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The Motor System Estimates Uncertainty and Higher Order Statistics for the Control of Grip Forces

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***Abstract*—Successful manipulation of an object requires exerting grip forces (GF) sufficient to prevent slippage. To prevent slip in more uncertain environments, GF would need to increase. Here we investigate the brain's ability to efficiently control grasp by producing GFs that correspond to confidence estimates of uncertain environments that are characterized by probability density functions of different variances and higher order moments. We found that GFs increased dramatically with the level of environmental uncertainty, and even when environmental uncertainty was held constant while higher order moments were varied, GFs changes in a way that was appropriate for kurtosis.**

I. INTRODUCTION

When holding an object steady, the minimum grip force (GF) required to avoid slip is a function of both the weight of the object and the friction coefficient. For load forces orthogonal to the axis of grasp (Fig. 1), the GF must be at least as great as the load force divided by the coefficient of friction. A safety margin above this minimal required GF is often maintained [1] and serves to reduce the chance that unexpected perturbations, mis-estimation of load forces, or errors in GF production result in slippage.

Previous work has shown that GFs can be controlled to account for fluctuations in environmental dynamics in a predictive, feed-forward manner. GFs increase in anticipation of increases in the load force [2] and are modulated in parallel to load forces even when load forces fluctuate rapidly [3,4]. These studies focused on the relationship between GFs and the expected value of environmental dynamics. However, here we suggest that the trial-to-trial variability of environmental dynamics drive this predictive control as well. Consequently, the safety margin for GF control would be a function of both the expected value and the variability of environmental dynamics.

An illustration of why increased environmental variability should lead to increased GFs is shown in Fig. 2. We interact with an object through two kinds of forces: grip and manipulatory forces (MFs). In order to keep the object in position, MFs need to counter load forces. The optimal MFs in this case would be equal and opposite to the expected value of the perturbation, and would not be affected by differences in environmental variability (Fig. 2A,C). However, increased variability means that strong load forces are encountered more often. Thus, to maintain a fixed confidence level against slip, higher GFs would be required for environments of increased uncertainty (Fig. 2B,D). If the variability in dynamics is normally distributed, then knowledge of the standard deviation (σ) would be sufficient to determine the GFs required to maintain a desired confidence level (α) against slip. However, maintenance of a fixed α for non-Gaussian distributions would require knowledge of higher-order statistics as well.

Here we studied whether the nervous system can make use of high-order statistics to better control GFs. We show (1) that when σ is increased, GFs are increased to maintain stability against slip and (2) that the control of GFs can make use of high-order statistics during exposure to environments with identical σ but different high-order moments.

II. METHODS AND RESULTS

We used an experimental setup similar to our previous work [5] (Fig.3A,B). Subjects grasped a manipulandum using a precision grip (Fig. 1) and performed point-to-point reaching movements. The grasped object was fixed to a robotic arm in a way that allowed the grasp axis to be

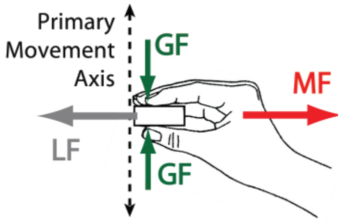

Fig. 1. Diagram of the forces exerted on and from the subject during movement along the primary axis. Leftward load forces (LF) are being compensated by the manipulatory force (MF) while the subject holds on to the object exerting grip forces (GF) lateral to MF and LF.

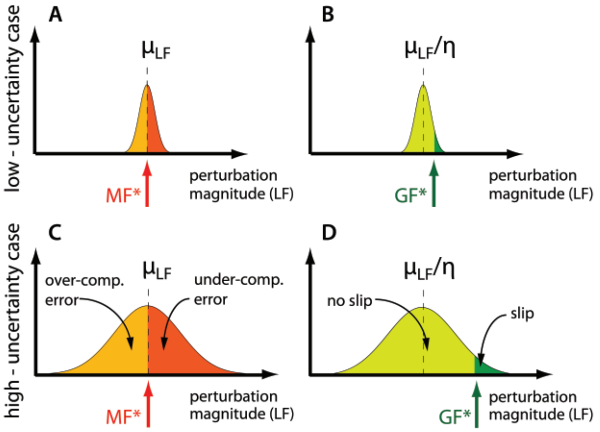

Fig. 2. GF and MF under dynamics of different uncertainty. (A,C): MF adapt to the expected value of the perturbation regardless of whether uncertainty is low (A) or high (C). (B,D): Adaptation of GF to the same environments. For a more uncertain perturbation (D), GFs need to be much stronger in order to maintain the same confidence level against slippage, compared to a less uncertain perturbation (B).

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orthogonal to the load force axis throughout each movement. Movements were perturbed by a load force (F_L), applied by the robotic arm and directed laterally to the movement. The perturbing force F_L consisted of a viscous force-field with a randomly selected strength b and a force offset, F_0, large enough to ensure that the net force direction did not change when $b < 0$ (Fig. 3A):

$$F_L = \begin{bmatrix} F_0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & b \\ -b & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix} \qquad \text{(Equation 1)}$$

In experiment 1, b was drawn from a normal probability distribution function (pdf) with zero mean and a standard deviation that could assume four different levels (Fig. 3B). We found that GFs clearly increased when variability levels were higher (Fig 3CD), whereas MFs did not ($p > 0.35$). The modulation of GF with environmental variability was highly significant, as shown in Fig. 3D ($p<10^{-6}$).

