Consciousness as the Emergent Property of the Interaction Between Brain, Body, and Environment

Implications for Robot-Enhanced Neuromotor Rehabilitation

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Abstract. Neuromotor rehabilitation, typically seen with stroke patients, is usually mistakenly focused on the recovery of movements while disregarding the insufficient or missing awareness of the affected part of the body. Thus, the functional recovery of sensorimotor abilities is fundamentally a problem of consciousness. The paper addresses the implications of this concept in the design of optimal robot-assistance in the training of patients, according to the assumption that consciousness is the emergent property of the interaction between brain, body, and environment. Optimal assistance is formulated as a process that follows three basic guidelines: (1) limitation of the assistance level to the minimum value capable of allowing patients to initiate the movements; (2) trial-to-trial reduction of assistance in order to promote the emergence of voluntary control; (3) nonmonotonic modulation from session to session in order to promote memory consolidation.

Keywords: consciousness, stroke, rehabilitation, robotics

Consciousness as an Emergent Property of Action

That consciousness cannot be a purely mental phenomenon has become the common wisdom in recent years among roboticists, neuroscientists, and a new wave of philosophers. The idea, concisely and effectively formulated by Chiel and Beer (1997), is that “the brain has a body.” Moreover, the “body” interacts continuously with the “environment” in a bidirectional manner, which means that even the most abstract cognitive processes are formed and informed by the physical processes going on in the real world (Figure 1).

The intimate relationship between the brain and the body and the importance of this relationship for the maintenance of the sense of self is evident in different pathological conditions, such as the phantom limb syndrome, in which the brain is orphan to a part of the body. There is an elaborate folklore surrounding it. For example, Admiral Nelson, who...
lost his right arm during an unsuccessful attack on Santa Cruz de Tenerife, experienced compelling phantom limb pain and interpreted it as a “direct proof of the existence of the soul.” The first clinical description of phantom limbs was provided by Silas Weir Mitchell in 1872 (see Melzack, 1992, for a review). In general, it is possible to learn a lot about the question of how the self constructs a body image and becomes conscious about it by studying patients with phantom limbs. Until recently, the dominant theory was that phantom limbs were caused by irritation in the severed nerve endings (called “neuromas”). However, T. Pons et al. (1991) showed that the brain can reorganize if sensory input is cut off and from this a team of researchers lead by V. S. Ramachandran demonstrated that phantom limb sensations can be explained in terms of a remapping hypothesis that determines the cross-wiring in the somatosensory cortex (Ramachandran & Blakeslee, 1998).

In a sense, the phantom limb syndrome can be regarded as a kind of sensorimotor illusion in which the patient projects to the outside world what is in fact a process of the brain. However, this is not limited to pathological conditions; on the contrary, it appears to be a general and powerful tendency of the brain. Consider the use of a tool that requires some kind of sensorimotor skill to handle, for example, a screwdriver or a surgical scalpel: After some practice one often begins to feel the tip of the screwdriver as part of his body that, in a sense, finalizes all its resources to carry out the task. In a more formal way, it is possible to study sensorimotor illusions in normal people who share the same background with the phantom limb syndrome. Consider the phantom nose illusion (Lackner, 1988): Subjects were asked to sit blindfolded at a table, with their arm flexed at the elbow, holding the tip of their own noses. The experimenter applied a vibrator to the tendon of the biceps: The subjects not only felt that their elbow joints were extended (a classical result in the literature on the tonic vibration reflex), but also that their noses had actually lengthened. This kind of experiment demonstrates the striking plasticity or malleability of our body image and the corresponding conscious experiences, despite the apparent solidity and feeling of its permanence. Moreover, explicit neural correlates of plasticity of the “body schema” were found in animal studies concerning the use of a tool to reach for a distant object (see Maravita & Iriki, 2004 for a review): This extended motor capability, following a suitable training process, is followed by changes in specific neuronal networks, which hold an updated map of body shape and posture, and these changes are compatible with the notion of the inclusion of tools in the body schema. The experiments mentioned above also emphasize the fact that, despite the power of vision and the ubiquitous influence of visual signals throughout the brain, the body schema and the sense of the self basically emerge from the efferen-ce reafference cycle, where proprioception has a fundamental role.

The link between the phantom limb syndrome and post-stroke hemiparesis was recently emphasized by Antoniello, Kluger, Sahlein, and Heilman (2009), who reported that the occurrence of the syndrome in stroke patients is a strongly underreported phenomenon. On the other hand, the work of Schacter (1991) points to the unawareness of deficits in neuropsychological syndromes, which further motivates us to integrate systems concepts in robot-driven rehabilitation methods which focus on the recovery of the awareness of the body schema, in addition to motor recovery per se.

The neuronal substrate of conscious experience and the theoretical tools for understanding its dynamics have been the subject of a number of studies. Consider, for example, the concept of “global workspace,” as defined by Dehaene, Kerszberg, and Changeux (1998); the “quantitative measure of neural complexity” proposed by Sporns, Tononi, and Edelman (2002); the “information integration theory of consciousness” developed by Tononi (2004) and the associated “Connectome Project” (Tononi, 2005); and the “metric of consciousness” developed by Seth, Izhikevich, Reeke, and Edelman (2006).

