GRIP FORCE FLUCTUATIONS ARE MORE THAN JUST NOISE

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INTRODUCTION

Statically grasping an object with three fingers is one of the most fundamental element of dexterous manipulation dexterous manipulation. Here we show that the sensorimotor system does not exhibit structured dynamical coordination among fingers only as the task becomes "complex", but quite to the contrary, such low-level coordinated activity also underlies static grasp. As in the case of isometric force production with a single finger [1], actively enforcing the equilibrium constraints of static grasp in the presence of unavoidable noise also requires structured dynamical coordination among fingers. This work, which extends techniques used to analyze other dynamical system such as postural stability or diffusive processes [2], opens a window into the previously undetected low-level dynamical control that underlies even the simplest of multi-finger tasks.

METHODS

The test device is a three-armed object (Fig. 1), whose arms lie in a plane and can rotate about a common center hinge. The relative angles of the arms were adjusted and locked in a configuration appropriate for a regular 3-finger grasp. A miniature 6-axis force transducer (ATI Nano 17) attached to the outer end of each arm served as the finger pad, giving each arm a total length of approx. 3 cm. The finger pads were covered with Teflon film. Various weights (50 g, 100 g or 200 g) were attached to the center hinge to change the total required grip force to hold the object statically while resting the wrists on a cushioned surface (Fig. 1). We sampled the forces and torques applied at each finger pad with 16-bit resolution at 400 Hz.

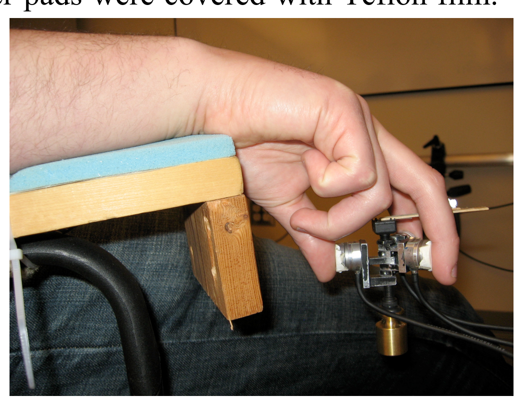


Figure 1: The test device with a 50 g weight attached to it

Five right-handed healthy male adults (ages: 24-43) participated in the experiment. Our 3x2 factorial design consisted of simply holding the object for 128 s, for each of the three weights both with and without visual feedback of the total grip force. The experiment was distributed over 2 days to preclude fatigue effects, and at least one minute of rest was provided between trials. On the first day visual feedback was not provided and subjects simply looked across the room, whereas on the second day feedback was provided and subjects were instructed to keep the cursors on a computer screen on a line representing the desired sum of normal forces applied to the object constant. We recorded three trials per weight, for a total of 9 trials per day.

For the data analysis, we focused on the normal forces, but the results are unaffected when looking at full 3D force vector magnitudes. We removed the first 8 seconds of each trial to prevent the influence of initial transients, and here we report the results of the subsequent 60 s of each trial. After determining that the power spectrum was flat beyond 10 Hz, we down-sampled the data to 40 Hz for computational efficiency. Given that the analysis used requires non-stationary data (i.e., constant mean and time-interval dependent autocorrelation), we transformed our data by using a Savitsky-Golay filter to compute first derivatives and remove trends [2].

The data are assumed to result from a noise process, which can be modeled by a Langevin equation $\dot{x} = f(x) + G(x)\xi$, where f(x) is a deterministic function of the state (normal force), G(x) is a tensor and ξ white noise. The time evolution of the associated state space probability density $\rho(x,t)$ can be described by the Fokker-Planck equation [4]:

