Interaction between information representation and physical dynamics as a key to understand cognitive processes

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We assume the embodiment, physical and dynamical nature of the body contributes to implementation of cognitive processes. Our working hypothesis is that interplay between "physical computation" phenomena in body dynamics and information representation in variable metric is an essential contribution.

The former, physical computation phenomena can be regarded as solutions of specific (i.e., not general) problems based on the variational principle, such as Snell's law in optics or the collapse of wave function in quantum mechanics (e.g., [1]). In biology, morphogenesis is based on exploitation of surface area minimization and this feature can be simulated in digital computer [2]. While the digital computer can solve this problem, it suffers combinatorial explosion in high-dimension case and it is not efficient for this type of problem.

The efficiency of physical computation is thought to be due to its parallelism. This aspect is one of the essential part of "quantum approach to mind" (e.g., by Penrose [3]) where superposition principle is employed; all possibilities are evaluated in a parallel manner. We do not think quantum mechanical phenomena directly affect for mind (or cognition) and solution of variational problem are obtained in other layers, like neural network or nonlinear body dynamics.

In addition to parallelism, we assume deformation of the coordinate system is another important feature. In 1960s, Amari [4] proposed that encoding process of telecommunication is represented by Riemannian geometry, as the prototype of his theory of information geometry proposed in 1980s. In this theory, the encoding method is represented as an embedding method into a high dimensional space.

Here, an encoding process is regarded as a mapping to a deformed coordinate system (i.e., transformation of the metric). Although this theory was abandoned, the idea that encoding process can be represented as geometry suggests deformation can be realized using neural circuits. In brain, especially in human, cognitive process spans across many areas of cortex and we can expect communications via neural transmission occur frequently.

The use of deformation in information representation, i.e., the latter feature of our hypothesis, has the key role of our idea. This feature can be represented by exterior algebra. While this is commonly used in physics where the effect of deformation of the space is significant (e.g., general theory of relativity), it is also used in motor control.

Tanaka [5] showed that equation of motion of arm movement is substantially simplified by exterior algebra. Instead of using joint angles, CoM (Center of Mass) of each body segment and its derivatives are used in cross product form, e.g., $\mathbf{X} \times \mathbf{V}$. An obvious merit of this formalism does not suffer combinatorial problem when Lagrangian is differentiated. On the other hand, a disadvantage is that positions of CoMs need to be obtained, by visually or by kinematically.

Considering redundancy and constraints in human kinematics, solution of above representation of equation of motion based on exterior algebra can be regarded as a variational problem in Riemannian geometry. Constraints, such as coordination pattern or cost functions, are thought to effectively deform the space to obtain controllability in physical computation. In other words, brain adopts constraints to the body to reduce degree of freedom (DoF) and body dynamics physically solves variational problem. Also, feedback information, such as somatic sensation (i.e., from the body) and visual and other sensations (i.e., from the environment) updates the information representation in brain for better understanding and planning of movements. Thus, feedback loop of interplay between information representation and physical dynamics is formed. This idea is thought to contribute to find an answer for the question 6: **What is the role of embodiment in the synthetic exploration of cognition?** The idea of interplay suggests that physical dynamics is not completely controlled by the brain and cognitive process is helped by physical dynamics.

Our practical approach to this problem is to understand motor control of human brain by adopting external constraints (i.e., change of metric) to the body. In this approach, interaction between constraints and physical dynamics (i.e., physical computation of variational problem) is expected to emerge versatile controllability of body dynamics. Because still we do not know how the brain-body interaction is implemented, our approach is to analyze human as a testbed. We are currently developing exoskeleton mechanisms with number of motion sensors and braking mechanisms.

Using this device, we are planning to analyze the variability of motion trajectory under different constraints in the exterior algebra space to find appropriate metric to explain it. Physically, the change of metric may correspond to modification of strength of coordination pattern among joints (e.g., co-activation pattern of muscles). We have found that that hierarchical differentiation of coordination pattern in skillful movements [6] and its representation in appropriate metric space will be a possible direction. Mathematically, the metric is thought to correspond encoding method in Amari's theory and may be an essential part of motor planning mechanism in brain. We still do not have whole picture of synthesis of cognition but we believe understanding of encoding method greatly contributes: the information representation that encoded in brain is thought to give basis of cognitive processes.

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