Handedness in a virtual haptic environment: Assessments from kinematic behavior and modeling

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ARTICLE INFO

ABSTRACT

This study evaluated hand asymmetries in performance of a dexterous, controlled task under haptic feedback. Participants punctured a virtual membrane with a pushing or pulling movement, using the left or right hand. For pulling movements, the dominant (right) hand exhibited faster average stopping latency and shorter skidding distance. When the kinematic data were fit to a three-phase model previously applied to this task (Klatzky et al., 2013), the right hand exhibited faster force decay attributable to biomechanical factors. Analyses of the aggregated performance measures and model parameters showed that the left and right hands are associated with two different distributions, supporting handedness effects. Furthermore, while the majority of participants expressed right-hand dominance, which was consistent with their self-reported hand preferences, others showed partial or no dominance. This approach could potentially be extended to quantify and differentiate individuals with difficulties in manual behavior due to abnormal motor control (e.g., dyspraxia), progressive deterioration (e.g., Parkinson's syndrome) or improvement (neural regrowth after transplant).

1. Introduction

The motor behavior and dexterity of the human hands are well known to be asymmetrical. The term *handedness* refers to differential capabilities and use of the left and right hands while performing different types of manual tasks (Hammond, 2002). Handedness is usually evaluated in terms of preference (self-reporting questionnaires); in addition, tasks such as tapping, reaching, aiming, finger sequencing, or peg moving may be used to compare the relative performance of the hands (Bernard, Taylor, & Seidler, 2011; Borod, Caron, & Koff, 1984; Hoffmann, 1997; Mutha, Haaland, & Sainburg, 2013).

Although the lay interpretation of handedness is that the dominant hand is superior in virtually any manual task, there is a substantial body of research showing that the asymmetry in hand performance is in fact task-dependent (Bagesteiro & Sainburg, 2002; Borod et al., 1984; Flowers, 1975; Garonzik, 1989; Hoffmann, 1997; Sainburg, 2002; Serrien, Ivry, & Swinnen, 2006; Watson & Kimura, 1989). For example, Flowers (1975) found that participants with clear hand preference exhibit a significant advantage for the dominant hand in performance on a visually controlled aiming task (closed loop), but not in a rhythmic tapping task that is ballistic (open loop). These results led Flowers and others to postulate that dexterity differences between the

hands arise from initiating motor commands in response to afferent input, but not in the efferent output itself, thus sparing ballistic tasks. However, although some studies support these findings (e.g., Hoffmann, 1997), other attempts to differentiate hand dominance based on performance in open and closed loop tasks have yielded conflicting results (Carson, Chua, Elliott, & Goodman, 1990; Carson, Goodman, & Elliott, 1992; Roy & Elliott, 1986).

Handedness is complex not only with respect to task specificity, but in terms of the neural mechanisms that produce it. The most general model assumes that the brain differentiates control of the left and right hands, that there is an asymmetry in this control, and that this asymmetry is perpetuated through the motor-control system. The differential control is complex, however, violating any simple assumptions about the asymmetry being dichotomized by the left and right hemispheres of the brain. While the descending motor pathways of the corticospinal tracts cross, so that each hand is controlled by its contralateral hemisphere, this is not enough to create handedness: What is needed is functional asymmetry in the hemispheres themselves, as has been demonstrated in M1, the premotor cortex, and supplementary motor areas (Bernard et al., 2011; Hammond, 2002; Mutha et al., 2013; Sainburg, 2002, 2010; Serrien et al., 2006; Winstein & Pohl, 1995).

Control of the relative contributions of the hemispheres appears to be complex, however, and to vary with a number of task parameters, including extent of reliance on feedback and locus of task demands (e.g., response selection vs. execution, or specific response components

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such as trajectory control vs. endpoint placement). Considering the first of these, reliance on feedback, the studies cited above provide behavioral evidence for and against the idea that feedback-dependent tasks are more likely to show handedness. This controversy is also reflected in neuroscience studies of hemispheric control. One hypothesis is that in goal-directed reaching tasks, the left hemisphere controls the open-loop aspects of the movement and therefore mainly relies on pre-planning, whereas the right hemisphere controls the aspects of a task that depend on sensory feedback (Sainburg, 2002). However, while some research supports this hypothesis (Haaland & Harrington, 1994; Winstein & Pohl, 1995) other studies yield results that contradict this feedback-based dichotomy (Haaland, Prestopnik, Knight, & Lee, 2004). Mieschke, Elliott, Helsen, Carson, and Coull (2001), for example, found right-hand superiority in movement execution, particularly late corrections, implicating the left hemisphere in closed-loop control. In contrast, the same study showed a left hand advantage for planning aiming movements to specified targets.