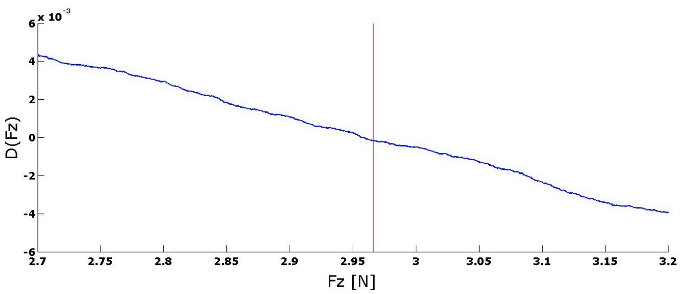
$$\frac{\partial \rho(x,t)}{\partial t} = -\sum_i \frac{\partial D_i(x)\rho(x,t)}{\partial x_i} + \sum_{i,j} \frac{\partial^2 D_{ij}^{(2)}(x)\rho(x,t)}{\partial x_i \partial x_j}$$

where drift $D_i(x)$ and diffusion $D_{ij}^{(2)}(x)$ are the first and second moments of that distribution, respectively, both assumed to be time-independent. Roughly speaking, this formulation explicitly separates determinism – the mean behavior – from stochasticity – the variability. We calculated the moments in the following way [3]:

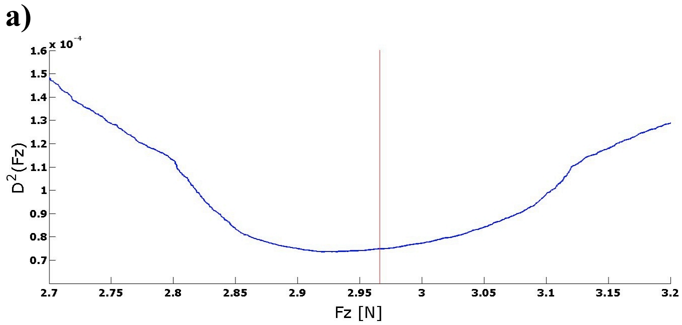
$$D_i(x) = \lim_{\Delta \to 0} \frac{1}{\Delta} \left\langle x_i(t+\Delta) - x_i(t) \right\rangle_{x(t)=x}$$

$$D_i^{(2)}(x) = \lim_{\Delta \to 0} \frac{1}{2\Delta} \left\langle (x_i(t+\Delta) - x_i(t))(x_j(t+\Delta) - x_j(t)) \right\rangle_{x(t)=x}$$

Where $\langle \ \rangle_x$ denotes the mean of data points in a sufficiently large neighborhood of x. We then fitted a line to the first moment and a parabola to the second moment to compare changes in the coefficients with respect to varying the task conditions. To this end, we performed a two-way ANOVA.



a)



b)

Figure 2: Sample drift (a) and diffusion (b) plots for thumb normal force. The vertical line indicates the mean force value: it coincides with the fix point (a) and a noise minimum (b).

RESULTS AND DISCUSSION

The two fundamental findings common to all subjects are: a) the system actively tries to maintain a force set point and b) the force set point coincides with a variability minimum.

The first finding is supported by the fact that the mean force level roughly coincided with a zero force change, i.e. was a fix point, while force changes scaled linearly in magnitude with deviation from and on average, in a direction towards that force level (Fig. 2 a), while the second finding is supported by the variability minimum being always close to the mean force level (Fig. 2 b). Again, variability scales with deviation, indicating an increased effort, which leads to an increase in noise. Adding visual feedback decreased the drift slope and offset significantly ($P < 0.01$), indicating that the drift truly reflects the controller effort. Weight only had an effect on the offset ($P < 0.01$), indicating an increased effort but unchanged sensitivity. Feedback also significantly increased the slopes of the diffusion parabola and its offset ($P < 0.01$). Since the feedback induces increased activity on the part of the subject, this finding shows that the diffusion reflects the variability increase with activity.

CONCLUSIONS

Despite the apparent simplicity of statically grasping and object, the analysis of the grip force fluctuations reveals determinism and thus the workings of a controller. By creating a stable force equilibrium point, this controller is able to maintain a desired force level even in the presence of unavoidable stochastic perturbations inherent in the sensorimotor system. Importantly, the controller's effort to maintain this force level scales with the deviation from it. This work is the first to show, to our knowledge, the presence of a continuously active, low-level dynamic controller during static grasp; and opens up future research avenues to understand the fundamental neuromuscular components for the sensorimotor control of multi-finger manipulation, and its disability.

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