Equilibrium Point Hypothesis Revisited: Advances in the computational framework of Passive Motion Paradigm

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The underlying motivation behind the equilibrium point hypothesis (EPH) is the understanding that during movements a huge amount of energy can be stored passively in the biomechanics of the muscle system and controlling the flow of such energy can improve/simplify the motor control task for the brain. Although such "energy" can be attributed to the mechanical properties of tendons and muscles, this by no means is the only possibility. A plausible generalization of the EPH concept (in a purely computational sense) is that the goal and multiple constraints (structural, task specific etc) that characterize any given task can be implemented as superimposed force fields that collectively shape an energy function, whose equilibrium point drives the trajectory formation process of the different body parts participating to a motor task. This was the central idea behind the formulation of the Passive Motion Paradigm (PMP, Mussa Ivaldi et al,1988). The basic PMP framework has evolved in the recent years into a plausible language for describing motion planning in both humans and humanoids. The key advances are: a) Integration with terminal attractor dynamics for controlling the timing of the PMP relaxation, synchronization between motion of different body parts (Tsuji et al 2005); b) Formulation of branching nodes, for structuring PMP networks in agreement with the body that needs to be coordinated like humanoids, wheeled platforms etc (Mohan et al 2009) and the kinematic constraints of a specific task (when external objects are coupled to the body); c) integration with higher level cognitive layers like reasoning and mental simulation of action (Mohan and Morasso 2007); d) synergy formation during whole body reaching (Zenzeri et al 2009). In this paper, we present two composite PMP networks to highlight these advances 1) PMP network to coordinate the 'Left arm-Trunk-Right Arm' chain of the 53 degrees of freedom humanoid iCub ; 2) PMP network for focal and postural synergy formation during whole body reaching (WBR). As seen in panel C (figure 1), the computational model is a fully connected network of nodes either representing forces (shown in pink) or representing displacements (shown in blue) in different motor spaces (end-effector space, joint space, muscle space, tool space etc). There are two kinds of connections 1) Vertical: between each force and displacement node that describes the elastic causality of the coordinated system (stiffness and admittance matrices) and 2) between two different motor spaces that describes the geometric causality of the coordinated system (Jacobian matices). In complex kinematic structures we also introduce three additional nodes: Ground node that determines from the parts of the body through which the induced force fields propagate; Sum and Assignment nodes to add or assign displacements and forces to different connecting elements of the kinematic chain. The motion of the kinematic chain evoked by the activation of a target is equivalent to integrating non-linear differential equations that, in the simplest case in which there are no additional constraints, takes the following form: $\dot{x} = J\,A\,J^T\,K\left(x_T - x\right)$. However, multiple constraints can be concurrently imposed in a task-dependent fashion by simply switching on/off different task relevant force field generators. For example, the computational scheme of panel C integrates an external constraint of reaching the goal with a specific hand orientation and an internal constraint of keeping the motion of all joints in mid range of the permissible limits, with the root goal of bimanually reaching the large cylinder. Similarly, in the case of WBR, the focal and postural components can be associated to two force fields 1) applied at the finger tip for reaching the target and 2) force field applied at the hip to keep the projection of the center of mass within the bipedal support area. Ongoing experiments with the iCub suggest that PMP indeed is an efficient, real time computational framework for motion planning in humanoid robots. On the other hand, simulations of the PMP network for WBR shows that it exhibits many of the spatio-temporal features found in experimental data 1) the motion of the center of mass appears to be synchronized with the motion of the hand and with a proportional amplitude 2) the joint rotation patterns can be accounted well by a single functional degree of freedom, as shown by principal component analysis. Further, recent findings in motor imagery support the idea that the PMP network may represent the motor cognitive part of synergy formation, uncontaminated by the effect of execution. In conclusion, our experimental results demonstrate that EPH has a range of validity which is much wider than initially proposed and is indeed a very general mechanism for the formation of complex synergies like whole body reaching and coordination of movements in humanoid robots.

