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

Satyajit Ambike, Tao Zhou, Vladimir M. Zatsiorsky, Mark L. Latash

The Pennsylvania State University, Department of Kinesiology, PA, USA. {ssa17, tz109, vxz1, mll11}@psu.edu

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 from 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., FGRIP - FRHAND coupling is reflected in the underlying neural control signals.

Relevant 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 (1) 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 λ of all involved muscles [3].

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)
- Qualify motion capture system measures handle movement and actual aperture (Q)

Computation

- Consider a time slice (Poincaré section) at t = t*, i.e., a phase in the oscillation cycle
- Collect data (FRHAND, Q1) and (FGRIP, Q2) 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 R² > 0.6 accepted

Results

- We have demonstrated 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 FRHAND-FGRIP coupling emerges from the underlying constraint on the control variables

Conclusions

- 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 FRHAND and FGRIP. Predicted forces closely matched the measured forces (RMS error ~ 3 % force amplitude for FRHAND, and ~ 20 % force amplitude for FGRIP)
- Quadratic relation between FGRIP and FRHAND at all frequencies
- Median R² of quadratic fits = 0.9 across all subjects and frequencies
- Single linear constraint between referent variables: kG = kH(νG + νH) + νH
- Median R² = 0.8 across all subjects and frequencies

Assumptions

- The central nervous system specifies (rH(t), kH(t)) and (rG(t), kG(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

Computational procedure

Grip-force-load coupling

Experimental setup

References