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Research article

Anticipatory synergy adjustments reflect individual performance of feedforward force control

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HIGHLIGHTS

- We tested whether anticipatory synergy adjustments are related to feedforward control.
- We observed significant ASAs before a quick change of the total finger force.
- The ASA properties were correlated with the error of force pulse.
- Almost all subjects showed an increase of the variance that affects the total force.
- Multi-digit synergy is weakened to reduce future error based on prediction error.

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ABSTRACT

We grasp and dexterously manipulate an object through multi-digit synergy. In the framework of the uncontrolled manifold (UCM) hypothesis, multi-digit synergy is defined as the coordinated control mechanism of fingers to stabilize variable important for task success, e.g., total force. Previous studies reported anticipatory synergy adjustments (ASAs) that correspond to a drop of the synergy index before a quick change of the total force. The present study compared ASA's properties with individual performances of feedforward force control to investigate a relationship of those. Subjects performed a total finger force production task that consisted of a phase in which subjects tracked target line with visual information and a phase in which subjects produced total force pulse without visual information. We quantified their multi-digit synergy through UCM analysis and observed significant ASAs before producing total force pulse. The time of the ASA initiation and the magnitude of the drop of the synergy index were significantly correlated with the error of force pulse, but not with the tracking error. Almost all subjects showed a significant increase of the variance that affected the total force. Our study directly showed that ASA reflects the individual performance of feedforward force control independently of target-tracking performance and suggests that the multi-digit synergy was weakened to adjust the multi-digit movements based on a prediction error so as to reduce the future error.

1. Introduction

Humans grasp and manipulate objects by dexterously coordinating their multi-digit, especially the four fingers that oppose the thumb: the index, middle, ring, and little fingers. These four fingers produce a total finger force that is balanced by the thumb force to stably grasp objects. Multi-digit coordination is a mechanism that stabilizes the total force of fingers through the compensation of the variability of some fingers by other fingers. This point of view of coordination is based on the "principle of abundance" [1] in which the human central nervous system (CNS) finds not a unique optimal solution but a solution manifold to solve Bernstein's redundancy problem [2]. Neurophysiological mechanisms generating multi-digit coordination are collectively called multi-digit synergy.

Uncontrolled manifold (UCM) analysis has been proposed [3–5] and used to evaluate and quantify this multi-digit synergy [6–11]. In the framework of UCM analysis, the variance of coordinated multi-elements across trials is projected onto two orthogonal sub-

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spaces: one consisting of a subset of multi-elements that does not affect a performance variable important for task success (UCM) and another that directly affects the performance variable (orthogonal to the UCM). The two projected variance elements are called UCM and ORT components, respectively. Using these two variance components, an index of synergy is defined to quantify a degree of coordination. UCM analysis, which has been used for multi-digit synergy and also the motor synergies of various movements, e.g., upper limb movements [12,13], whole body movements [14,15], and walking [16,17], has revealed a coordinated control mechanism of CNS.

When we voluntarily produce a finger force with one finger, the other fingers produce involuntary forces. The non-independence of individual fingers is called "enslaving" [18], which is due to various factors, e.g., a biomechanical property of hand musculotendon and a neurological property of overlapping finger representations in the motor cortex. A motor command for individual fingers without the enslaving effect is called the "finger mode." A previous study using UCM analysis suggested that CNS controlled the finger modes by multi-digit coordination to stabilize the total force and the total moment of force [19]. In this study, we considered the coordination among the finger modes, i.e., finger mode synergy, to be multi-digit synergy.

The synergy index dropped when the performance variable quickly changed at self-paced timing [8,20]. Moreover, the initiation time of the synergy drop was faster than the change's initiation time in the performance variable. This phenomenon is called an anticipatory synergy adjustment (ASA), which reflects the pre-adjustments of a synergy for quick changes of the performance variable. Moreover, ASA's time of initiation of patients with motor impairment was slower than the control group [21,22], which implies that ASA is an index related to motor control ability. However, since the relationship between ASA properties and individual performance of motor control was not examined, ASA's functional role remains unclear. Previous studies concluded that ASA was observed before the voluntary quick change of the performance variable [8] and was affected by cerebellar disorders [21]. Based on these studies, we hypothesized that ASA is related to individual performance of feedforward force control.