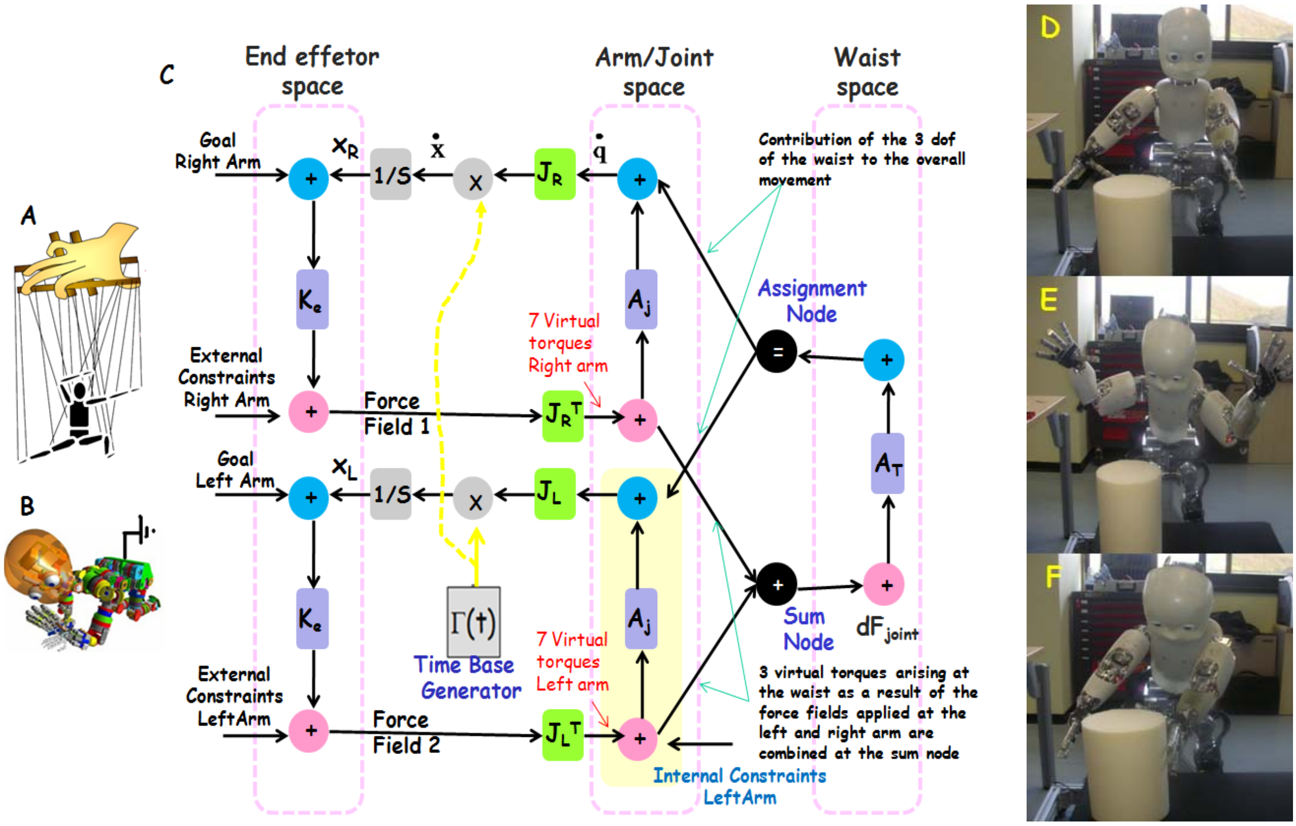

Figure 1. Panel A The "computational mechanism of relaxation under the attractor landscape of PMP is analogous to coordination of the movements of the puppet by menas of attached strings, strings in our case being the virtual force fields representing the goal and task specific constraints involved in the motor task . Panel C: Composite PMP network for Upperbody coordination in iCub. A virtual spring attracts the two end-effectors to the target, thus generating attractive force fields $F=K_e(x_T-x)$, where K plays the role of a virtual stiffness in the extrinsic space. These fields, can be integrated at runtime with other force fields that express various external (like, appropriate wrist orientation) and internal constraints(like, joint limits) related to the task. A_J and A_T are the virtual admittance matrices in the joint and waist space respectively. Modulating them affects the contributions of different joints to the overall solution. The waist joint of the robot is "grounded" in this case (as shown in panel B). The "sum node" allows force fields in different PMP subnetworks to be combined in determining the motion of the waist. The "assignment node" propagates to the two arms the motion of the waist. Panels D-F: Goal is to to bimanually reach the large cylinder (placed asymmetrically w.r.t. the robots body); Panel D shows the solution obtained if the network is grounded at the shoulders, i.e waist is stiff and only the DoF of the two arms are involved in the PMP relaxation; Panel E-F shows the solution obtained by the PMP relaxation applied to the whole upper body in order to achieve