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Online kinematic regulation by visual feedback for grasp versus transport during reach-to-pinch

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ABSTRACT

Purpose: This study investigated novel kinematic performance parameters to understand regulation by visual feedback (VF) of the reaching hand on the grasp and transport components during the reach-to-pinch maneuver. Conventional metrics often signify discrete movement features to postulate sensory-based control effects (e.g., time for maximum velocity to signify feedback delay). The presented metrics of this study were devised to characterize relative vision-based control of the sub-movements across the *entire* maneuver.

Methods: Movement performance was assessed according to reduced variability and increased efficiency of kinematic trajectories. Variability was calculated as the standard deviation about the observed mean trajectory for a given subject and VF condition across kinematic derivatives for sub-movements of inter-pad grasp (distance between thumb and index finger-pads; relative orientation of finger-pads) and transport (distance traversed by wrist). A Markov analysis then examined the probabilistic effect of VF on which movement component exhibited higher variability over phases of the complete maneuver. Jerk-based metrics of smoothness (minimal jerk) and energy (integrated jerk-squared) were applied to indicate total movement efficiency with VF.

Results/discussion: The reductions in grasp variability metrics with VF were significantly greater ($p < .05$) compared to transport for velocity, acceleration, and jerk, suggesting separate control pathways for each component. The Markov analysis indicated that VF preferentially regulates grasp over transport when continuous control is modeled probabilistically during the movement. Efficiency

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measures demonstrated VF to be more integral for early motor planning of grasp than transport in producing greater increases in smoothness and trajectory adjustments (i.e., jerk-energy) early compared to late in the movement cycle.

Conclusions: These findings demonstrate the greater regulation by VF on kinematic performance of grasp compared to transport and how particular features of this relativistic control occur continually over the maneuver. Utilizing the advanced performance metrics presented in this study facilitated characterization of VF effects continuously across the entire movement in corroborating the notion of separate control pathways for each component.

1. Introduction

The reach-to-grasp maneuver is commonly performed during activities of daily living. It requires coordination between the reaching hand and the involved grasping digits relative to the target object (Jeannerod, 1981). For manipulation of smaller objects following reach, it is precision pinch grasp between the thumb and index finger that is utilized (Dubrowski, Bock, Carnahan, & Jungling, 2002). The composite reach-to-pinch function includes both global transport of the entire hand towards the object along with the opening and closing of the grasping digits upon the object. While the individual grasp and transport motion components are distinctly apparent, they are integrated into a single movement function (Coats, Bingham, & Mon-Williams, 2008). There is debate as to what extent these individual components are independently regulated (Jeannerod, 1984) versus the existence of more holistic control (Castiello, Bennett, & Chambers, 1998). Typically, assessments about presumed control structures were made according to discrete timing and kinematic features of the movements (e.g., time/amplitude of peak velocity, phase onset times, movement duration). While valid, these metrics only describe distinct cumulative features of the sensory-affected movement, such as feedback delays, but they do not necessarily indicate how control of kinematic performance is continuously regulated across the entire movement. Relative kinematic performance of these sub-movements under controlled provision of sensory feedback using metrics indicative of the continuous and whole-movement performance can serve to better indicate online sensory regulation by either singular versus separate control pathways.

The role of visual feedback has been extensively studied in reach-to-grasp performance to understand the interplay between the reach and grasp components, including effects of direction-dependence (Rossetti, Desmurget, & Prablanc, 1995; van Beers, Sittig, & Gon, 1999), integration with proprioception (Scheidt, Conditt, Secco, & Mussa-Ivaldi, 2005), and selective visual perturbation of the target (Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991). These and other previous studies examining visual feedback have typically reported how kinematic hallmarks of the sub-movements are synchronized as evidence of mutual coordination. For example, it has been established that initiation of grasp closure is typically correlated with the onset of the deceleration phase of transport (Jeannerod, 1984). Additionally, discrete changes in several transport and grasp component kinematic parameters can occur according to the level of visual feedback during the early phase of movement (Fukui & Inui, 2006). Models have also been developed to demonstrate stereotypical kinematic features of reach-to-grasp to postulate their mode of control. These models include those coupling grip aperture and transport velocity (Hu, Osu, Okada, Goodale, & Kawato, 2005), describing the temporal coordination of reach and grasp under optimal hand positioning (Hoff & Arbib, 1993), and quantifying the contributions of vision and proprioception in position estimation for motor planning (Sober & Sabes, 2003). As such, assessing the dependence of readily evident kinematic parameters has provided insight into fundamental operating principles governing reach-to-pinch function. While vision-based paradigms have proven reliable in