To test this hypothesis, in this paper, we examine whether ASA properties (its initiation time and the magnitude of the drop of the synergy index) correlate with individual performance of feedforward force control. To observe an ASA phenomenon and to evaluate performance of feedforward force control, we used a quick force pulse production paradigm [8,21,22]. The quick force pulse production task consisting of two phases: a target-tracking phase and a force pulse production phase. In the conventional quick force pulse production task, subjects produced force pulse at self-paced timing and with visual information. In this study, we changed the force pulse production phase into a phase in which subjects produced force pulse at a specific given time point and without visual information to more strongly require subjects to perform feedforward control. Since the force pulse production with above conditions is ballistic and quite fast movements, we considered that the force pulse production task is mainly performed by feedforward control, and evaluated the performance of feedforward force control by an error from target force. We assumed that the force pulse production contains a part of individual target-tracking ability, because the target of force pulse was given by visual information. Therefore, we also check the relationship between the ASA properties and individual target-tracking performance, i.e., tracking-error during steady state of the target-tracking phase. The ASA is occurred when the UCM component decreases and/or the ORT component increases. Therefore, we also investigate the changes in the UCM and ORT components from ASA's time of initiation to the time of the change's initiation in the total force. Finally, we discuss its functional role.

2. Methods

2.1. Subjects

Twenty healthy right-handed volunteers (19 males and 1 female) participated in our experiments. Their average age was 25.4 (22–42 years). The experiments were approved by the ethics committee at Advanced Telecommunication Research Institute International. All subjects received explanations about the experimental procedure and gave their written informed consent.

2.2. Apparatus

Four custom-made force sensors (FSR 402, Interlink Electronics Inc., CA, USA) were used to measure the finger forces in the vertical direction (Fig. 1a). The circular contact surface of each sensor was covered with a rubber pad. The positions of the force sensors were adjusted in the horizontal plane to match the individual finger positions in which the subjects easily produced finger force. A cushion material was placed under the subject's palm. The subject's forearm was fixed to the device by a strap. The force signals were recorded using an AD/DA device (DAQ NI USB-6353, National Instruments, TX, USA) at a 600-Hz sampling rate. The visual information related to each task was displayed on a computer screen (Fig. 1b and c).

2.3. Task procedures

Subjects sat on a chair with their right hands fixed to the finger force measurement device. The measurement experiments consisted of three tasks: (1) a maximal voluntary contraction (MVC) force production task, (2) a single-finger ramp-tracking task, and (3) a quick force pulse production task. Before the experiments began, the experimenter demonstrated the actual experimental procedure by briefly performing all of the tasks.

1. MVC force production task: We measured the MVC force of the four fingers. The subjects pressed on the force sensors with four fingers and produced a maximal total force after a 3-s countdown. The total force was visually fedback by the height of the vertical bar. This task was repeated twice. We determined the MVC force as the highest value of the finger force.
2. Single-finger ramp-tracking task: Subjects tracked the force target template by producing an individual single-finger force (from the index to the little finger). The force target template and the produced finger force are displayed in Fig. 1b. The small filled circle was horizontally moved for 20 s at a constant speed. The height of the circle corresponded to the force of the tested finger. During the first 4 s, subjects kept 0% MVC force of the tested finger (rest). Over the next 12 s, they gradually increased the finger force of the tested finger from 0 to 40% MVC. Finally, they kept 40% MVC of the tested finger for 4 s and only produced finger force using the tested finger while keeping the rest of their fingers on the sensors.
3. Quick force pulse production task: The subjects tracked the force target template with visual information, and then, quickly produced a force pulse without visual information using all four fingers. The force target template and the produced total finger force are shown in Fig. 1c. The small filled circle was horizontally moved for 8 s at a constant speed. The height of the circle corresponded to the total force of the four fingers. The circle disappeared at the "Go" line (vertical solid line) and remained invisible until after the force pulse was produced. The target force template consisted of a target-tracking phase (first 4 s) and a force pulse production phase (last 4 s). During the target-tracking phase, the subjects produced 5% MVC of total force to track the target line. At the initiation of the force pulse pro-