

Biomimetic control for redundant and high degree of freedom limb systems: neurobiological modularity

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Abstract. We review the current understanding of modularity in biological motor control and its forms, and then relate this modularity to proposed modular control structures for biomimetic robots. We note the features that are different between the robotic and the biological ‘designs’ with features which have evolved by natural selection, and note those aspects of biology which may be counter-intuitive or unique to the biological controls as we currently understand them. Biological modularity can be divided into kinematic modularity comprised of strokes and cycles: primitives approximating a range of optimization criteria, and execution modularity comprised of kinetic motor primitives: muscle synergies recruited by premotor drives which are most often pulsatile, and which have the biomechanical effect of instantiating a visco-elastic force-field in the limb. The relations of these identified biological elements to kinematic and force-level motor primitives employed in robot control formulations are discussed.

Keywords: motor primitives; synergies; pattern generators; stability; hierarchy; modularity; degrees of freedom.

1. Introduction

Over the last 40 years or so our understanding of modularity in the motor control systems of animals has grown enormously. The problems animals face in controlling a high degree of freedom articulated skeleton with redundant actuation were first discussed in detail by Bernstein (1967). The biological system manages the degrees of freedom remarkably well. The complex body mechanism and its neural controls provide animals with exquisite mechanical abilities. The motor system’s redundancy allows routine motor acts to be performed in various flexible ways: the *motor equivalence* notion introduced by Bernstein. We can sign our name with a precision grip on a pen, a power grip on a chisel or our toe in the sand at the beach and all will likely be recognizably our signature. Motor equivalence can support inventive and novel behaviors in many species. Humans may also routinely develop and perform novel manipulative acts which were perhaps never before used in human history: for example working under a car to undo an oil nut, or a novel choreography in the arts. Biological systems also allow flexible movement synthesis and exploration while mostly avoiding catastrophic failures and instability, despite using controls with long delays. At the same time as biological control supports such flexibility and novel action, much action is not likely to be learned: many animals can also develop complex actions remarkably fast. A wildebeest calf in the Serengeti is walking with the herd in a few hours and newly hatched turtle on a caribbean beach is rapidly

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locomoting down the beach to the water – usually in seconds to minutes. Biological systems thus show immense flexibility, robust controls, and rapid construction of effective action ‘out of the box’. Our purpose here is to give a brief overview of our understanding of biological motor control modularity and how its features may be related to ideas in robotic control and bio-inspired frameworks.

2. Neurobiological modularity

Modularity is seen at several levels in biological motor control. At kinematic levels of description, clearly repeatable action units are seen. These units also have modular underpinnings at kinetic and actuator control levels of description. In the biological perspective, modularity is observed as a reduction in degrees of freedom. There exist compact representations of animals’ movements and their controls, despite the potential high degrees of freedom available. It is possible to make representative recordings of limb and body kinematics and the electrical/neural drive signals in, or travelling to, the muscles that are generated by the central nervous system (CNS). Such data can then be used to infer the controls and drives for the actuation of movement by the muscles pulling on the skeleton and generating appropriate torques. In ‘reduced preparations’, (animals with large parts of CNS removed), it is also possible to humanely perform experiments to directly record the muscle forces, or the forces in the limb while it is held immobile. In such preparations, it can be shown that the animal’s remaining CNS has significant capacities and ably controls the body to move to some limited but significant purpose such as scratching or walking. It is then possible to analyze and dissect the patterns and modes of change in the kinematics, kinetics, and muscle spatial and temporal drive patterns and their controls, so that the biological control schemes can be ‘reverse-engineered’. These efforts have generated a body of information on the phenomenology of movement controls, the strategies used to manage the limb and motor degrees of freedom, and the structure of the neural controls.