Implications for Neuromotor Rehabilitation

The experiments on referred sensations in phantom limbs are important because they open a window to the fundamental plasticity of the human brain. In particular, they suggest that, contrary to the static picture of brain maps provided by neuroanatomists, the brain topography is extremely labile. Even in the adult brain, massive reorganization can occur over extremely short periods, and referred sensations can therefore be used as markers for plasticity in the adult human brain. This kind of fundamental plasticity, which explains many of the aspects of the phantom limb syndrome, can be the starting point for designing new approaches to the rehabilitation of neurological patients such as stroke survivors affected by hemiparetic syndrome. In the phantom limb syndrome, the brain is an orphan to a part of the body, whereas in the hemiparetic syndrome part of the body is an orphan to a part of the brain.

The conventional wisdom about stroke patients is that there is little ground for functional recovery a few months after the ictus, when they become chronic. The hemiparesis is the result of damage to the efferent pyramidal fibers in the internal capsule; but in the first few days after a stroke, edema and diaschisis may contribute to paralysis. Is it conceivable that during this period the negative feedback from the paralyzed limb leads to a form of learned paralysis analogous to that seen in the phantom limb syndrome, so that even after resolution of the swelling the paralysis remains. The affected limb, despite intact muscle actuators and proprioceptive sensors, becomes paralyzed in part because of the destruction of some brain tissue, in part because in absence of purposive movement the brain does not receive organized kinesthetic information and is thus deprived of functional haptic patterns. The consequence is a kind of functional amputation with two aspects: (1) The
limb assumes a standard, nonfunctional pathological posture. (2) The limb tends to be ignored by the patient and is thus functionally cut off from the conscious body schema that guides purposive behavior.

The considerations above can provide useful guidelines for the design of novel approaches to neurorehabilitation based on two basic concepts: (1) Even the brain of the hemiparetic adult patient has a tremendous reserve of neural plasticity. 2) What matters is not the recovery of movement per se, but the recovery of the conscious body schema that is the inner source of movement and skill. In fact human and animal studies (Nudo, 2006) have shown that, beyond the time-dependent spontaneous neurological recovery, the principal process responsible for functional recovery is the use-dependent reorganization of neural circuitry made possible by neural plasticity. Moreover, rehabilitation techniques inspired by this concept can be efficient only if they can promote increasing levels of motor skill: Repetitive use alone, without learning-inducing variability, is unlikely to promote the large-scale, long-lasting changes in cortical networks necessary for recovery of functions.

These ideas can be linked to the so-called schema theory (ST; Schmidt, 1988), which provides a general framework for formulating principled approaches to treatment. ST posits that people do not learn specific movements, but rather construct generalized motor programs (GMP) that relate control parameters to movement outcome during training. People learn more quickly the relationship between parameters and a desired movement outcome if they have practiced a task in a wide variety of situations and experienced errors in that process. A practice that lacks variety but is instead merely repetitive does not provide enough information for learning the rules that underlie the GMP.

Another general concept that can provide solid ground for the optimal design of assistance in neuromotor rehabilitation is the equilibrium point hypothesis (EPH; Bizzi, Polit, & Morasso, 1976; Feldman, 1966). According to this view, body posture is not controlled explicitly in a detailed way, muscle by muscle, but is the "biomechanical consequence" of the equilibrium of the muscular and environmental forces. Movement is then a consequence of "equilibrium breaking," that is, the transition from one equilibrium state to another, according to nonlinear attractor dynamics. This mechanism is made possible by the fact that muscles are not pure force generators, but rather devices that can store and return large amounts of mechanical energy. In other words, the computational power of EPH comes from the ability to solve the degrees of freedom problem formulated by Nikolai Bernstein (1967) in a biomechanical manner. The notion of "equilibrium" is closely related to that of "energy function" and "force field" (Shadmehr, Mussa-Ivaldi, & Bizzi, 1993), i.e., to a mechanism of attractor dynamics which appears to characterize the interaction of cortical maps as well (Morasso, Sanguineti, & Spada, 1997; Mussa Ivaldi, Morasso, & Zaccaria, 1988) and can be applied successfully to the control of humanoid robots (Mohan, Morasso, Metta, & Sandini, 2009). Put succinctly, the planning, preparation, and execution of purposive movements can be understood in terms of forcefields in a uniform way, which is why the application of suitable external forcefields, either by a human physiotherapist or a robot-therapist, has a chance of promoting the (re)formation of internal control models and thus the recovery of lost sensorimotor functions.

