Manipulating Bullwhip – Simple Control of a Complex Object?

Aleksei Krotov[a], Reza Sharif Razavian[b,c], Marta Russo[b,c], Mahdiar Edraki[d], Moses C. Nah[f], Neville Hogan[g], and Dagmar Sternad[b,c,e]

Departments of [a]Bioengineering, [b]Biology, [c]Electrical and Computer Engineering, Mechanical Engineering[d], and Physics[e], Northeastern University, Boston MA. [f]Department of Mechanical Engineering, [g]Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, MA

krotov.a@northeastern.edu, r.sharifrazavian@northeastern.edu, edraki.m@northeastern.edu, marta.russo.phd@gmail.com mosesnah@mit.edu, neville@mit.edu, d.sternad@northeastern.edu

Introduction

Daily life is full of dexterous skills that include interactions with objects that have complex dynamics, such as spreading a tablecloth or tying shoelaces. Examples also abound in the animal world, as seen in birds eating a worm or beavers making a lodge with sticks. To date, most research on human motor control has examined simple movements, such as reaching to a target or transporting solid objects, that facilitate data recording and analysis and ensure scientific rigor. Many of these studies suggested that motor control relies on internal models of the body and the world, although the structure of such models has not yet been resolved. When manipulating real-world objects, ubiquitous in any form of tool use, such internal models necessarily become high-dimensional and nonlinear. This raises the question how humans and animals manage this computational challenge. This study aims to identify strategies that human and animals may use to successfully manage such seemingly daunting tasks.

To embrace the full complexity of object interactions, we examined humans manipulating a bullwhip to hit a target, i.e., controlling an object with nonlinear dynamics and infinitely many degrees of freedom [1-5]. Assuming that humans learn a detailed model of the infinitely-dimensional whip seems implausible. Therefore, we conjectured that humans learn strategies that create simpler dynamics and exploit the passive dynamics of the whip.

To gain insight into such strategies, we considered two one-dimensional models where the whip assumed simplified dynamics. The first model considered the whip straight and rotating, similar to swinging a pendulum's bob. The second model allowed the whip to unfold in a traveling wave-like fashion. We then compared the simulated whip motions with movements generated by humans. We hypothesized that humans choose one of the two strategies (rotation or unfolding), rather than controlling the entire whip dynamics.

Methods

Experiment. 16 volunteers used a 1.60m-long bullwhip to hit a target at ~2.2m distance (Fig.1). The thin end pieces, fall and cracker, were removed to facilitate recording. 12 participants had no prior whip-cracking experience and 4 participants had moderate experience. Each participant performed 5 blocks of 30 trials each (150 trials) in the two styles. In the rhythmic style, participants aimed to hit the target, but maintained a continuous action without letting the whip touch the floor between hits (Fig.1A). In the discrete style, participants executed a single attempt to hit the target, then returned the whip to the starting position on the floor in front of them (Fig.1B). The continuous kinematics of the human body, whip and target were recorded using 3D motion capture with a total of 33 reflective markers at 500 Hz sampling rate (Qualisys, Goetheborg, Sweden). This work only used data of 9 customized high-endurance markers on the whip, 1 at the distal part of the handle, 2 on the target, and 1 conventional marker at the hand.

Data Analysis. The continuous kinematic data were low-pass filtered and numerically differentiated. The continuous recordings of each block were parsed into individual trials at the moment when the whip passed closest to the target (Fig.1). For each trial the interval of whip flight was defined as follows: it started when the handle marker reached peak speed; the end was marked when the whip was the closest to the target. The speed profiles of the 9 whip markers during whip flight were used to examine the whip motion. These profiles were time-normalized and averaged across trials for each style and participant.

Simulations of Whip Dynamics. Two models were formulated to generate the whip motion consistent with the two strategies. The first model described a rod rotating about a fixed handle in the sagittal plane (exposed to gravity). This model was based on the angular momentum balance: $\ddot{\varphi} = -(mg / I)\cos\varphi$, where φ is the angle with respect to the horizontal plane, m = 0.33 kg and I = 0.145 kgm^2 are mass and moment of inertia of the rod. The initial conditions were set to $\varphi(0) = \pi / 12$ rad and $\dot{\varphi}(0) = 16$ rad/s, consistent with the observed whip inclination and the peak tangential speed

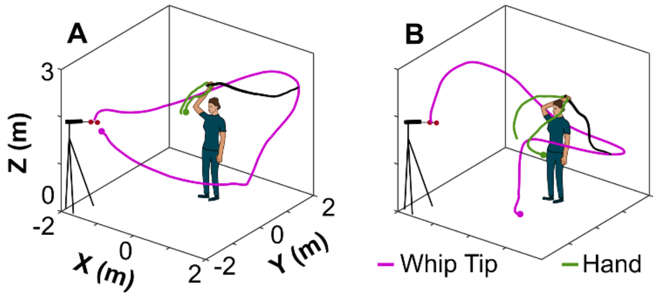

Figure 1: Hitting a target with a bullwhip. **A:** Exemplary trajectories of whip (pink) and hand (green) during a rhythmic trial. **B:** Exemplary trajectories of whip and hand in a discrete trial.

of the handle marker (~10 m/s). The model simulated the rotation of the rod until it became planar (Fig.2A).