2.1 Kinematic modularity

Human and animal movements show a range of interesting features and modularities. In general, limb end-point motions show fairly straight, unimodal and bell-shaped tangential velocity profiles. These profiles and the resultant segmentation into ‘kinematic strokes’ were noted by Viviani and Terzuolo (1982) and Hogan (1984), Flash and Hogan (1985). The profiles are consistent with a kinematic optimization: trajectories are well predicted and fitted by an endpoint minimization of jerk (Hogan 1984). For point to point motions, these features are preserved by neural adaptation processes under a range of loads and in different environments (Flash and Hochner 2005, Burdet and Milner 1998, Rohrer *et al.* 2002). At the same time, largely as a result of features of biological limb design, the kinematic optimization observed is also consistent with various kinetic and task optimizations (e.g., minimum torque change, and minimized signal dependent noise at the muscle, see Wolpert *et al.* 2001). A range of learning, correction and rehabilitation phenomena are consistent with superposition of collections of kinematic strokes by the CNS (Rohrer *et al.* 2002, Sossnik *et al.* 2004). More mathematically principled stroke bases suitable for understanding complex 3D kinematics are under development by Flash and colleagues (Polyakov *et al.* 2009).

A second natural modularity observed in the kinematics of animal motion is into cyclic patterns, for example in stepping or running or breathing or chewing etc. These cycles are usually viewed as

being qualitatively different in their neural control and neural support structures from point to point strokes. The differences between rhythmic and discrete unitary motions are an area of active investigation (Hogan and Sternad 2007). Kinetically there may be energy storage, transfer and conservation throughout such cyclic motions, and thus optimizations of these. In rhythmic stepping motions it has been shown that many different types of optimizations are nearly satisfied simultaneously by the patterns of motion chosen (Collins 1995), subject to the limitations of the biomechanical models used (see Pai 2010). This kinematic/kinetic optimization overlap and its matching is a strong feature of biological design and control. Desirable as they are functionally, these many overlaps also confound efforts to use simpler analyses of biological control optimizations and design principles. The framework of kinematic division into strokes and cycles has inspired several motor control frameworks (see Raibert 1986, Koditschek *et al.* 2004) and a particular framework for modular robotic control design due to Ijspeert, Schaal and colleagues (Ijspeert *et al.* 2003, Schaal *et al.* 2003, see below).

2.2 Modular patterning systems

At the level of actuation, modular and repeatable neural controls for rhythmic motions have been established by work of Wilson, Grillner and their successors in both vertebrate and invertebrate animals (Wilson 1961 and see review of Marder and Bucher 2001). The central nervous system can organize modular patterns for many different types of behaviors (usually rhythmic) independent of feedback or patterned input. A fully paralyzed ‘reduced’ animal (achieved through muscular blocking agents) can nonetheless generate locomotor-like patterns and so on. The nervous system, it is inferred, thus has a feedforward drive system for rhythmic activities that anticipates the features of driven mechanical events – at least to some extent. These drive systems, termed ‘central pattern generators’ (CPGs), are embedded in spinal or other lower CNS neural structure. CPGs can be shown to have some internal modularity. It has been suggested that they may comprise collections of oscillating systems for different body parts (e.g., individual legs, and maybe individual limb joints or assemblies of these etc). Ensemble coordinated and syncopated patterns of movement may arise from the coupling of such collections of oscillators in the overall CPG. Coupling may be wholly central (in paralysis) or achieved using (or even dominated by) feedback in unparalyzed motions so as to adapt the rhythmic processes to body mechanics and kinetic conditions. The operationally defined and dissected biological ‘CPG’ could represent several types of controller. For example, there might be neural networks in CNS implementing dynamical system limit-cycle oscillators, or there might be a kind of finite state machine that cycles through states in the absence of rhythmic inputs. Recent data from paralyzed decerebrate cat research supports a possible hybrid of these: a rhythmic or clocking system layer (building the oscillatory timing features and perhaps performing state sequencing) is hierarchically placed above (and controls) a pattern shaping layer. The latter is responsible for building the detailed motor pattern sequences and/or contingent states for locomotion and choosing which muscles are activated in what order (McCrea and Rybak 2007, Quevado *et al.* 2005, Lafreniere-Roula and McCrea 2005).