We next examined the effect of high order statistics in the pdf characterizing environmental variability. For a Gaussian distribution, knowledge of μ and σ is sufficient for the brain to compute the GF required to maintain a certain α level against slippage. However, other distributions would require different GFs for the same α level, even when μ and σ are fixed, because of differences in high order statistics (e.g. kurtosis, the 4th standardized moment, Fig. 4). For example, the Gaussian and bimodal distributions shown in Fig.4 have the same σ, but different 95% α levels (1.64σ vs. σ).

To test the ability of the motor system to represent higher order statistics, we compared GF modulation for Gaussian and bimodal distributions with the same σ. In some blocks of trials b was distributed under a normal distribution of mean zero and standard deviation of 3.6 Ns/m, and in other blocks b was drawn from a bimodal distribution with identical μ and σ (Fig. 5A). Each type of block was presented twice, one after the other with each presentation lasting 150 trials. A total of 38 healthy subjects participated in the experiment. In order to give the motor system a reasonable amount of experience with each probability distribution, we focused our analysis on the last third of each block.

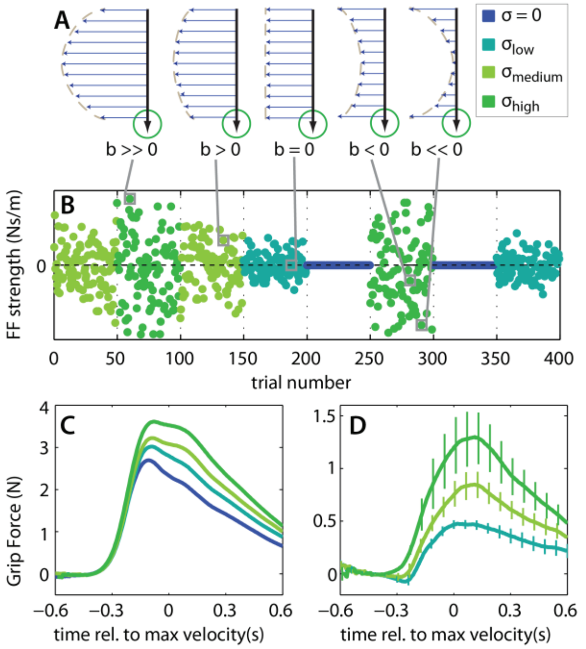

Fig. 3. Upregulation of GF with uncertainty. Experiment design and results from [5]. (A) Characteristic load force patterns. (B) Example distributions of the viscous force-field coefficient b. Results: (C) GF profiles for each condition and and (D) change from zero-σ level.

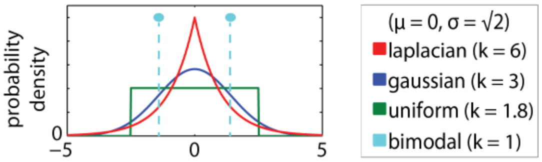

Fig. 4. Four distributions with identical mean μ and standard deviation σ but different kurtosis, k.

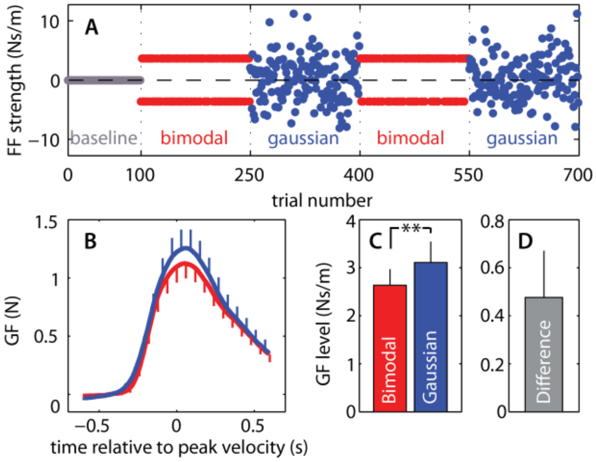

Fig. 5. Design and results for the current experiment. (A): sample training schedule (values of b). (B): average baseline-subtracted GF profiles for each block type. (C): Corresponding GF adaptation metrics.Two stars indicate p <0.01. (D): difference in GF adaptation between the two conditions. Error bars indicate s.e.m. across subjects.

Figure 5B shows GFs from these trials, averaged across subjects for each distribution. Baseline force profiles (last 50 trials before the onset of the first force-field) were subtracted in order to focus on the learning related change in the GF profiles. As previously (Fig. 3D), we found a significant increase above baseline for both of these high-variability conditions. To assess the strength of GF, we linearly regressed GF profiles onto the viscous component of the perturbing force at each trial. If the nervous system could not make use of higher order statistics in the control of GF levels, both the Gaussian and the bimodal conditions would yield the same results. However, the coefficients we obtained were significantly stronger ($p<0.01$, paired t-test) for the Gaussian (3.11 ± 0.43 Ns/m, mean ± standard error across subjects) vs. the bimodal condition (2.63 ± 0.34 Ns/m). This amounts to 18% higher GFs for the Gaussian pdf and indicates appropriately smaller GFs for the bimodal pdf.

These results illustrate that GFs adapt in a manner that is dependent on both variance (σ^2) and higher order statistics. These findings demonstrate that the nervous system can make use of higher order moments in a statistical distribution to accurately maintain a confidence level for GF control. Future work will examine whether GF will be appropriately upregulated during exposure to a distribution of environmental dynamics that has longer tails (higher kurtosis) compared to Gaussian noise.

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