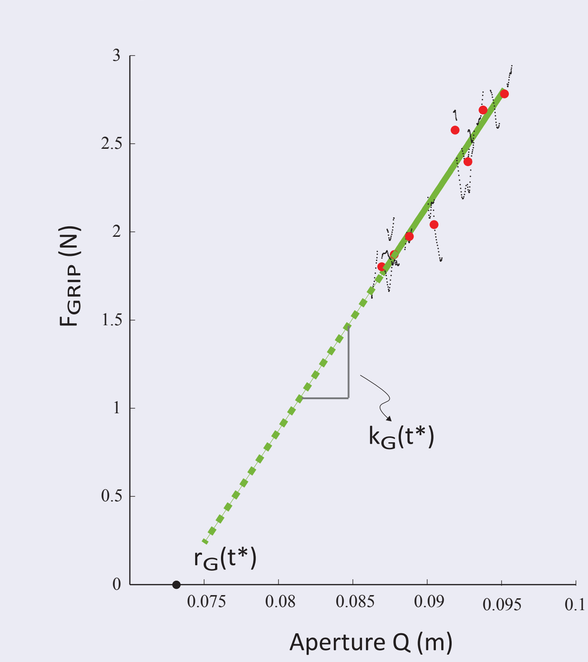
- Conside a time slice (Poincare section) at t = t*, i.e., a phase in the oscillation cycle
- Collect data **{F_{HAND}, h}** and **{F_{GRIP}, Q}** from the multiple oscillation cycles in a time window centered at t*
- Average the force and displacement data into equispaced bins
- Regress the binned force vs displacement data for both tasks separately
- **Slope of regression provides estimate of apparent stiffness k(t*)**
- **Intercept on the displacement axis (Force = 0) provides estimate of referent coordinate r(t*)**
- Repeat regression procedure for all oscillation phases; results with R^2 > 0.6 accepted

Example computations at t = t*



Explicit task

(Handle oscillation)

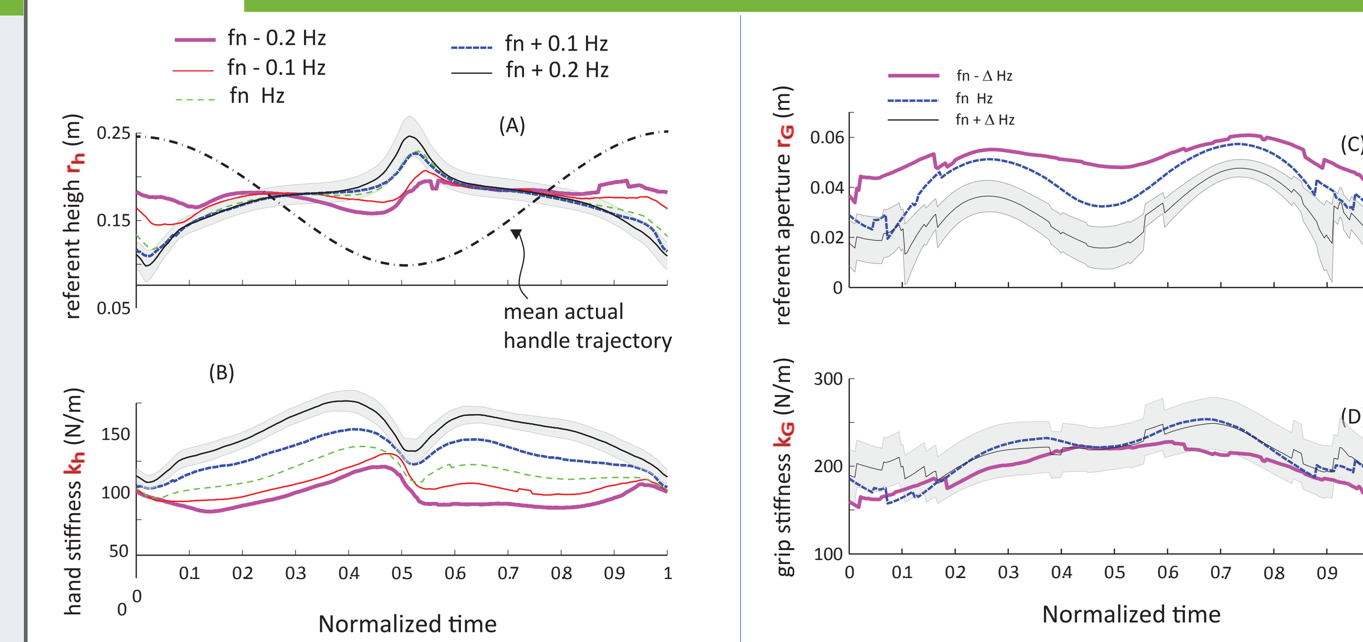


Implicit task

(Grip-force modulation)

Results

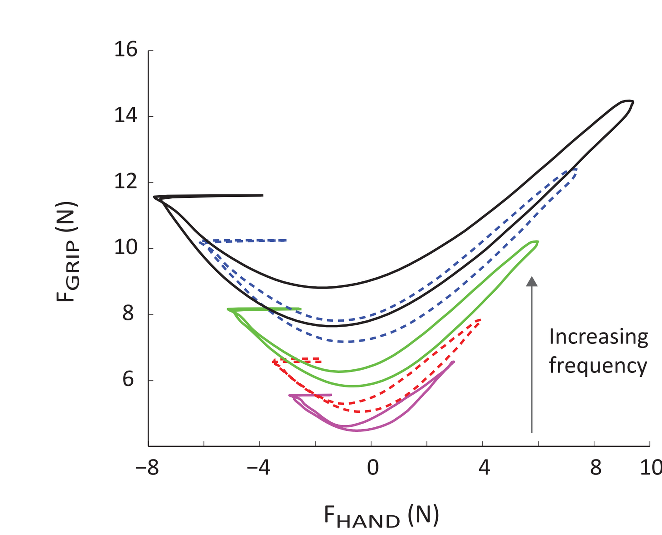
Referent coordinates and apparent stiffness for both tasks



- Panels (A) and (B) show the referent height and apparent hand stiffness, respectively, for all oscillation frequencies. Curves are averages across subjects
- Panels (C) and (D) show the referent aperture and apparent grip stiffness, respectively, for all oscillation frequencies. Curves are averages across subjects
- Data for grip-force modulation were averaged for the smallest two and the largest two frequencies
- All control variables display consistent and systematic variation over the oscillation cycle. Referent aperture oscillates at twice the frequency of the other parameters
- **Model validation:** Computed referent variables were used as inputs to predict F_{HAND} and F_{GRIP}. Predicted forces closely matched the measured forces (RMS error ~ 3 % force amplitude for F_{HAND}, and ~ 20 % force amplitude for F_{GRIP})

Grip-force-load-force coupling

- **Quadratic relation between F_{GRIP} and F_{HAND} at all frequencies**
- Median R^2 of quadratic fits = 0.9 across all subjects and frequencies
- **Single linear constraint** between referent variables:
  $k_G + a(r_G) = b(r_h) + c(k_h) + d$
- Median R^2 = 0.8 across all subjects and frequencies



Conclusions

- We have *demostrated for the first time the computation of the hypothetical control variables for a multi-effector, multi-action movement* using the referent-configuration framework
- The classical *F_{GRIP}-F_{HAND} coupling emerges from the underlying constraint on the control variables*

[1] Johansson and Westling, 1988, Exp Brain Res
[2] Feldman A, 2009, Exp Brain Res
[3] Latash ML, 2012, *Fundamentals of Motor Control*, Elsevier

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