2.3 Low-level actuation structure modularity

Statistical analysis of motor patterns has been used in animal and human systems to examine modularity (Tresch *et al.* 2006, Hart and Giszter 2004). In both rhythmic and non-rhythmic biological systems, ranging from the frog spinal cord to the intact or injured human being, applications of

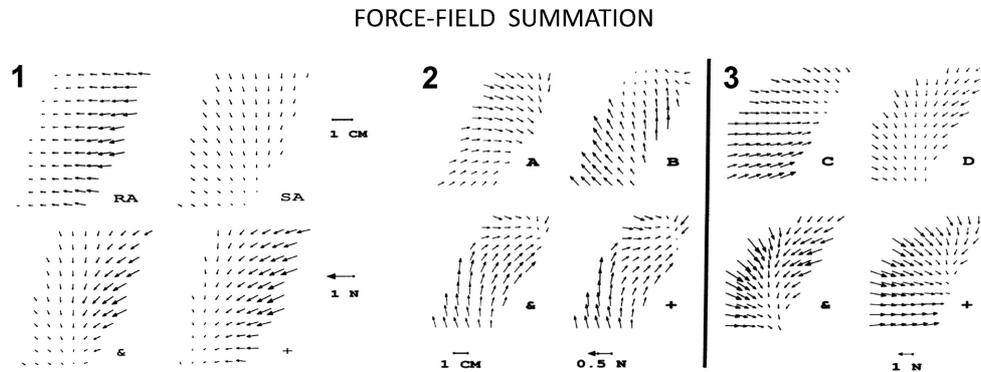


Fig. 1 *Panel 1*. Muscle field summation: two muscles rectus anticus (RA) and Sartorius (SA) of a spinal bullfrog were activated by electrical stimulation of the individual muscles and then coactivated. The effect of the coactivation (&) is a near calculated vector sum (+) of the fields elicited, separately. *Panel 2 and 3* Force-field primitive superposition. In each case a group of muscles was activated by stimulating spinal interneurons targets and fibers at sites A,B, (in 2) and at sites C and D (in 3). The costimulation effects (&) and vector sum (+) of each field combination A and B, and C and D are displayed. Linear superposition of fields held in 80% of combinations (A+B) in 2. In 20% of costimulations instead of the sum, a winner take all response resulted (shown in 3). Summation is seen in spinal behaviors (see Figs. 2 and 3). Assembled from figures in Mussa-Ivaldi *et al.* PNAS (1994), with permission

statistical decomposition techniques and other manipulations reveal a remarkably similar breakdown of the muscle activation patterns into modular muscle groups (or synergies or drive motor primitives). These groups or synergies are activated as pulses in sequence or simultaneously, and adjusted and adapted in response to the task conditions (Hart and Giszter 2004, Cappellini *et al.* 2006, Torres-Oviedo *et al.* 2006, Torres-Oviedo and Ting 2007, D'Avella *et al.* 2008, Muceli *et al.* 2010). Dimensionality reduction is thus clearly the rule in the motor pattern. The data are generally consistent with a separate sequencing and control of a smaller set of premotor drives in each task. The principle problem currently facing researchers in motor control in this area is the precise origin of these modular structures that are observed in task execution: are they built-in by evolution, learned in child development or developed de-novo on-line in task solutions?

2.3.1 Premotor drive modularity

Drive pattern modularity as described above (groups of muscles coalesced into a single unit of common drive) has been observed in almost all systems examined, with the exception of the finger controls in man (Kutch *et al.* 2008). In general as noted above, the drives are pulsed, often with limited temporal durations and in some instances even with fixed durations (Hart and Giszter 2004, Kargo and Giszter 2000). Drive pattern temporal decompositions of this kind can be constructed by both statistical and more direct physiological means (Kargo and Giszter 2000, 2008). These provide unified accounts of spinal reflex behaviors and adjustments, motor control for balance in cats and man, stroke and normal arm control in man, and cat locomotion, human locomotion, and human locomotion stroke recovery (Kargo *et al.* 2010, Cappellini *et al.* 2006, Krouchev *et al.* 2006, Cheung *et al.* 2009, Torres-Oviedo and Ting 2007). As noted above, different researchers view the drive pattern modularity observed in different ways with regard to its fundamental origins: some favor built-in structure (evolutionary constraint and adaptation, Giszter *et al.* 2007, 2010), and others a stronger

