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THE SPATIO-TEMPORAL STRUCTURE OF FORCE VARIABILITY IN STATIC GRASP SUGGESTS A CONTINUALLY ACTIVE NEURAL CONTROLLER

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ABSTRACT

Fingertip forces during simple and static tripod grasp exhibit a surprisingly rich dynamics [1]. Here we explore the hypothesis that, even for this apparently simple manipulation task, these fluctuations are shaped by a neural controller rather than by signal-dependent motor noise. We fed band-limited noise processes scaled to mean force level into a 21-muscle model of 3-finger grasp, and compare model output with experimental force recordings. We find that the spatial and spectral characteristics of simulated force fluctuations differed greatly from those observed in actual static tripod grasp. In light of current literature [2], we propose that a continually active neural controller is at work even for this simplest example of multifinger manipulation.

INTRODUCTION

Motor behavior exhibits variability. Some of this variability arises from signal-dependent noise (SDN) at the muscle level, and its standard deviation scales approximately linearly with mean force magnitude. These normally distributed fluctuations are temporally uncorrelated across muscles, and arise primarily from the properties of muscle recruitment [3].

We have found that fingertip forces exhibit complex dynamics static tripod grasp that exhibit long-range temporal correlations on the order of hundreds of milliseconds [1]. To understand the origins and consequences of these fluctuations in multifinger manipulation, we begin by investigating whether the structure of these fluctuations can be explained by uncorrelated SDN, or

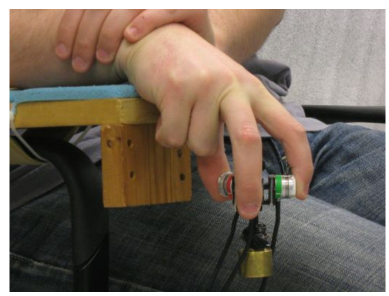

FIGURE 1. The grasp device in the typical static tripod grasp.

whether other neural processes and control strategies play the dominant role. The structure of force variability in static grasp is reminiscent of Levy flights: phases of stochastic clustering separated by large, periodic jumps. Levy flights have been shown to be present in sophisticated neural control tasks such as saccadic eye movements [4] and stick balancing [5].

METHODS

Human subject testing of static grasp

Ten consenting adult subjects (ages: 24-44 years) held a 120 g device statically (see Figure 1) with the thumb, index and middle fingers of their dominant hand for 1 minute. Each finger was in contact with a 6-axis force transducer (ATI Nano 17) sampled at 400 Hz and later downsampled to 100 Hz and 4th-order Butterworth low-pass filtered at 40 Hz for the analysis.

Computer simulation of static grasp under SDN

We simulated the production of static fingertip force $\mathbf{w}$ by multiplying tendon tensions by the matrix $\mathbf{w}(t) = J^{-T}R\mathbf{f}$, where

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J^{-T} is the inverse transpose of the finger posture-dependent Jacobian (that maps joint torques to endpoint forces), R is the moment arm matrix (that maps muscle forces into joint torques), and $\mathbf{f}$ is the vector of tendon tension time histories (8 for the thumb, 7 for the index, and 6 for the middle finger). The fingers are assumed to be simple 3-link pendula with 2 hinge joints distally and one ball joint proximally. The link lengths, moment arms and muscle force ranges were taken from the literature [6, 7]. We used finger postures that resemble the experimental grasp.

To compute distributions of muscle forces satisfying the static grasp constraints of zero translation and rotation of the object (i.e. $\sum \mathbf{F}_{object} = \mathbf{0}$ and $\sum \mathbf{M}_{object} = \mathbf{0}$), we concatenated the matrices $J^{-T}R$ from each finger into a grasp map G [8] and computed its null space, a region in 21-dimensional space which describes the set of tendon tensions that produce static grasp.

We iteratively selected randomly admissible solution vectors $\mathbf{f}$ from the null space. For each solution we created time series $\mathbf{f}(t)$ with SDN by adding uncorrelated beta-distributed noise proportional to each muscle's force–bandlimited to a physiologically realistic 0-20 Hz. Noise magnitude was based on published CV of 0.02 [3] to simulate the linear signal-dependence of noise on mean force. This produced a $\mathbf{w}(t)$ fingertip force vector for each finger.

RESULTS

A representative plot of the three noise-generated fingertip normal forces $\mathbf{w}(t)_{normal}$ against each other for a valid solution reveals a dramatically different structure (Figure 2) than that seen in the experimental trials. As can be expected from a linear mapping, the forces cluster into an ellipsoid of data points, whose dimensions are a function of the linear model transformation; and lack large, periodic jumps. However, only a numerical simulation is able to reveal the detailed magnitude and distribution of these fluctuations. Furthermore, the power spectral distribution is significantly different: most power in the recorded data is contained in the very low frequencies, whereas with pure SDN input there is an even distribution of noise over a long range of frequencies.

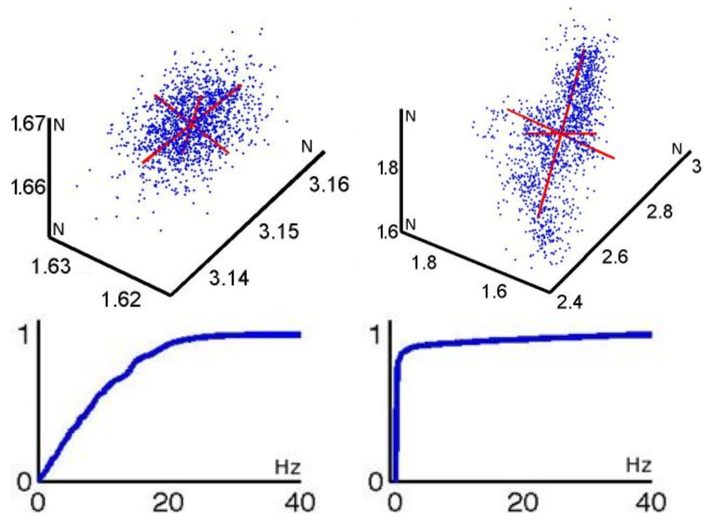

FIGURE 2. *Upper row*: The three fingertip normal forces plotted against each other, in the pure noise (*left*) and the experimentally recorded case (*right*). The directions and lengths of the principal axes of the distributions are plotted in red. *Lower row*: The cumulative proportion of power in the pure noise (*left*) and experimentally recorded case (*right*) (for the thumb only).

DISCUSSION AND CONCLUSIONS

Pure uncorrelated and band-limited noise processes does not give rise to the type of grasp force dynamics we observe in static grasp. The SDN simulations lack temporal structure and have Gaussian-like spatial structure. These findings strongly suggest that grasp force dynamics cannot be attributed to motor noise alone. We propose that simple static tripod grasp is a task subject to a continually active neural controller, much like during the production of accurate fingertip forces [2]. These data and simulations justify future work to identify the dynamic neural controller at work in static grasp.

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