REDUCTION IN STABILITY OF MANUAL BEHAVIOR IN UNCERTAIN CONDITIONS

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INTRODUCTION

Ensuring the stability of motor action is critical for executing successful movements. However, maximizing stability is not always desirable [1]. For example, a transition between motor states must be preceded by the destabilization of the prior state. *Anticipatory synergy adjustments* describe the destabilization of a motor state that begins ~300 ms before the intended change in that state is observed [2]. Similarly, when rapid movement is expected in the near future, the motor system must manage two contrasting objectives: (1) ensure the stability of the current state, and (2) achieve rapid transitions to new states, if required. We argue that the stability of the current motor state is modulated to lower values to account for uncertain task requirements and to achieve dexterous task switching.

Here, we verify if stability reduction enables the dexterous use of the fingers. Subjects performed four-finger, isometric, constant force production tasks in two conditions. In the first (stable) condition, subjects produced one constant target force and had a-priori knowledge of the target's invariance. In the other (dexterous) condition, subjects tracked a longer, unknown, randomly varying trajectory that included the constant-force target as an integral part. We hypothesize that the stability computed during the constant force-production phases in the two conditions (1) will be maximal for the stable condition, and (2) will be progressively lower as the task demands increase.

METHODS

Twenty-five healthy subjects (6 male, 20.4±2.5 yrs) participated in the study after providing informed consent. Subjects were seated comfortably in a chair with their forearms resting on top of a table. They placed the distal phalanx of each finger of their dominant hand on one force transducer (Nano-17; ATI Automation). The transducers recorded each finger's downward vertical force at 1000 Hz. Visual feedback on the total force, F_T, was provided for all trials via a computer screen placed in front of the subject. F_T was computed as the sum of the vertical downward forces of all fingers ($F_T=\sum F_i$; i=1 to 4).

For the stable condition (Task 1), subjects produced a constant F_T value (10% of maximum voluntary contraction - MVC) for 7 s with the knowledge of the target's invariant location. This task was repeated 16 times [2]. For the dexterous condition (Tasks 2 and 3), the subjects modulated their total finger force and tracked an F_T target that randomly changed its vertical position on the screen. The target F_T profiles lasted for 30 s and consisted of smooth transitions between varying durations and magnitudes of constant F_T, including one instance of 10% MVC which lasted for at least 4 s. There were 8 distinct target F_T profiles for Tasks 2 and 3 each, which were repeated once to obtain a set of 16 trials for each task type. The target moved faster for Task 3 compared to Task 2, making Task 3 harder. The trials were randomized within each task, and the tasks were block randomized across subjects.

The last 4 s of Task 1 (Fig. 1A), and the first 4 s of Tasks 2 and 3 were used for further analysis, after the data were time aligned to match the start of the 10% MVC portion (Fig. 1B). The individual finger forces (F_i) were filtered using a zero-lag, 4th-order, low-pass Butterworth filter (10-Hz cut-off). The stability of behavior was quantified using the uncontrolled manifold (UCM) analysis [3]. The UCM analysis partitions the variability in the input finger forces into a component along the UCM which does not affect the output force (*good* variance: V_U), and variability orthogonal to the UCM that affects F_T (*bad* variance: V_O). The relative amount of good variance, normalized by the total variance V_T, computed per degree of freedom, yields the synergy index: $\Delta V = (V_U/3 - V_O)/(V_T/4)$. ΔV is z-transformed to yield ΔV_Z for statistical analysis. $\Delta V_Z > 0.549$ indicates that the fingers covary to stabilize F_T, i.e., if one finger force increases, others compensate by reducing their force to maintain F_T. A *synergy* exists between the fingers, and a greater ΔV_Z indicates a stronger synergy and higher stability. Conversely, $\Delta V_Z < 0.549$ implies covariation between the fingers that destabilizes F_T. The time function $\Delta V_Z(t)$ was computed using across-trial finger forces at each time instant *t*. ΔV_Z values for two Phases (Phase 1: 2-3 seconds and Phase 2: 3-4 seconds) were averaged within those time bins for each subject and subjected 2-way, repeated-measures ANOVAs with factors *Phase* (2 levels) and *Task Type* (3 levels). Bonferroni corrections were used for pair-wise comparisons.