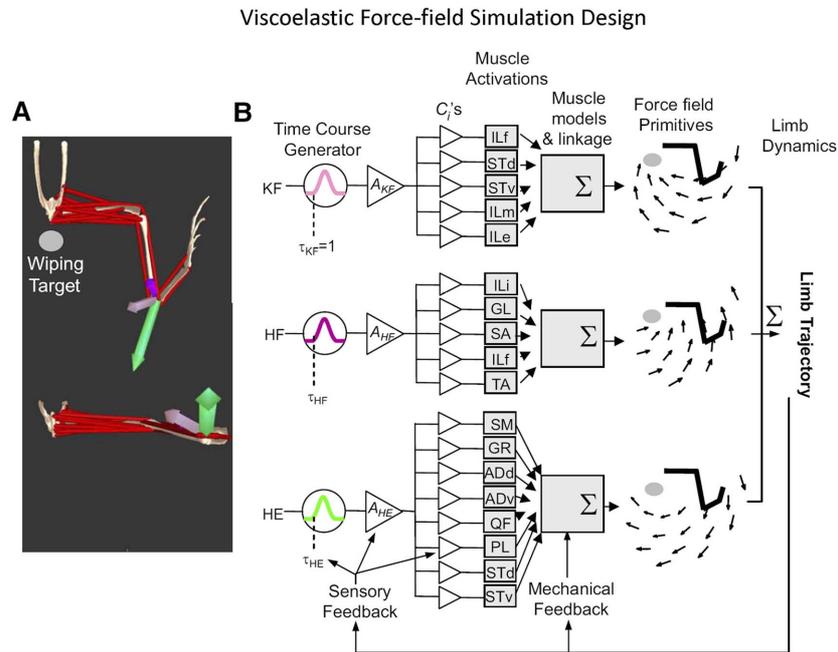


Fig. 2 Simulating hindlimb wiping with a detailed model of the frog pelvis–hindlimb complex. *A*: the 13 hindlimb muscles forming the model are shown as red lines. Colored arrows mark the direction of the 3 force primitives that comprise the isometric wiping response: *KF* (knee flexor primitive), light purple; *HE* (hip extensor primitive), green; *HF* (hip flexor primitive), dark purple. *B*: the framework used to simulate wiping (left to right): each primitive had a time-course generator, which output a normalized waveform (peak = 1.0) at time τ . The variable A scaled this waveform, which was then distributed to each of the muscles comprising the primitive. Each muscle had a muscle-specific variable C that scaled the excitation waveform. The muscles generate contractile forces MF that are transmitted through the limb to produce an isometric endpoint force (at one position) or force field FF (when forces are measured across a range of positions). Normalized force fields produced by each primitive are shown in the far right. When the model limb is freed to move, MF s drive the motion of the model. MF values are in turn regulated by limb motion (e.g., force–velocity and force–length properties of muscle and stress–strain properties of in series connective tissue). In our model, sensory feedback from muscles potentially regulate τ , A , or C . Reproduced from Kargo *et al.* 2010 *J. Neurophysiology* 103:573-590 with permission

role for development and/or motor learning (Bradley *et al.* 2003, 2005, 2008, Schouenborg 2004) or for adult or on-line identification and adaptation of drives (Todorov and Gharamani 2003, Chabra and Jacobs 2006). However, the outcome is similar: pulsed unitary drives are employed for movement construction in a task-specific or task-generalized fashion, and whether built-in or constructed anew in each task control (Fig. 2). The driving of a group of muscles as a unit observed in so many tasks and species in biomechanical terms provides a specific type of kinetic module – a force-field primitive–which can be used as a compositional basis and has been tested directly in other experiments. This description forms a natural link to the compositional elements used in robotic frameworks with biological inspiration or linkage.