the goal. We can observe the contribution of all three DoF of the torso (coupled with appropriate adjustments in the right arm chain) in order to enable the left arm to cover the additional distance necessary to reach the target (along with the right arm).

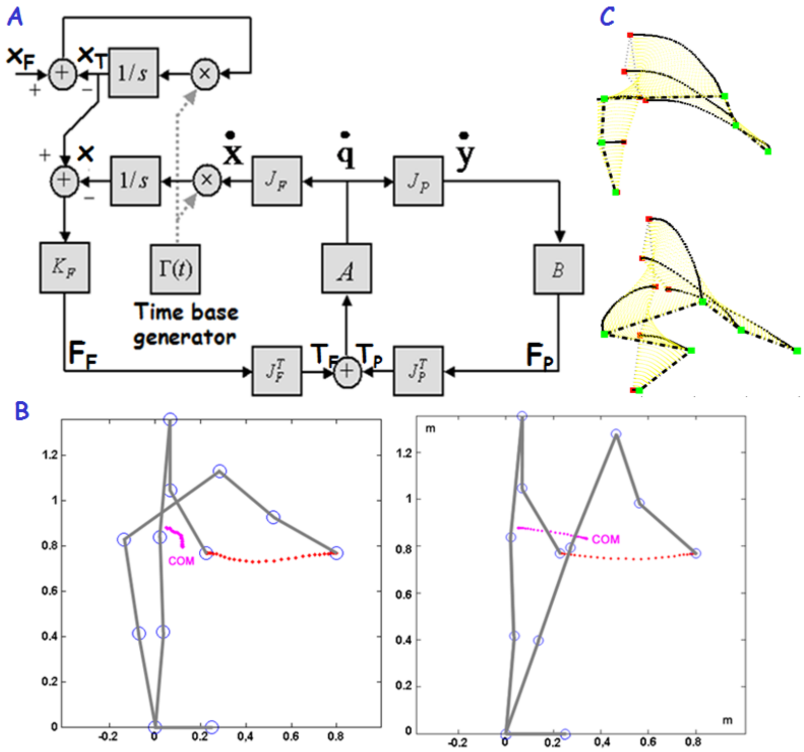

Figure 2. Panel A: PMP network for the coordination of balance and focal movements. J_F is the Jacobian matrix of the overall kinematic chain (from feet to hands) used for the focal part of the task and K_F is the corresponding stiffness matrix in the extrinsic space; J_P is the Jacobian matrix of the subset of the kinematic chain, up to the hip, that is used for the postural part of the task; 'A' is the admittance array in the intrinsic space; 'B' is the viscosity matrix, in the intrinsic space, which aims at reducing the forward shift of the CoM; Γ(t) is the time base generator that induces terminal attractor dynamics. Panel B: Simulation of the PMP network with (left, topmost panel) or without (right, topmost panel) the activation of the postural part of the network. In absence of the postural field (right part of the top panel) the CoM would overcome the limit of the support base and thus induce a forward fall. The activation of the field induces the following effects: 1) a much smaller forward shift of the CoM; 2) a backward shift of the hip (typical of the so called "hip strategy"); 3) a forward tilt of the trunk associated with the lowering of the CoM. Panel C: Reaching a far away target from a quiet standing posture using Hip Strategy (knee freezing) and Normal reaching.

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