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Stabilization strategies for unstable dynamics

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ABSTRACT

The stabilization of the human standing posture was originally attributed to the stiffness of the ankle muscles but direct measurements of the ankle stiffness ruled out this hypothesis, leaving open the possibility for a feedback stabilization strategy driven by proprioceptive signals. This solution, however, could be implemented with two different kinds of control mechanisms, namely continuous or intermittent feedback. The debate is now settled and the latter solution seems to be the most plausible one. Moreover, stabilization of unstable dynamics is not limited to bipedal standing. Indeed many manipulation tasks can be described in the same framework and thus a very general protocol for addressing this kind of problems is the use of haptic virtual reality where instability is generated by some kind of divergent or saddle-like force field. Several studies demonstrated that human subjects can choose to adopt a stiffness or feedback strategy as a combination of biomechanical and task constraints and can learn to switch from one strategy to the other if it is feasible or to use one or the other is infeasible. Understanding such mechanisms is relevant, for example, for the design of novel ergonomic man-machine interfaces in difficult, unstable tasks.

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1. Introduction

Movements of the human body, namely kinematic/dynamic patterns, are meaningless unless associated with a goal or a task. The combination of task and movement is what identifies an "action". The brain is concerned with actions, not movements per se, both overt (real) and covert (imagined) ones, which operate on an internal representation of the body or *body schema.*

The fact that humans have an integrated, internal representation of their body (the body image or body schema) is strongly suggested by the variety of pathological conditions, which can only be explained by a deficient internal representation (Head and Holmes,

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1911). More recent studies (for reviews see: Graziano and Botvinick, 2002; Haggard and Wolpert, 2005) have identified the different cortical areas that may contribute to this function and the multimodal integration of proprioceptive, visual, tactile, and motor feedback (efference copy) signals that are necessary for maintaining a coherent spatio-temporal organization. It has also been suggested that such continuous body experience may be one of the key elements for allowing the emergence of individual self-consciousness (Morasso, 2013). In this view, running internal simulations on an interconnected set of neuronal networks is perhaps one of the main functions of the body schema. Therefore, the body schema must not be considered as a static structure, like the Penfield's homunculus, but is a dynamical system that generates goal-oriented, spatio-temporal, sensorimotor patterns.

This view of the body schema is clearly *multireferential* and resonates well with many ideas investigated in the framework of embodied cognition: (1) *cognition is situated*, in the sense that it is an on-line process which takes place in the context of task-relevant sensorimotor information; (2) *cognition is time-pressured*, i.e. it is constrained by the requirements of real-time interaction with the environment, what is also known as 'representational bottleneck' (Brooks, 1991; Pfeifer and Scheier, 1998, among others); (3) the *environment is part of the cognitive system*, including both the physical and the social one; (4) *cognition is intrinsically action-oriented* and even "off-line cognition", namely cognition without overt action, is body-based as argued by (Lakoff and Johnson, 1999), who remarked that in most occasions abstract concepts are based on metaphors grounded on bodily experience/activity.

One can agree with (Brooks, 1991) that "the world is its own best model", but it also common wisdom that a human being, as well as a humanoid robot, needs an internal model or representation of its own body or body schema, extended with an internal representation of the environment and the mastered tools that allow him/her/it to succeed in physical/social interaction. Such body schema does not need to be a faithful biomechanical model, including the finest details of flesh and bones. It is just a skeleton or middleware representation where it is possible to play plausible spatiotemporal games, required at the same time and formulated in the same language by *motor cognition* and *motor control*. The power of this concept is that a well-trained agent can use it to interpret/anticipate the actions of other agents or also imagine actions that are physically impossible, but crucially important for figuring out the solution of a difficult task.

The introduction of the body schema as a middleware implies two important concepts in the analysis of the organization of action: one is the necessity and the convenience to separate motor cognition from motor control, in a multi-referential framework; the other is the identification of different time frames. The first concept is related to flexibility and the necessity of degrees of abstraction in the acquisition of skills. Mental reasoning and mental training can be powerful and effective only if it is possible to abstract from specific environmental conditions that can require different control strategies. The capability of abstraction is made possible by a body schema that allows people to formulate real and imagined actions in the same format. Moreover, this logic separation of motor cognition and motor control implies the identification of three different time frames: (1) *learning time*, for acquiring an approximate representation of the body model; (2) *preparation time*, for recruiting the necessary body parts, configuring the networks and setting up the specific task-dependent components; (3) *real-time*, for running the internal simulation of the body model and thus generating control patterns either for covert or overt actions.

Fig. 1 illustrates that the body schema can be considered as an internal model, which serves as a middleware between the covert virtual movements generated by a cognitive machinery and the overt movements generated by the motor controller. Motor cognition is concerned with synergy formation, namely the spatio-temporal recruitment of degrees of freedom appropriate for a given task, whereas motor control selects the motor strategies (for example a mixture of stiffness strategy, feedback strategy, and feedforward strategy) that are necessary for the dynamic constraints determined by biomechanics and/or environmental physics. From what is known about the organization of motor cognition, one can say that it tends to abstract from the specific effectors chosen for carrying out a task and from the specific control strategies used for activating the employed effectors. Indeed motor cognition shares, with a large variety of open systems, the property of Equifinality, leaving open the issue of how humans choose a specific control strategy for a specific action or family of tasks, such as unstable tasks.

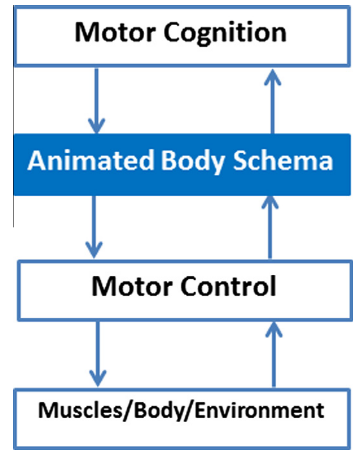

Fig. 1. Multi-layered organization of action and the role of the body schema as middleware between motor cognition and motor control.

Using a tool or shaping a new tool for solving a task are important aspects of sub-symbolic human cognition, but this is not a prerogative of humans: primates (Visalberghi, 1993) and even crows (Weir et al., 2002) can exhibit such skilled behavior. Moreover, it has been demonstrated that the skilled use of tools implies a modification of the body schema that incorporates the tool as a functional extension of the body (Maravita and Iriki, 2004). If a task is stable and the tool is sufficiently rigid, the incorporation of the tool in the body schema and its control require a rather straightforward reorganization of the coordination patterns, equivalent to the modification of the Jacobian matrix of the end-effector. On the contrary, compliant tools employed in unstable tasks require learning a novel control mechanism by careful integration of multi joint/multi-limb coordination with the stabilization aspects. An example of an underactuated compliant tool is a fishing rod, which is characterized by an infinite number of uncontrollable degrees of freedom. The arm-rod system is described as underactuated because the configuration of the rod is only partially affected by the motor control patterns of the arm but is mainly determined by its intrinsic dynamics. On the other hand, unstable tasks are common components of human activities, like screwing/unscrewing, drilling, inserting a peg in a hole, chiseling, manipulating soft tissues (like in surgery), balancing a pole etc.

A biomechanical system, comprising the dynamics of the human body, the muscles, and the interactions with environmental physics, is unstable if, starting from an equilibrium configuration, any small perturbation is generally capable to induce boundless growth of state variables or some sort of catastrophic crashing. A biological controller, by using a combination of control strategies, is supposed to compensate the biomechanical instability and bring the controlled system to some form of stability, such as *asymptotic*