The second model used the linear momentum balance to generate the unfolding of a horizontal string (without gravity), where each element stopped instantaneously once it had unfolded (Fig.2B). This model included a tapering cross-section consistent with the tapering of the real whip (linear decrease from 13 to 6 mm radius at the tip). The governing equation was: $\ddot{x} = (1/(L-x) - \rho'/\rho)\cdot\dot{x}^2$, where L =1.6 m is the length of the string, x is the length of unfolded part, ρ is the linear density, and $\rho' = d\rho/dx$. The initial conditions were set to $x(0) = 0$ m, $\dot{x}(0) = 5$ m/s, the latter corresponding to the rate of increase of the resting part, or half of the speed of the moving part. This model simulated the string movement until it unfolded.

Results

All participants performed the task hitting the target in 5-60% of trials in each block. Each participant demonstrated repeatable patterns of the whip kinematics, as shown in representative speed profiles in Fig.2C. The figure shows the temporal evolution of each marker speeds (each marker has one color).

The simulated whip rotation from model 1 yielded proportional speed profiles of all markers that only varied slightly due to gravity (Fig.2A). The simulated whip unfolding of model 2 displayed equal but rapidly accelerating speeds of all markers until one after the other came to an instantaneous stop (Fig.2B).

The patterns of both simple models resulted in experimentally plausible patterns of speed values and total times of rotation or unfolding. Qualitative comparison of the human performance in the two styles with the simulated whip models showed that in the rhythmic style, all participants chose to manipulate the whip in a way that resembled unfolding as shown in the leftmost panel of Fig.2C. However, in the discrete style, the whip patterns were more diverse resembling either of the three patterns shown in Fig.2C. In 7 participants' data the whip best matched the unfolding pattern, while 9 participants moved the whip more in a rotation-like manner.

Discussion

To study human control of complex objects, we explored the exotic task of manipulating a bullwhip to hit a target. We hypothesized that humans adopt a control strategy that reduces the complexity of the whip dynamics. To test this hypothesis, we used two one-dimensional models that simplified the dynamics to either a rotation of the whip about the handle or a flexible wave-like unfolding of the whip. We posited that these two strategies afford a reduction of dimensionality in the object and humans exploit this passive dynamics in their movement strategies.

First qualitative comparisons of the two models with the data were promising. However, our results in the discrete style also indicated that rotation and unfolding might not be the only possible dynamics of the whip. In some participants, neither of these two patterns seemed to sufficiently match their behavior. As additional analyses revealed, this mismatch was

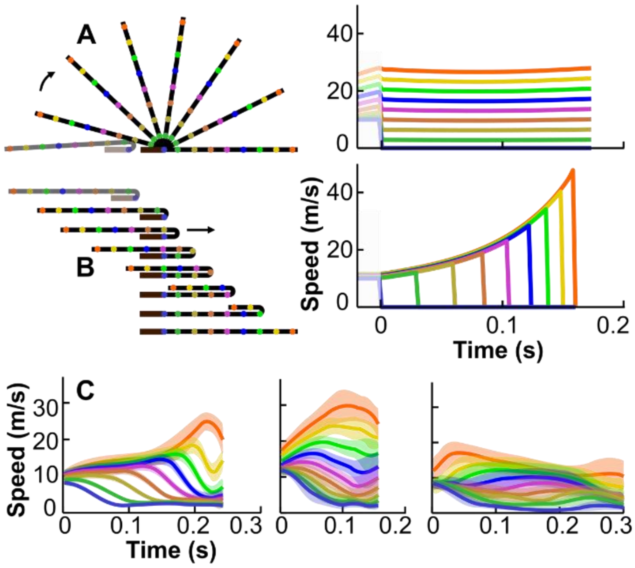

Figure 2: Simulated whip movement and speeds of whip markers. **A**: Simulation of a rod rotating about the handle. **B:** Simulation of a string unfolding with respect to the handle. Seven strobes of the whip were taken at equal time intervals to illustrate the models and the corresponding marker positions. The curve in the whip was added for illustration. **C:** Representative averaged-within-participant speed profiles of whip markers observed in the experiment. Shading is one standard deviation away from mean.

not correlated with the skill in performance. More insights may be gained from quantifying or combining features of both patterns in a model.

To conclude, the presented research aimed to unravel mechanisms underlying the complex behavior in interaction with the environment seen across the animal and human world. This presents a significant step beyond the typical laboratory tasks that explicitly reduce the variety and dimensionality of movements to afford precise modeling and insight. However, it is uncear whether insights gained also transfer to more complex behavior. Our approach used simplified models to identify possible control strategies. Specifically, this work aimed to show how the infinitely-dimensional whip may give rise to relatively simple passive dynamics that may be exploited in control strategies.

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