Adaptive Assistance in Robot-Driven Neuromotor Rehabilitation

Using ST and EPH, as basic building blocks for the principled design of robot-assistance in neuromotor rehabilitation, we can refer to the following formulation:

\[ P = f(A + C) \]

This equation simply says that performance \((P\), or outcome\) is a function of assistance \((A\), or movement\), provided either by a human or a robot therapist, and voluntary control \((C\), or decision\), provided by the patient. This function is obviously monotonically increasing in terms of both arguments, \(A\) and \(C\). For example, given a task, it is always possible to find a level of assistance that allows one to achieve errorless performance, but this is not what we want because it would be equivalent to a purely passive movement. Rather, we are interested in an optimal assistance strategy that attempts to maximize \(C\) for a given \(P\), which requires keeping \(A\) to the lowest possible level in relation to the ongoing level of assistance. More precisely, a class of optimal assistance strategies can be formulated on the basis of the following general guidelines about the modulation of assistance:

- Assistance should be large enough to allow the subject to complete the task, although in an imprecise and/or slow manner (to avoid frustration);
- Assistance should be small enough to motivate the subject to contribute as much as possible to the outcome (to avoid laziness);
- Assistance should be reduced from trial to trial as performance improves (to promote the emergence of voluntary control);
- Assistance should be boosted at the beginning of each session (nonmonotonic modulation) to promote memory consolidation.

We carried out some preliminary clinical studies that apply this general strategy in different assisted training actions (ATAs), using the common experimental setup illustrated in Figure 2. The robot is a haptic manipulandum (Braccio di Ferro, shortly BdF: Casadio, Morasso, Sanguineti, & Arrighiello, 2006) that has high mechanical compliance (low inertia and low friction) and a sufficient range of forces in order to allow even severely impaired patients to complete a desired movement in a large workspace. BdF can generate

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assistive force fields with different features in different ATAs:

- In assisted reaching movements (Figure 3, panel A), the force field has a constant amplitude, which is initially chosen, different for each patient, as the minimum value capable of allowing the subject to start moving. As performance improves, the assistance level is decreased from trial to trial. Each session goes back to the initially chosen assistance and then keeps decreasing it as a function of performance (Casadio, Giannoni, Morasso, & Sanguineti, 2009).

- In assisted tracking movements (Figure 3, panel B), the force is directed to a moving target, which slides along a pathway shaped like an 8. The amplitude of the field is proportional to the square root of the tracking error, and the gain is modulated by performance and by the sequence of epochs (Vergaro, Casadio, Squeri, Giannoni, Morasso, & Sanguineti, 2010).

- In assisted bimanual coordination (Figure 3, panel C), there is a double task: (1) reaching two targets in an alternated way; (2) keeping the balance between the paretic and the unaffected arm. Reaching movements are assisted by a force field, whereas unwanted unbalanced movements of the two limbs are punished by a resistive force field (Squeri, Casadio, Vergaro, Giannoni, Morasso, & Sanguineti, 2009).

- Assisted wrist movements (Figure 3, panel D): The three degrees of freedom of the wrist (pronosupination, flexoextension, adduction/abduction) are trained separately with suitable, adaptive force fields, related to a periodically moving target, whose frequency is modulated by performance (Masia, Casadio, Sandini, & Morasso, 2009).

In all these ATAs, the assistive force fields did not impose the trajectory or the timing of the movements, but simply provided force vectors of minimal intensity directed toward the current target. Moreover, the tasks were performed under two conditions alternated in subsequent target-sets: (A) with vision of the fixed or moving target position and the current position of the hand, which were displayed on a computer screen; (B) blindfolded, i.e., without visual feedback. In both conditions, however, the subjects had a proprioceptive feedback about the position of the arm with respect to the target and could thus be trained to recalibrate the spatial representation of the paretic arm. This aspect of the patient-robot interaction protocol proved to be very effective and motivating for the patients (Casadio, Morasso, Sanguineti, & Giannoni, 2009). In a general sense, it can be considered as a mechanism of proprioceptive training. It is also worth remarking that the visual feedback could

Figure 2. Robot-training by means of the self-adaptive haptic interaction between patient and robot-therapist.

Figure 3. Four examples of training stroke patients with the assistance of robots. Panel A: Reaching with BdF robot; Panel B: Tracking with BdF robot; Panel C: Bimanual coordination with bimanual extension of BdF robot; Panel D: Wrist robot.
have a different role in different subjects, at least at the beginning of training: Some patients performed better with vision, whereas other patients performed better without vision. However, at the end of the training sessions the discrepancies of performance in the two modes tended to vanish, suggesting a recalibration of the visual and proprioceptive channels. Moreover, the patients reported a better subjective awareness of the paretic limb.

Conclusions

The experiments reported are only preliminary implementations of the guidelines formulated in the previous section. The approach must be validated by controlled clinical trials to be carried out in the near future. In general, we can say that, although the motor deficit of stroke patients is the more evident aspect of the pathology, proprioceptive deficits may be just as important, albeit somehow hidden and difficult to measure. However, it is quite clear that if functional recovery is achieved, this is not restricted to the motor side (force increase and coordination improvement), but also extends to the improved awareness of the affected part of the body, mainly through the proprioceptive channel.

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References


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