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Multiple timescales of body schema reorganization due to plastic surgery

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ABSTRACT

Plastic surgery modifies the distribution of mass centers of a person's body segments, changing his or her posture. The functional reorganization processes that lead subjects to re-integrate these body changes into a new stable body (posture) schema is poorly understood but current theories suggest the possible contribution of two components: a feedback mechanism that strongly depends on sensory input and an internal model that is relatively less dependent on sensory input and improves posture control, for example by compensating for delayed feedback. To assess the relative contributions of these two mechanisms during the functional reorganization of a posture scheme, we have conducted a longitudinal postural study in a population of healthy adults who were subject to breast plastic surgery to reduce or augment body weight. We measured participants' orthostatic posture and ground reaction force immediately after, after 4 months, and 1 year after the surgery. To investigate the role of visual sensory information in the reorganization process we tested the participants with eyes open and closed. Our results indicate that participants find a new dynamical equilibrium within a few days. However, posture maintenance remains sub-optimal long after the center of masses and the resultant of ground reaction force stop changing; in some cases, for more than 4 months. Furthermore, the re-adaptation process is faster and more efficient in the eyes-open than in the eyes-closed condition. These results suggest that the reorganization involves different subsystems (responsible for the biomechanical changes,

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the re-calibration of feedback mechanisms, and the re-adaptation of internal models), which act at different timescales.

1. Introduction

The term *body schema* originated in the neurological and psychological literatures (Bonnier, 2009; Head & Holmes, 1911; Piaget, 1952). It refers to a pragmatic representation of the body and its possibilities of action, which is learned during infancy on the basis of a synthesis of proprioceptive, vestibular, and kinesthetic information.

The human's body schema is subject to permanent or temporary modifications and re-adaptations in the course of life. For example, limbs grow as a result of development and accurate motor control requires re-adaptation (Kording, Tenenbaum, & Shadmehr, 2007; Shadmehr, Smith, & Krakauer, 2010). In some cases, when fast re-adaptation is required (e.g., due to amputations) specific deficits in body representations can occur such as the phantom limb phenomenon (Haggard & Wolpert, 2005). The body schema is temporarily re-adapted during tool use, too. Some tools such as sticks or rackets can be incorporated in the body representation to serve as "elongated effectors" (Johnson-Frey, 2003; Ladavas & Serino, 2008; Maravita & Iriki, 2004) that can be used almost as reliably as one's own effectors – a phenomenon which is particularly visible in athletes (Fourkas, Bonavolont, Avenanti, & Aglioti, 2008; Pezzulo, Barca, Bocconi, & Borghi, 2010). The fact that learning to use tools does not interfere with older skills suggests a modular control scheme. In this perspective, it has been proposed that the brain uses multiple *internal models* – or neuronal process that simulate the input/output dynamics of the motor system – each specialized for a specific sensory context, which are plausibly encoded in the cerebellum (Caligiore, Pezzulo, Miall, & Baldassarre, 2013; Haruno, Wolpert, & Kawato, 2001; Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003; Kawato, 1999; Koziol et al., 2013; Pezzulo, Candidi, Dindo, & Barca, 2013).

Permanent modifications of the body determine profound neuronal reorganizations. A study of achondroplastic dwarfs submitted to progressive elongation of lower limbs reported cortical modifications in the primary somatosensory cortex for foot stimulation, with somatosensory cortices coding the elongated limbs that "invade" neighbor brain areas and "retreat" after 6 months. The study reported also cortical modifications in higher order somatosensory cortices for foot and knee, which tended to persist more (Di Russo et al., 2006).

A so-called "posture scheme" underpins *posture maintenance* and is a key precondition for most successful voluntary actions (Arbib, 1981). The posture scheme has been defined as a "stored body model of the body's metric properties, such as body part size and shape" (Longo & Haggard, 2010). The way the postural scheme permits to maintain balance has been often investigated in a control-theoretic perspective (Shadmehr et al., 2010). In this perspective, to maintain stable upright posture (the goal state) despite disturbances (detected as internal or external sensations), the central nervous system (the controller) has to generate appropriate motor commands (a control policy) for all the muscles in the movement system (the plant to be controlled). Posture maintenance requires a quick and automatic response to disturbances; a "direct control" strategy that pre-specifies the whole control policy does not work well but additional components are necessary to overcome the disturbances.

Studies by Morasso, Baratto, Capra, and Spada (1999) and Morasso and Schieppati (1999) have shown that intrinsic muscle stiffness is not sufficient to stabilize posture despite disturbances, pointing to additional mechanisms whose nature – reactive (or feedback-based) or anticipatory (or feed-forward) – is however disputed. Feedback and feed-forward mechanisms can be used in isolation or combined in various ways. Some early models suggest that feedback loops are sufficient to provide efficient posture maintenance and to guide action (Peterka, 2002; Peterka & Loughlin, 2004). This implies that there is no *a priori* motor plan, but motor commands are (reactively) generated on-line by the feedback controller, with a continuous comparison of the desired and actual location or