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Adaptive intermittent control: A computational model explaining motor intermittency observed in human behavior

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HIGHLIGHTS

- We proposed a computational model explaining human intermittent motor behavior.
- It segments the time axis to perform feed-forward control for continuous motor task.
- We compared behaviors of several different control models with human behavior.
- The proposed model replicated the human behavior with less computational costs.
- The functional meaning of motor intermittency is discussed.

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ABSTRACT

It is a fundamental question how our brain performs a given motor task in a real-time fashion with the slow sensorimotor system. Computational theory proposed an influential idea of feed-forward control, but it has mainly treated the case that the movement is ballistic (such as reaching) because the motor commands should be calculated in advance of movement execution. As a possible mechanism for operating feed-forward control in continuous motor tasks (such as target tracking), we propose a control model called "adaptive intermittent control" or "segmented control," that brain adaptively divides the continuous time axis into discrete segments and executes feed-forward control in each segment. The idea of intermittent control has been proposed in the fields of control theory, biological modeling and nonlinear dynamical system. Compared with these previous models, the key of the proposed model is that the system speculatively determines the segmentation based on the future prediction and its uncertainty. The result of computer simulation showed that the proposed model realized faithful visuo-manual tracking with realistic sensorimotor delays and with less computational costs (i.e., with fewer number of segments). Furthermore, it replicated "motor intermittency", that is, intermittent discontinuities commonly observed in human movement trajectories. We discuss that the temporally segmented control is an inevitable strategy for brain which has to achieve a given task with small computational (or cognitive) cost, using a slow control system in an uncertain variable environment, and the motor intermittency is the side-effect of this strategy.

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1. Introduction

Human sensorimotor system contains many delay/lag elements in the control loop, including sensory processing, neuronal transmission and muscle activation. It is a fundamental question how our brain achieves real-time motor control with this slow system. Computational theories have pointed out that feed-forward control with internal models is essential for overcoming this problem (Engel & Soechting, 2000; Kawato, 1999; Kawato & Wolpert, 1998; Wolpert & Miall, 1996; Wolpert, Miall, & Kawato, 1998). The validity of feed-forward control has been mainly discussed in the case of ballistic movements such as reaching, presumably because it assumes that motor commands be calculated before the movement onset. Nevertheless, feed-forward control must be indispensable also in continuous, environment-dependent motor tasks (such as target tracking) even though it requires motor planning for every motor action, because ordinary feedback control cannot effectively work with the large delay (Paul, 1981).

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In the present study, we propose a hypothetical control model called "adaptive intermittent control" or "segmented control" as a possible mechanism for operating feed-forward control in continuous motor tasks. The principle is that brain divides the time axis into discrete segments and executes feed-forward control in each segment. It is close to the scheme of model predictive control (MPC) proposed in the field of control theory (Maciejowski, 2002).

Most control models for sensorimotor functions (especially for continuous motor tasks) implicitly assume that the control system is stationary: They keep receiving sensory information and producing motor commands in a seamless manner. However, it seems more plausible that the motor control process in our brain is temporally organized: Different computational processes (e.g., model estimation, future prediction and motor planning) work in a temporally non-uniform manner dependent on the internal and external events (Sakaguchi, 2008). One example of control models realizing such a non-stationary control process is "intermittent control", which occasionally updates the control signals at certain sparse points in time (Karniel, 2013). This concept has been proposed in the fields of control theory, biological modeling and non-linear dynamical system. As a classical work, Craik (1947, 1948) discussed the intermittent nature of the behavior observed in human operators in the control system, and other researchers (Keele, 1968; Keele & Posner, 1968; Navas & Stark, 1968; Pew, 1966; Vince, 1948a, 1948b) have pointed out the intermittent mechanism of human motor control. As an example of recent studies, moreover, Gawthrop, Loram and their colleagues (Gawthrop, 2010; Gawthrop, Loram, Gollee, & Lakie, 2014; Gawthrop, Loram, Lakie, & Gollee, 2011; Gawthrop & Wang, 2006, 2009, 2010, 2011; Gollee, Mamma, Loram, & Gawthrop, 2012; Lakie & Loram, 2006; Loram, Gawthrop, & Lakie, 2006; Loram, Gollee, Lakie, & Gawthrop, 2011; Loram, van de Kamp, Gollee, & Gawthrop, 2012; Ronco, Arsan, & Gawthrop, 1999; van de Kamp, Gawthrop, Gollee, & Loram, 2013; Vieira, Loram, Muceli, Merletti, & Farina, 2012) have published a series of works proposing the intermittent control model from a viewpoint of control theory, and examined its validity from a viewpoint of biological modeling. Specifically, Gawthrop and Wang (2011) proposed a model based on model predictive control that updated motor commands only intermittently ("i.e., intermittent MPC"). This model has two types of command update rules: Clock-driven and event-driven. In the former type, the motor command is updated with fixed intervals (based on a time clock) while in the latter type, it is updated when the task error exceeds a specific threshold. One merit of intermittent control is to reducing the amount of computation because motor planning requires the heaviest calculation (i.e., optimization) in motor control process (see Section 4.4 for a related issue). Another merit is to be able to stabilize the control system with large sensorimotor delay, as we mention below.