2.3.2 Force-field primitives

Muscles are intrinsically visco-elastic and these properties vary quantitatively and systematically

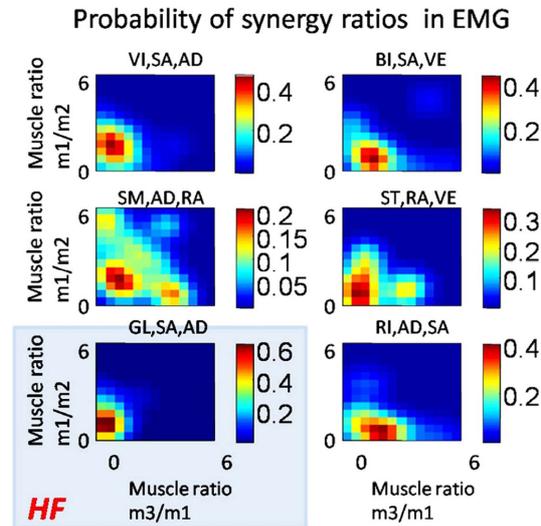


Fig. 3 Stability of muscle proportionality ratios in the 6 main primitives observed across frogs, and behaviors. The action of the spinal cord across the tested behaviors was to recruit the muscles in a fixed ratio and couple muscles to generate specific force-field primitives and preflex responses. Reflex actions (i.e., feedback effects) modulated these primitives, and thus acted on their component muscles as groups. Reproduced from Figure 10A in Kargo *et al.* 2010 *J. Neurophysiology* vol 103: 573-590 with permission

with activation, level of contraction, and history of activation. The activation of an assembly of muscles as a unit thus potentially generates a well-defined and time-modulated visco-elastic field in the limb which depends in its details on the initial limb state. This visco-elastic field description has been shown to capture the actions of muscle drive synergies (Bizzi *et al.* 1991, Giszter *et al.* 1993, Mussa-Ivaldi *et al.* 1994, Kargo and Giszter 2000) and to represent the output of the spinal cord under artificial electrical stimulation (Bizzi *et al.* 1991, Giszter *et al.* 1993, Tresch and Bizzi 1999, Lemay and Grill 2004). The visco-elastic fields generated have well defined properties and structure through time (Giszter *et al.* 1993, Kargo and Giszter 2000, 2008). They show the nice property of near linear vector superposition when combined through electrical stimulation, or through natural drive co-activation (Mussa-Ivaldi *et al.* 1994, Kargo and Giszter 2000, 2008, Giszter and Kargo 2000). See Fig. 1. Feedback systems in the spinal cord also appear to support, rather than disrupt, these visco-elastic force-field structures (Kargo and Giszter 2008), and see Fig. 3. The limb driving forces and actions of feedback systems thus act in concert through the complex soft tissue ligament and tendon systems and through the resulting moment arms and linkage Jacobean to generate a scaled and summable viscoelastic field. This force-field is a predictable pattern whether measured or activated as a 'preflex', reflex or voluntary driven pattern, and can be characterized as a scaled version of a 'force-field motor primitive' corresponding to the premotor drive primitive pulses occurring in the motor pattern. The action of a group of muscles recruited en masse by a unitary premotor drive can also be expressed as a linear sum of the individual muscles viscoelastic contributions. At the level of the motoneurons the premotor drives sum linearly, although the nervous system has the ability to modulate recruitment gain more broadly across the entire ensemble of motor pools from task to task with various neuromodulators. Accordingly, the actions of multiple simultaneously pulsed drives and their associated muscles recruitment effects can be summarized as

$$F(q, \dot{q}, t) = \sum_i A_i a_i(t) \Phi_i(q, \dot{q}) \quad (1)$$

where q is a configuration vector, F is the total limb force-field, A_i is the amplitude of the activation of the i th force-field motor primitive, $a_i(t)$ is the normalized activation time course of the i th primitive (in practice a similarly scaled pulse), and Φ_i is the normalized viscoelastic field associated with the i th premotor drive and its collection of associated muscles. See Fig. 2. This mechanism of summation was demonstrated experimentally (Mussa-Ivaldi *et al.* 1994, and Fig. 1). (Note: Because the fields Φ_i consist of a sum of scaled individual muscle fields it is also possible to expand this framework of constrained low degree of freedom motor primitives easily to the fully capabilities of the motor system mechanism if individuated muscles are driven independently from the constrained drive set, and in Fig. 1 panel 1.)

