THE CONTINUUM OF MIXTURES OF FEEDBACK AND FEEDFORWARD CONTROL STRATEGIES USED IN DYNAMICAL DEXTEROUS MANIPULATION CAN BE EXPLORED AT THE BOUNDARY OF INSTABILITY

[1]Madhusudhan Venkadesan*, [1]Stephanie Roach, [2]John M. Guckenheimer and [1]Francisco J. Valero-Cuevas
[1]Department of Mechanical & Aerospace Engineering, [2]Department of Mathematics, Cornell University, Ithaca, NY, U.S.A.
*email: mv72@cornell.edu, web: www.mae.cornell.edu/nmbl

INTRODUCTION

Characterizing the roles of feedback and feedforward control, during any motor behavior is essential, albeit challenging, to further our understanding of the human sensorimotor system. The repertoire of control methodologies used by the sensorimotor system to accomplish any task can be classified as (i) passive mechanics (e.g., soft contact of finger pulp, etc) (ii) feedforward control (e.g., high stiffness, internal model, etc.), or (iii) feedback control (e.g., visual, tactile, etc.). The sensorimotor system may use any control strategy chosen from a continuum of mixtures of the above methodologies. Additionally, activities of daily living often necessitate active and dynamic regulation of fingertip position and forces to stabilize objects (e.g., rolling a pen)[1]. Our past studies [2] have suggested that nonlinear dynamical analysis of a neuromuscular system at the boundary of instability is a powerful paradigm for understanding complex dynamical sensorimotor behavior. In this study, we extend our past work to explore the continuum of control strategies used by the sensorimotor system during dynamical dexterous manipulation by exploiting the dependence of its behavior at the boundary of instability on the specific composition of the control strategy.

METHODS

As in our previous work [2], 13 consenting unimpaired subjects (25±2 yrs, 8 males) used their thumbpad to compress and hold at maximum possible compression, a slender spring (D=8.7mm,d=0.787mm,N=24,L_0=76mm) prone to buckling while we recorded 3D position/orientation of the spring's endcap and vertical compressive spring force (Fig 1). Audio feedback was provided as a tone of diminishing volume for increasing vertical load. The goal was to maximize vertical compressive load, i.e., minimize the volume of the audio feedback. The protocol consisted of 2 days: Day1 – "testing" before and after 110 trials of practice; Day2 – "testing" before and after a digital nerve block of the thumb (1% Lidocaine at the base of proximal phalanx, blocking the digital nerve branches of the median and radial nerves). A "test" is defined as at least 3 satisfactory compressions (a steady hold within 90% of the maximal load ever reached by the subject). The response variable used for all analyses presented here is μ_S (Fig 1). Mixed-model ANOVA using contrasts for post-hoc tests were used to test for differences in μ_S with changes in tactile feedback and learning. Maximal static key and opposition pinch strength were also recorded in all subjects.

RESULTS AND DISCUSSION

The value of μ_S after practice on Day 1 was 305gm ± 4.8%. The mixed-model ANOVA results show a significant drop due to loss of tactile feedback (23gm, p<0.0001) and a significant, but smaller rise due to learning (11gm, p=0.0086) in μ_S that carried over to the next day. The deficit in μ_S after the nerve block quantifies and characterizes the role of tactile feedback. The performance after the nerve block by itself, characterizes the combined contribution of other sensory feedback (e.g. visual), feedforward control and passive mechanics.

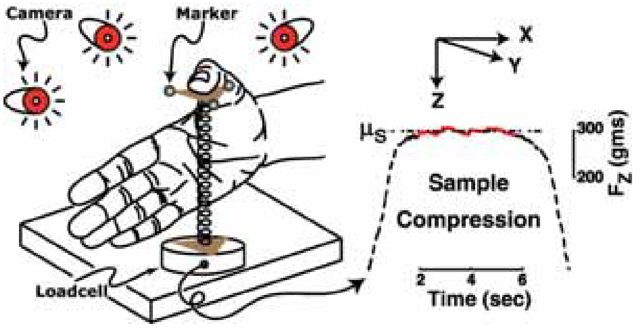

Figure 1: Schematic of the experiment. The unused digits were restrained against a vertical post and the arm using a vacuum pillow (not shown). μ_S is the mean sustained vertical load (F_Z).

With tactile feedback, μ_S was strength independent (R^2=0.01,p=0.81;[2]), but without tactile feedback, μ_S was not strength independent (R^2=0.64,p=0.02). Together with the previous result, this strongly indicates that without tactile feedback, a high stiffness strategy (feedforward) dominates, with little contribution from vision or passive mechanics. Interestingly, we observe that stiffening is not the best strategy when tactile (short latency) feedback is available.

CONCLUSIONS

The sensorimotor system has a different behavior at the boundary of instability for every distinct condition of sensory feedback or quality of feedforward control used (i.e., learning), as seen above. Hence, we can quantify and characterize the contributions of the feedback, feedforward and passive components at the boundary of instability. The set of control strategies available to the sensorimotor system is a continuum of mixtures of feedback and feedforward strategies. Each member of this continuum of control strategies causes a different type of instability. This feature of our paradigm that maps different controller compositions to different behavior at the boundary of instability facilitates the exploration of the continuum of control strategies used during dynamical dexterous manipulation. This can be extended to sensorimotor behavior in general using an appropriate dynamical task.

REFERENCES

1. Valero-Cuevas FJ, et al. *J Biomech* **36**, 265-270, 2003.
2. Venkadesan M, et al. *Adv in Comp Motor Control II. Symposium at the 33th Annual Meeting of the Soc for Neurosci*, New Orleans, LA, 2003.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0237258 (CAREER award) to F.J.Valero-Cuevas