In the field of non-linear dynamical system, Minton and his colleagues (Cabrera & Milton, 2002, 2004; Hosaka, Ohira, Luciani, Cabrera, & Milton, 2006; Milton, Cabrera, & Ohira, 2008; Milton, Cabrera et al., 2009; Milton et al., 2013; Milton, Ohira et al., 2009; Milton, Townsend, King, & Ohira, 2009) proposed a theoretical control model to discuss the phenomena caused by the interaction between delayed feedback and intrinsic noise. They picked up "stick balancing" as an example of human behavior and showed that their theory could explain the nature of human behavior, especially, the occurrence of "escape" (i.e., the fall of stick). They also showed that given an appropriate threshold for corrective action, the system could avoid escape (Milton et al., 2013).

Therefore, the concept of intermittent control has been already discussed from various viewpoints. Here, we propose an adaptive intermittent control from a viewpoint of "system model of sensorimotor mechanism", aiming to simulate the information processing in our brain. This model could be regarded as an expansion of the conventional intermittent MPC scheme, but includes a novel idea of adaptive determination of the timing of motor updates. As described above, previous intermittent control models update motor commands (or make corrective actions) in a passive manner: Clock-driven controllers update motor plan regularly (i.e., with intervals of a fixed length), and event-driven controllers update when the error exceeds a given threshold. In contrast, the proposed model updates motor plans dependent on the relationship between the prediction error and "reliability" of the prediction.

Motor planning for feed-forward control is inevitably based on the future prediction, but the prediction is not necessarily correct, especially when the environment is not stationary: Motor plan based on wrong prediction might result in a task error. For minimizing the risk of this task error, shorter segment (i.e., more frequent motor update) is preferable. On the other hand, frequent update increases computational cost for motor planning. Coping with this cost/risk trade-off, the proposed model determines the segment length adaptively according to the "reliability" of internal model (Sakaguchi & Takano, 2004), which is measured by the residual error in estimating the internal model (i.e., greater residue brings shorter segment). This adaptive segmentation is a key feature of the proposed model.

With the intermittent control, it is expected that body motion may change discontinuously at segment boundaries because motor commands may sometimes change abruptly. This would be remarkably observed when the motor commands in the previous segment are planned based on erroneous prediction. In concert with this expectation, human motion often shows intermittent discontinuities with variable time intervals in continuous motor tasks (Beppu, Nagaoka, & Tanaka, 1987; Beppu, Suda, & Tanaka, 1984; Miall, Weir, & Stein, 1986, 1993; Sakaguchi, 2013; Wolpert, Miall, Winter, & Stein, 1992). More specifically, when people try to follow a moving target with their hands, the velocity profile of the hand movement shows small humps with variable time intervals even if the target moves smoothly. In the present paper, we call this intermittent discontinuity found in movement trajectory "motor intermittency" though other researchers sometimes use this term to represent the discontinuities in the force profile instead of those in the velocity profile (e.g., Asai et al., 2009). Motor intermittency is commonly observed in various tracking tasks and never a measurement artifact. Previous researches have suggested that it originates from the update of motor commands based on visual feedback (Inoue & Sakaguchi, 2014; Miall, Weir, Stein, 1993; Novak, Miller, & Houk, 2000; Pasalar, Roitman, & Ebner, 2005; Roitman, Massaquoi, Takahashi, & Ebner, 2004), and here we hypothesize that it should be the side effect of the abrupt change in motor commands resulting from intermittent control.

Because the primary aim of the present study is to simulate the human sensorimotor process, replication of motor intermittency is an important issue for evaluating the model's validity. In contrast, it seems that previous intermittent control models did not pay much attention to this point. Most control theory studies place importance on theoretically demonstrating its advantage as a control mechanism (i.e., to prove its stability or to prove good performance with less computational cost), rather than replicating human behavior. For example, Gawthrop et al. (2011) compared the tracking behaviors of human participants with those of their intermittent MPC controllers (Fig. 11 of their paper), but they neither mentioned the motor intermittency observed in human behavior (which can be readily found in panel (a) of Fig. 11) nor tried to replicate it. As an example of dynamical system studies, Milton et al. (2013) dealt with the stick balancing problem and compared the stochastic properties of occurrence of failure between human participants and mathematical model, but they did not mention intermittent discontinuities observed in the trajectory data (Fig. 3 of their paper): Their primary interest seems to be in the nature of

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