To generate a time varying drive field and torques needed for an action using the individual premotor drive pulses these may be repeated and staggered in different combinations

$$F(q, \dot{q}, t) = \sum_i A_i a(t + \tau_i) \Phi_i(q, \dot{q}) \quad (2)$$

Where τ_i represents the time shift of the i th drive pulse. The competence of this framework to represent

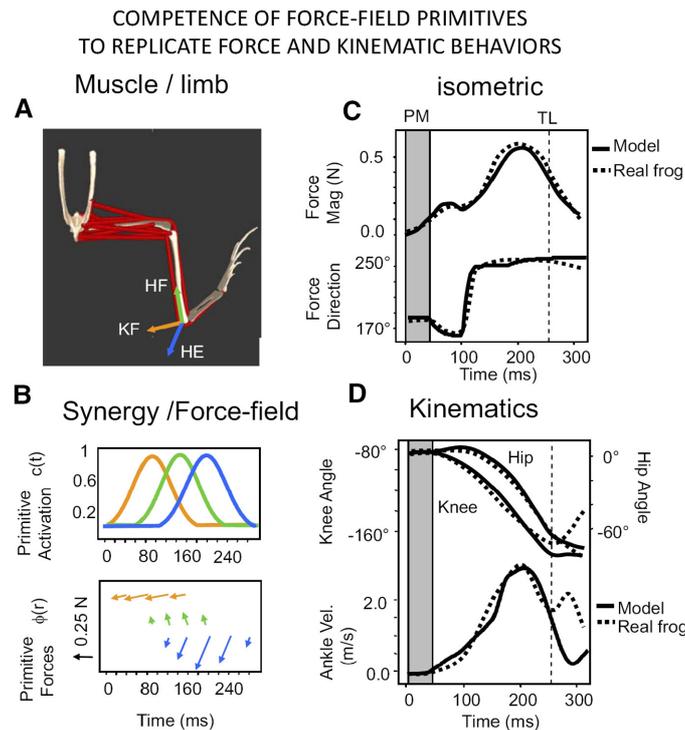


Fig. 4 Simulating wiping forces and kinematics with the primitive framework and model frog. *A*: model structure. *B*: activation of muscles was constrained to conform to a set of synchronous synergies/primitives of fixed endpoint forces. *C*: the isometric force pattern produced by the model frog (solid lines) closely matched the force pattern recorded experimentally (dotted lines). *D*: after making minor adjustments to the isometric motor pattern (see text), the model frog also reproduced the free limb kinematics of the experimental frog. The *top row* shows hip and knee angles. The *bottom row* shows ankle velocity. Dashed line marks the time of target limb contact in the real frog. The gray area (PM) represents the 40-ms premovement period between EMG onset and motion onset that is observed in real frogs

spinal generated behaviors has been tested (Kargo *et al.* 2009, see Fig. 4). This framework maps cleanly onto the inferred hierarchical control behavior of the pattern shaping systems in the two layer scheme of pattern generation suggested by McCrea, Rybak and others. Rhythmic motion could then derive from rhythmic recruited pulsing of premotor drive/ force-field primitives, and unitary kinematic strokes derive from systematic sequencing of pulsed premotor drive/ force-field primitives. This bipartite biological scheme and the modularity observed at kinematic and kinetic levels has parallels in bioinspired and biomimetic controls of robot systems.

