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Estimate of body motion during voluntary body sway movements

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ABSTRACT

Balance control can be interpreted as a combination of state feedback control with optimal state estimation. In this framework, state estimation uses an internal model of body and sensor dynamics to process sensory information and determine body orientation. The aim of this study was to assess the ability of the brain to create accurate state estimation when the congruence between sensory information was altered. Participants stood upright on a force platform with a monitor directly in front of them at eye level displaying their center of pressure (CP) position in real-time. When a target appeared on the monitor, participants had to move their CP as fast and as accurately as possible within the target. Voluntary balance pointing movements were made with the head either straight or rotated about the trunk, and mapping directions of the CP were changed on the basis of experimental conditions. Manipulating the sensory information congruency caused less accurate state estimation of the body motion leading to larger signed and absolute angular errors and a greater area of the final CP position were measured. These results suggest that performing head-centered to trunk-centered sensorimotor transformation reduces the accuracy in the state estimation of body motion during a balance pointing task.

1. Introduction

During human movements, the brain does not know the exact state of the motor apparatus because of unavoidable delays in the conduction of efferent and afferent signals and central neural processing. Consequently, it is hypothesized that the brain generates an estimate of the true state of the motor system, by integration of the latest afferent sensory information with an efferent copy of motor commands using prior knowledge of the relationships between efferent signals and the subsequent sensory reafference [1]. During upright standing, vestibular and visual system signals are influenced by changes in head and eye position, while the somatosensory system monitors motion of the joints, modification of muscle state and contact force between the feet and ground. Balance control can be interpreted in terms of a combination of state feedback control with optimal state estimation. In this framework, state estimation uses an internal model of body and sensor dynamics to process sensory information and determine body orientation. The estimation of body orientations involves an integration of different sensory systems each with its own coordinate frame. This model has been successful in studying balance control [e.g., 2,3]. From this framework, it is expected that imprecision (or a loss) in state estimation leads to inaccuracy in balance pointing because the balance motor commands signal is not adjusted (or based on out-of-date) to precise sensory information. Consequently, a rapid displacement of the center of pressure (CP) toward the target with inaccurate estimation of the body motion would tend to cause balance pointing error [4]. There are theoretical and experimental evidences supporting this framework during arm reaching movement [5,6]. Furthermore, recent results suggest that humans construct and update internal models of verticality based upon somatosensory information [7].

Head orientation about the trunk has been shown to be crucial in various sensorimotor tasks, such as walking [8], standing upright [9–11] and reaching [12]. An interesting demonstration of the effect of head orientation on balance control is provided by unilateral galvanic stimulation studies [13]. When the head is facing forward, cathodal current across the right labyrinth produces body sway toward the left (i.e., anode side). When the head is rotated to the right or left, however, the same stimulation causes forward or backward sway, respectively. Previous experiments have assessed the effect of head position on upright balance stability in normal subjects and unilateral vestibular patients [14,15]. For example, subjects with unilateral loss of vestibular function mainly sway in the direction of the disordered labyrinth. Therefore, on turning their head to the right, patients with left unilateral loss sway forward. On the other hand, stability in healthy participants is uninfluenced by head position. Both

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labyrinthine and cervical receptors are stimulated during head-on-trunk movements. In the healthy vestibular system, upright stance is correctly regulated, presumably by subtractive interaction between these signals as a result, the balance control mechanisms are able to activate different sets of postural muscles according to head position [16].

Results of a deafferented subject (DS) suggest that, during balance control, the coding of head position with respect to the trunk helps in controlling balance [17]. The authors created a mismatch between body motion and vestibular information by rotating the DS's head in absence of vision. When head orientation changes with respect to the trunk, in absence of vision, it is suggested that the lack of cervical information prevented the transformation of the head-centered vestibular information into a trunk-centered frame of reference of body motion. In this circumstance, the vestibular signals did not provide the DS with veridical information about her trunk displacements in space. In other words, the lack of sensory information reduced the accuracy in state estimation leading to large body sways. In contrast, when vision was available, thus permitting a better state estimation, her body sways drastically decreased.

Even in healthy individuals, physiological sensors have some inaccuracies, intensify by neural noise, leading to errors in the measurements. Altering the relationship between the efferent signals and the sensory reafference could add some difficulties in predicting the current state of the body orientation. To verify this suggestion, the congruence between efferent signals and sensory reafference was altered. We hypothesized that such situation could cause state estimation inaccuracy leading to larger balance pointing errors.

