Flexible Control of Flexible Objects. Focus on “An Experimentally Confirmed Mathematical Model for Human Control of a Non-Rigid Object”

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Many goals of human motor behavior, such as reaching out to hold a child’s hand, specify the end point of movement but do not constrain the movement made between initial posture and final target. In this issue, Dingwell et al., pp. 1158–1170, write about a newly discovered normal human behavior that challenges a classic hypothesis that people plan such movements to optimize hand-trajectory smoothness. Their results suggest that when interacting with certain non-rigid (flexible) objects, people generate movements that sacrifice hand smoothness to optimally control the object.

Extensive experimental and computational research has shown that normal human adults generate arm movements that smoothly connect the start and end of movement (Desmurget et al. 1998; Morasso 1981; Wolpert and Ghahramani 2000). Whereas unsmooth movements feature unnecessary accelerations and decelerations, optimally smooth movements feature a speed profile that is unimodal in its single acceleration phase followed by a single deceleration phase. This behavior is consistent with motor planning that attempts to minimize high temporal derivatives of the hand path; a prominent theory posits that people indeed plan movements to minimize jerk, the third time derivative of position (Flash and Hogan 1985; Hogan 1984). Competing theories suggest human motor planning optimizes the smoothness of other movement features, such as muscle force (Soechting and Flanders 1998) or joint torque (Uno et al. 1989); still other theories suggest that people aim to optimize not their average behavior, but the variance of their behavior around the desired goals of movement (Harris and Wolpert 1998; Todorov and Jordan 2002). The goal of all of these theories is to identify the fundamental computational strategies underlying motor planning. Although trajectories predicted by these hypotheses vary in their curvature, all extant hypotheses are consistent with the unimodal speed profile generated by people reaching with their free arm.

In our daily lives, however, people make movements while holding many different objects with many different dynamic properties. While smooth trajectories characterize normal movement of the unencumbered arm, the additional dynamic demands of manipulated objects could alter the stereotypy of human behavior. Dingwell et al. have indeed identified a movement task, interacting with an unusual object, in which people generate trajectories very unlike standard minimum jerk behavior. Human subjects in this new study grasped a robotic manipulandum and watched visual feedback that together simulated a mass attached to the robot handle by a spring. The goal of the task was to make point-to-point movements such that both cursors, representing hand and mass positions, come to rest within the target. Subjects learned to successfully complete this task. At certain movement durations and with certain simulated masses and springs, people generated unimodal speed profiles reminiscent of minimum jerk trajectories. At other durations and with other masses and springs, however, most subjects generated speed profiles that were clearly bimodal with two prominent peaks of speed. The authors hypothesized that although this behavior clearly fails to optimize hand-trajectory smoothness, subjects instead generate hand movements that optimize object-trajectory smoothness.

Dingwell et al. demonstrated the mathematical impossibility of simultaneously moving the mass in a traditional minimum jerk trajectory and bringing both mass and hand to rest together at the target, so the authors instead derived trajectories that minimize crackle, the fifth time derivative of mass position. These derived trajectories fit human behavior quite well and specifically mimicked not only the emergence of bimodal speed profiles but also the transitional movement durations and object dynamics at which bimodality appears. These findings indicate that when motor tasks involve manipulated objects with complex dynamics, emergent human behavior can still feature optimally smooth trajectories but with optimal performance transferred from the hand to the object.

A particularly surprising aspect of these results is that people seemed to optimize object smoothness, but the task provided feedback on both hand and object and required subjects to control both hand and object simultaneously. A reasonable hypothesis might be that given the dual demands of the task, people would discover trajectories that were quite smooth for both hand and object, but instead people sacrificed the smoothness of their own hand for that of the controlled object. Further research is needed to determine why the novel object seemingly overtook the hand in importance for informing the emergent behavior.

These results form an important extension and refinement of descriptive models of human motor control. Dingwell et al. clearly identify a principle of “optimally smooth (object) transport” that characterizes smooth movement of the hand in free movement tasks and smooth movement of the mass in this novel task. This descriptive model, however, does not indicate that human motor planning aims to optimize object smoothness. Models have suggested that due to the computational structure of the neural systems learning novel dynamics, asymptotic behavior may deviate somewhat from desired behavior (Thoroughman and Shadmehr 2000). Even if asymptotic behavior mimics desired movements, several alternate hypotheses, such as minimization of torque change or movement variance, could also predict observed movement of the mass-spring system. Additional experiments, altering the encoun-

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tered dynamics and the task goals, may elucidate the underly-
ing computational principles generating stereotypical behavior.
On its own, however, this work constitutes a uniquely useful result in its identification of behaviors that deviate from traditionally understood trajectories and yet reaffirm the foundational hypothesis that movement smoothness is a central organizing principle of human motor control. The paper by Dingwell et al. is an important first step toward understanding how, across our behavioral repertoire, people generate normal movement and formulate underlying computational strategies.

REFERENCES


