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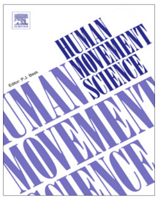

Changes in motor synergies for tracking movement and responses to perturbations depend on task-irrelevant dimension constraints

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ABSTRACT

We investigated the changes in the motor synergies of target-tracking movements of hands and the responses to perturbation when the dimensionalities of target positions were changed. We used uncontrolled manifold (UCM) analyses to quantify the motor synergies. The target was changed from one to two dimensions, and the direction orthogonal to the movement direction was switched from task-irrelevant directions to task-relevant directions. The movement direction was task-relevant in both task conditions. Hence, we evaluated the effects of constraints on the redundant dimensions on movement tracking. Moreover, we could compare the two types of responses to the same directional perturbations in one- and two-dimensional target tasks. In the one-dimensional target task, the perturbation along the movement direction and the orthogonal direction were task-relevant and -irrelevant perturbations, respectively. In the two-dimensional target task, the both perturbations were task-relevant perturbations. The results of the experiments showed that the variabilities of the hand positions in the two-dimensional target-tracking task decreased, but the variances of the joint angles did not significantly change. For the task-irrelevant perturbations, the variances of the joint angles within the UCM that did not affect hand position (UCM component) increased. For the task-relevant perturbations, the UCM component tended to increase when the available UCM was large. These results suggest that humans discriminate whether the perturbations were task-relevant or -irrelevant and then adjust the responses of the joints by utilizing the available UCM.

1. Introduction

Human multi-joint movements show coordinated flexibility that allows task-irrelevant variability (Latash, Scholz, & Schöner, 2002). Coordinated movements stabilize performance variables that need to be controlled during tasks while allowing the variability of motor elements that do not affect the performance variables or that are redundant in controlling the performance variables. Uncontrolled manifold (UCM) analyses have been proposed for the quantification of coordinated movements (Scholz & Schöner, 1999). UCM analyses use a UCM, which is the subspace of motor elements that constructs

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the same values of a performance variable, and quantitatively evaluate coordinated movements by dividing the variance of the motor elements into components that are parallel and orthogonal to the UCM. Many earlier studies that have applied UCM analyses to examine many kinds of motor tasks have revealed coordinated control strategies of humans (Latash, 2010, 2012; Latash, Scholz, & Schöner, 2007; Togo, Kagawa, & Uno, 2012, 2014). UCM analyses divide the variances of motor elements into two components: the UCM component, which does not affect the performance variable, and the orthogonal (ORT) component, which directly affects the performance variable. The ratio of the UCM and ORT components is used to quantify the coordination of motor elements, which is also called the task-dependent motor synergy.

Coordinated strategies that allow task-irrelevant variability and controls task-relevant variability have also been defined as the minimal intervention principle (Todorov & Jordan, 2002a, 2002b). The minimal intervention principle states that the human central nervous system (CNS) controls task-relevant variables in order to achieve the task. The findings of some studies have supported the minimal intervention principle based on observations of performance (task-relevant) variables (Liu & Todorov, 2007; Schlerf & Ivry, 2011; Valero-Cuevas, Venkadesan, & Todorov, 2009). In the framework of UCM analyses, the minimal intervention principle can be interpreted as control of only the ORT component, while the UCM component is unchanged.

Recently, changes in the UCM component in process of motor learning (Selgrade & Chang, 2015; Wu, Pazin, Zatsiorsky, & Latash, 2012, 2013; Yang, Scholz, & Latash, 2007) and constraints of motor elements (Togo et al., 2014) have been examined. In our earlier study, we reduced the available degrees of freedom of motor elements with mechanical constraints, and this induced an increase of the UCM component. Moreover, these findings suggested that changes in the available UCM induce changes in motor synergy. In this study, we consider cases in which the available degrees of freedom of motor elements are unchanged, while the dimensionality of the target of the performance variable is changed. In other words, when the available UCM is changed by increasing the dimensionality of the target of the performance variable, how does motor synergy change? Previous studies have examined changes in motor synergy when other physical performance variables are added (Mattos, Latash, Park, Kuhl, & Scholz, 2011) and when the required accuracy of the performance variable is changed (Rosenblatt, Hurt, Latash, & Grabiner, 2014; Tseng, Scholz, Schöner, & Hotchkiss, 2003). However, no studies have examined the effects of changes of the dimensionality of the same physical performance variable. These effects are important to understand in order to determine how changes in the available UCM affect motor synergy and better understand the flexible control mechanisms of human movements. In addition, responses to external perturbations contain important information on the stabilization of multijoint movements. Therefore, in the current study, we evaluated the motor synergies in tracking tasks and their responses to perturbation.

The present study investigated the changes that occurred in motor synergies when the dimensionalities of targets in tracking tasks were changed (Fig. 1a). In the target-tracking task, hand position was the performance variable, and joint angles were the motor elements. The constraint of the dimensionality of the target position of the hand (performance variable) made it possible to separately apply task-relevant and task-irrelevant perturbations. We analyzed the changes in the

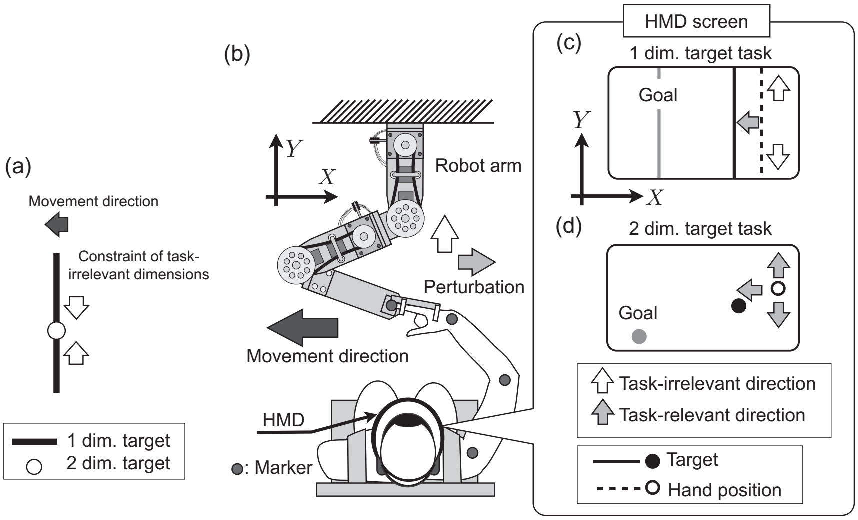

Fig. 1. Concept of one- and two-dimensional target-tracking tasks and schematic of measurement experiment. (a) The one- and two-dimensional targets are given by the line and point, respectively. The task-irrelevant direction of one-dimensional target is constrained by the two-dimensional target. (b) Schematic of the measurement experimental setup. The subjects performed one- and two-dimensional target-tracking tasks while sitting on a chair and wearing a seatbelt. The hand of the robot arm is connected to the subject's hand, and it applies mechanical perturbation. A head-mounted display (HMD) is secured to the head, and position measurement markers are placed on arm segments. The one- and two-dimensional hand position of the subject and target are shown on the HMD screen. (c) HMD screen for the one-dimensional target-tracking task in which the Y-direction is the task-irrelevant direction. (d) The HMD screen for the two-dimensional target-tracking task in which the Y-direction is the task-relevant direction.