2. Methods

2.1. Participants

Sixteen healthy subjects (7 males and 9 females) participated in this study (mean age ± 1SD = 22.8 ± 2.3 years). They had no history of neurological disease or vestibular, visual or somatosensory impairments. Before participating, all subjects gave their informed consent according to the ethics committee policy.

2.2. Task of the participants

Participants stood barefoot, with their feet 10 cm apart, on an AMTI force platform (Model OR6-1). A 17-in (43.2 cm) monitor was placed 1.5 m in front of them at eye level. CP was calculated in real-time to provide direct feedback about its position with a moving red crosshair (dimension: 0.1 cm × 0.1 cm) prominently displayed on a black monitor background. The participants' task consisted of altering their CP (i.e., crosshair) within a target (white circle: radius equal to 10% of the functional base of support). The distance between initial CP and target positions was determined by each participant's balance skills. Starting from an upright position, participants leaned forward as far and as fast as possible and returned to their initial position. They were instructed to only rotate about the ankle joints (i.e., to adopt an inverse pendulum strategy) and were not permitted to take a step, raise their heels or toes, or bend their knees. Failure to comply resulted in repetition of the trial. The target position was set at 70% of maximal forward CP displacement. Prior to each trial, initial CP position was determined by median CP position (2 s window) while participants stood upright as still as possible with their arms alongside their body. Then, after a period varying from 0.5 to 2 s, the target appeared on the monitor. At that time, they had to move their CP in the target area as fast and as accurately as possible.

2.3. Experimental paradigm

To verify our hypothesis, participants were subjected to 3 different experimental conditions (Fig. 1). In the first condition (condition A), they stood upright with their head straight about their trunk, facing the monitor. In this condition, forward (backward) body tilt led to upward (downward) CP displacement on the monitor, whereas left (right) body tilt created left (right) CP displacement. Consequently, to move their CP within the target, they only had to tilt their body forward; no left/right CP movements were necessary to attain the target.

In condition B, the participants' head still faced the monitor but their whole body was rotated clockwise by 90°; their chin was above their left shoulder. In this condition, forward (backward) body tilt caused right (left) CP displacement on the monitor, whereas left (right) body movement evoked upward (downward) CP displacement on the monitor. As in condition A, participants only had to tilt their body forward to move their CP in the target. In this condition, compared to condition A, the congruence of the sensory information was altered as ankle joint proprioception and planar sole mechanoreceptor signals detected forward movement (trunk-centered frame of reference), whereas visual and vestibular signals perceived rightward movement (craniotopic reference frame).

In condition C, the participants' position was identical to that in condition B except that forward (backward) body tilt created upward (downward) CP movement on the monitor. As in condition B, ankle joint proprioception and planar sole mechanoreceptor signals detected forward movement (in the trunk-centered reference frame), whereas visual and vestibular inputs signaled forward and rightward movement (in the head-centered reference frame), respectively. To control target position with respect to

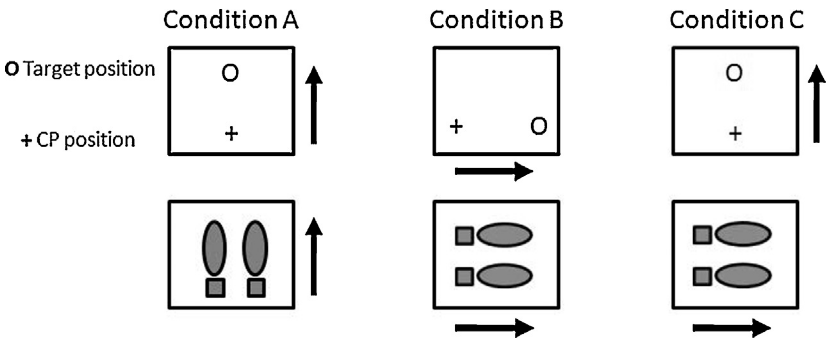

Fig. 1. The upper row depicts the monitor. "+" represents initial CP position, and "o", target position. The lower row illustrates the position of participants in each experimental condition (i.e., left column – condition A, middle column – condition B, and right column – condition C). Footprints in the lower panel correspond to the position of participants on the force platform (i.e., square). The arrow, next to the force platform, matches the direction required to move the CP within the target. The arrow next to the monitor shows the direction of CP (i.e., "+") displacement on the monitor.