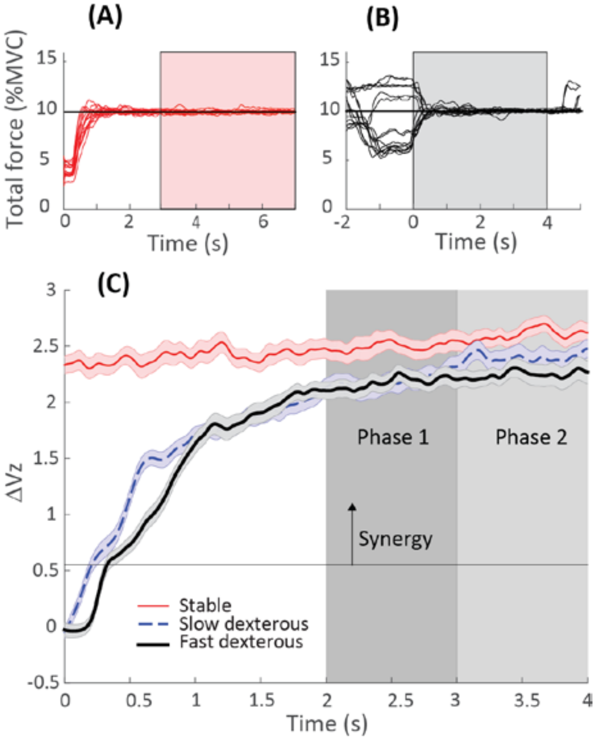

Figure 1: Representative data for Task 1 (A) and Task 2 (B). Data in the shaded rectangles is used for computing the synergy index. Across-subject mean±SE of the synergy index (C).

RESULTS AND DISCUSSION

The total force, F_T, in the 4 s window for Task 1 (Fig. 1A) shows fluctuations about the 10% MVC target. In contrast, F_T in the 4 s window for Tasks 2 and 3 (Fig. 1B) contain an initial period when force trajectories converge to the 10% MVC target from different previous states. So ΔV_Z for Task 1 displays a near-constant value, but ΔV_Z for Tasks 2 and 3 show a period (up to ~0.3 s) of covariation that achieves F_T convergence to 10% MVC ($\Delta V_Z<0.549$; Fig. 1C). Then, ΔV_Z gradually increases reflecting an increasing tendency to stabilize F_T. The key observation is that ΔV_Z values for the slow and fast dexterous tasks (Tasks 2 and 3) always remain lower than those for the stable task (Task 1).

The ANOVA revealed a significant effect of *Task Type* [$F_{(2,48)}=13.794$; $p<0.01$]. Pair-wise comparisons revealed $\Delta V_{Z\text{stable}}$ (2.55 ± 0.07) > $\Delta V_{Z\text{slow-dexterous}}$ (2.29 ± 0.08), and $\Delta V_{Z\text{stable}}$ > $\Delta V_{Z\text{fast-dexterous}}$ (2.21 ± 0.07). There was also a significant *Phase* effect [$F_{(1,24)}=21.953$; $p<0.01$]. Pair-wise comparisons revealed $\Delta V_{Z\text{Phase-1}}$ (2.29 ± 0.06) < $\Delta V_{Z\text{Phase-2}}$ (2.41 ± 0.06). The interaction was close to significant [$F_{(2,48)}=2.981$; $p=0.06$], and it suggested that the increase in ΔV_Z across the phases tends to be slower for fast dexterous task compared to the other two tasks.

Our first hypothesis was supported by the data. The stability associated with the constant F_T is reduced (~12%) when subjects expect to produce force changes of unknown direction and magnitude at an unknown time in the near future. Although the drop in ΔV_Z was similar for Tasks 2 and 3, it tended to last longer for Task 3 (near-significant *Task* × *Phase* interaction). These ΔV_Z changes are anticipatory synergy adjustments, but with two prominent differences: (1) they lasts over 8 times longer than the previously reported (~300 ms), and (2) we show limited destabilization that facilitates movement if and when required. In contrast, earlier work reports progressive destabilization of the current state that is necessarily followed by a state change in *self-paced actions* that do not involve uncertainty [2]. The relation between stability modulation and task performance remains to be established in our study. However, this is the first demonstration of task-specific stability reduction in hand function, and our results have implications for the understanding and the clinical assessment of manual dexterity.

REFERENCES

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