Modulation of cerebral asymmetry by task demands is another prevalent hypothesis. For example, it has been suggested that the left hemisphere specializes in controlling the movement trajectory, whereas the right hemisphere controls limb position and posture (Mutha et al., 2013; Sainburg, 2002). An alternative view (Serrien et al., 2006) is that the contribution of each hemisphere in controlling task movement is dynamically influenced by movement complexity, with more complex movements employing more distributed neuronal networks, often from both hemispheres via communication across the corpus callosum. The left hemisphere is especially implicated in planning complex sequential acts with notable response selection, preparation and/or retrieval components.

As indicated above, a substantial amount of research on handedness and motor control has been conducted using tasks such as tapping, reaching, and aiming, which rely on visual feedback. However, little is known about whether handedness emerges on complex tasks performed without vision. Here the sensory function of the hands is critical, and the lateralized pathways to the cerebral hemispheres contribute to asymmetries in hand function. Rather than examining manual dexterity, Tomlinson, Davis, Morgan, and Bracewell (2011) used a haptic object-discrimination task where the discriminating feature was either center of mass or surface texture, and the object was explored only with a pinching grasp and lift. An advantage was found for the dominant hand in the mass judgment, but it is not clear whether these results reflect motor control or a sensory advantage.

Hemispheric specialization has also been used to account for better performance with the non-dominant hand in non-visual tasks. Witelson (1974) found this to be the case in haptic-to-visual matching of unfamiliar shapes, but not letters, presumably reflecting right-hemisphere superiority in shape matching. Roy and MacKenzie (1978) used a kinesthetic task, moving either the thumb or arm to a remembered position. Note that the thumb is controlled almost completely by the contralateral hemisphere, whereas the arm has bilateral representation. Only the thumb showed a hand difference, again favoring the non-dominant hand.

In the current paper, we present an evaluation of handedness when performing a dexterous task that requires high precision and relies entirely on haptic feedback. The task is puncturing a virtual surface with a pulling or pushing movement, a controlled, spatially directed action where force constraints are of critical concern. Using the same simulation, Klatzky et al. (2013) developed a three-phase model to account for the kinematics of puncture. The present study extends the model to identify and functionally localize handedness effects to a particular stage of motor control.

The model of Klatzky et al. (2013) partitions the behavior of the hand after puncture into three phases that proceed from physically determined interactions, through decline of force due to biomechanical viscosity, to voluntary control. The first phase of the model represents the component of the hand movement that is directed by pure physics as the hand breaks through the membrane. It is parameterized by the
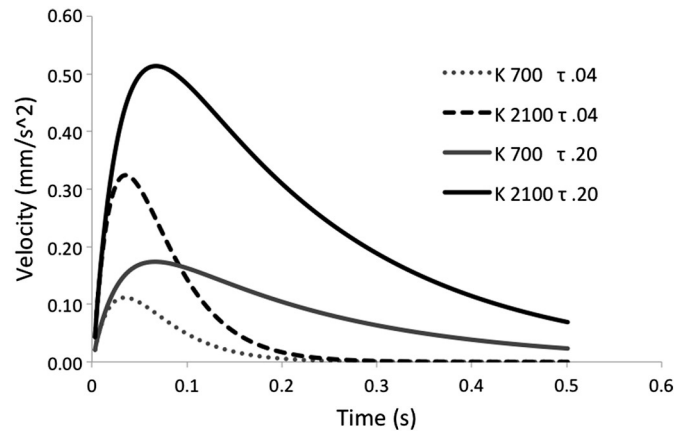

Fig. 1. Model behavior (velocity/time relation) under varying parameters of stiffness (K) and exponential time constant (τ).

mass of the hand/device coupling, which, in combination with the simulation-determined membrane parameters and instantaneous velocity, determines the force at breakthrough and hence the subsequent acceleration. The second phase of the model represents the exponential decay of force due to biomechanical damping arising from the viscous nature of the muscles and soft tissue under relaxation (e.g., Fung, 1967; Kisiel-Sajewica, Jaskolski, & Jaskolska, 2005; Sarver, Robinson, & Elliott, 2003); it is parameterized by the time-characteristic of the exponential function (τ). The third phase of the model represents the voluntary control of braking, which is parameterized by the time of deviation of the hand position from predictions of the force-decay function. Effects of membrane stiffness (K) and τ are shown in Fig. 1.

Our previous study with this simulation indicated that the ability of healthy participants to control their right hand movement was influenced by the direction of the movement, even when all other aspects of the task were kept the same. The control over the hand movement was greater when pulling compared to pushing through the same membrane. These differences were reflected in a shorter stopping distance, faster stopping time and earlier active braking while pulling (Klatzky et al., 2013). The observed effects of movement direction (pull vs. push) are consistent with other work that has analyzed the motor control of these hand movements in detail (Di Domizio & Keir, 2010; Seo, Armstrong, & Young, 2010). Di Dimizio and Keir found, for example, that engagement of pull while gripping affected all the forearm muscle groups, whereas pushing affected the extensor muscles in particular; wrist extension was also a differentiating factor. An important result for present purposes was that pushing generated greater unintended forces orthogonal to the intended direction of movement, which is

Fig. 2. Magnetic levitation haptic device (right hand operation).