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# Unintentional movements induced by sequential transient perturbations in a multi-joint positional task

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ABSTRACT

We explored the phenomenon of unintentional movements of a multi-joint effector produced by multiple transient changes in the external force. The subjects performed a position-holding task against a constant bias force produced by a robot and were instructed not to intervene voluntarily with arm movements produced by changes in the robot force. The robot produced a smooth force increase leading to hand movement from the trunk, followed by a dwell time. Then, the force dropped to its initial value leading to hand movement toward the initial position but with an undershot. Such perturbation episodes were repeated four times in a row. The accumulated perturbation and undershoot distances kept increasing without saturation within the sequence of four perturbation episode. The limb apparent stiffness before dwell time increased over sequential perturbations while apparent stiffness after dwell time decreased. We interpret the results as consequences of a drift of the hand referent coordinate (RC) caused by a hypothesized RC-back-coupling mechanism and a coupled drift of the apparent stiffness. The results show that RC-back-coupling continues to lead to unintentional movements over repeated perturbations and is accompanied by a relatively slow re-setting process.



## 1. Introduction

The hypothesis of movement control with referent body coordinates (RC-hypothesis, Feldman, 2009, 2015) assumes that the central nervous system (CNS) uses neural variables that translate into referent spatial values for a few task-specific salient variables ($RC_{TASK}$). Further, these values result in referent length values for all the muscles of the body corresponding to a body configuration at which all the muscles would be at the threshold of activation via the stretch reflex. Typically, this body configuration is not achievable due to external and anatomical constraints, and the body comes to a state with non-zero muscle activations and forces exerted on the environment.

According to the RC-hypothesis, transient perturbations are not expected to lead to discrepancy between the initial equilibrium state and the final state assuming that the person does not change neural commands during the application and removal of the perturbation. This phenomenon has been addressed as equifinality. Indeed, equifinality has been documented in several studies (Bizzi, Polit, & Morasso, 1976; Kelso & Holt, 1980; Latash & Gottlieb, 1990; Schmidt & McGown, 1980). A number of studies, however, reported violations of equifinality during movements performed in unusual situation, such as rotation in the centrifuge or moving in an artificial force field with negative damping (Dizio & Lackner, 1995;

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Hinder & Milner, 2003; Lackner & DiZio, 1994). These results have been interpreted as reflecting unintentional changes in the neural control signals, i.e., in $RC_{TASK}$ (Feldman & Latash, 2005).

Recent studies (Zhou, Solnik, Wu, & Latash, 2014; Zhou, Zhang, & Latash, 2015b) reported violation of equifinality during multi-joint positional tasks under long-lasting transient perturbations and the "do not intervene voluntarily" instruction. When a force change (perturbation) was applied and then removed, the hand stopped short of the initial position if there was a dwell time between the perturbation application and removal. These violations of equifinality have been interpreted as unintentional movements (Zhou et al., 2015b): Indeed, in the initial and final states, the external force was the same but the limb was in a different position. Somewhat similar phenomena of hysteresis were reported earlier (Feldman, 1979; Gottlieb & Agarwal, 1988; see also Archambault, Mihaltchev, Levin, & Feldman, 2005) in studies of joint reactions to loading–unloading sequences. These effects were, however, relatively small in magnitude and were observed in experiments without a dwell time between the loading and unloading phases.

Unintentional movements have been discussed as examples of a process referred to as RC-back-coupling (cf., Ambike, Paclet, Zatsiorsky, & Latash, 2014; Ambike, Zatsiorsky, & Latash, 2015; Reschechtko, Zatsiorsky, & Latash, 2014). According to this idea, even when the subject tries not to react to external force change, a drift in $RC_{TASK}$ towards actual values of the salient variables is triggered by a perturbation. The drift has been modeled as an exponential time process with the time constant of about 1 s (Zhou et al., 2015b).

The magnitude of violations of equifinality, the undershoot distance, seen under single transient perturbations (a perturbation is applied and removed only once) saturated with dwell times over 2 s (Zhou et al., 2015b). If another transient perturbation is applied following the first one, its consequences are expected to depend on ability of the system to re-set. If the hypothetical RC-back-coupling process has saturated, no further increase in the accumulated undershoot distance is expected (Hypothesis 1). We tested this hypothesis using sequences of four transient perturbations with the dwell times of 3 s within each sequence of force application and removal. Violations of equifinality were expected during the first episode of perturbation application-removal, while further transient perturbation episodes were not expected to lead to further drift in the hand position when the force returned to the bias magnitude.

An earlier study (Zhou, Zatsiorsky, & Latash, 2015a) has shown that the subjects co-adjust the apparent stiffness ($k$; see Latash & Zatsiorsky, 1993) of the limb with the RC drift to keep the hand motionless during the dwell time. Here we define $k$ as a scalar constant relating the hand force to the discrepancy between its actual and referent coordinates. In particular, the pre-dwell $k$ was smaller than the post-dwell $k$, which showed an exponential increase with the dwell time saturating in about 2 s. If no violations of equifinality are observed in response to perturbation episodes following the first one (as in Hypothesis 1), $k$ before and after those perturbation episodes should be the same (Hypothesis 2).

Another manipulation explored ability of the system to reset to the pre-perturbation state given different rest intervals between successive episodes of perturbation application-removal. We compared the responses to the second transient perturbation following the first one after the rest intervals of 3 s and 10 s. To avoid fatigue, only two perturbation episodes were used with the 10-s rest interval. This was an exploratory aim.

## 2. Methods

### 2.1. Participants

Eight self-reported right-handed male subjects took part in this study (age: 27.5 ± 0.8 years, height: 1.73 ± 0.07 m, and mass: 67.3 ± 5.4 kg; mean ± SE). All subjects were healthy and had no history of hand injury. All subjects provided informed consent in accordance with the procedures approved by the Office for Research Protection of the Pennsylvania State University.

### 2.2. Apparatus

The HapticMaster (Moog, The Netherlands), an admittance-controlled robot with an arm that possesses three degrees of freedom (DOFs), was used to apply external forces to a handle. The handle with three kinematic DOFs – pitch, roll and yaw – was attached to the end of the robot arm. The robot arm was used to generate both baseline force ($F_{BIAS}$) and perturbation force ($F_{PERT}$) (details in Section 2.3). During the experiment, subjects sat upright in the chair and held the handle attached to the robot arm with the right hand; gravity forces acting on the hand/arm were not compensated. Note that the robot was used in the force-control mode: It produced specified force changes, while the hand was free to stop at any position where its force balanced the robot force. The hand force changed during the robot-induced motion due to the well-known length dependence of muscle force due to both peripheral and reflex mechanisms. We performed two calibration procedures for the robot. One of them used the robot in a position-control mode and applied various external loads within the range used in our study. The other used the robot in the force-control mode, attached its handle to a spring and applied a baseline force of 20 N. Then the robot applied a transient 20 N perturbation with a dwell time (similar to those described later). In both cases, in the final state, the deviations of the robot handle from the initial state were on the order of 1–2 mm, which is an order of magnitude lower than the deviations observed in our study.