3. Frameworks for modular control

3.1 Kinematic motor primitives

Inspired by biological pattern generation and kinematic segmentation into strokes and cycles, Ijspeert and Schaal have developed a scheme of kinematic motor primitives. Their scheme was designed to capture kinematic imitation learning and is based on discrete and rhythmic kinematic control policies formulated as acceleration fields, and is essentially a planning framework (Ijspeert *et al.* 2003, Schaal *et al.* 2003, Schaal and Schweighofer 2005). Ijspeert *et al.* (2003) describe their design framework thus:

“The design parameters of the discrete system are τ , the temporal scaling factor, and g , the goal position. The design parameters of the rhythmic system are y_m , the baseline of the oscillation, τ , the period divided by 2π , and r_o , the amplitude of oscillations. The (*other control policy*) parameters w_i are fitted to a demonstrated trajectory using Locally Weighted Learning.” (*phrases in italics added here for clarity*)

Details of execution, and stability are not directly managed. A primary difference from the biological schemes outlined above is thus that a lower level controller in the robot that is hidden from the planning scheme is used to implement the acceleration fields that are constructed from the kinematic primitives in planning and imitation learning. It is this low level layer of control that is used to guarantee their execution and avoid instability. This scheme, corresponding well to the kinematic levels of modularity and description in the biological literature provides a powerful basis for imitation learning and generalization using the low-dimensional design parameters for single limbs. It does not directly manage forces or compliance as noted above, and thus despite its applications to limbed locomotion in salamander-like robots, it may be relatively brittle in dealing with closed kinematic chains in complex quadrupedal or bipedal locomotion in its original form. A related but alternative strategy of composition draws on the biological premotor drive and force-field primitives noted.

3.2 Force-field motor primitives

Mussa-Ivaldi (1992) developed a movement design and composition scheme based directly on the biologically force-field primitives (Mussa-Ivaldi and Giszter 1992, Mussa-Ivaldi 1996, Mussa-Ivaldi and Bizzi 1994). A driving force-field is constructed from a combination of radial basis force-fields, which can take one of two forms. Mussa-Ivaldi (1992) showed an arbitrary smooth static field may be approximated with a combination of equal numbers of static circulating and conservative fields

$$F(q) = \sum_i A_i \Phi_i(q) + \sum_i B_i \Theta_i(q) \quad (3)$$

Where the Θ are circulating fields and Φ are conservative fields. Extension of this framework to viscoelastic fields is trivial. With a combination of circulating and conservative fields both point to point and rhythmic motion could be synthesized using a static drive field (with clear links to the acceleration field framework above), thus driving motions without explicit time representation in principle. Comparing this framework to the biological data, what is remarkable in the biology is the total absence of the circulating fields in experimental data. In the biological schemes so far observed, circulating fields are avoided. This restricts the compositional system and may force an explicit time-representation. An answer to the conundrum as to why the biological system limits itself in this way may derive from other work on robotics stability issues, by Colgate and Hogan (1988), and presence of the biological delays and consequent stability difficulties inherent in circulating fields (see Hogan 1985). Their work has shown that by emulating passive and conservative systems stability can be guaranteed in coupling to other controls emulating passive and conservative systems. The biological system, by avoiding circulating fields even in the context of a need for cyclic motor acts, may be constraining motor production to regimes of guaranteed stability even the face of potentially infinitely varied compositional combinations.

In this case, the problem of motion synthesis and adaptation can be described as follows. We can write limb or body dynamics

$$M(q)\ddot{q} + G(q, \dot{q}) + E(q, \dot{q}, t) = F(q, \dot{q}, t) \quad (4)$$

Where $M(q)$ represents inertial terms, G interaction terms, E environmental forces, and F the torque generation by the musculo skeletal plant. The problem of movement generation and interaction is then to deliver an appropriate set of forces F to satisfy the task constraints. These constraints may be purely kinematic (e.g., pointing, or gesture), the action of counteracting an environmental force / load (e.g., stationary support of a book) or a combination of target motions and interaction forces with the environment (e.g., martial arts or manipulation of a paint brush, see Mussa-Ivaldi and Bizzi 2000). Following the approach of Mussa-Ivaldi, activity of muscles and feedback pathways as a group can be generically represented as a multidimensional time varying force-field in joint space

$$F(q, \dot{q}, t) = C(q, \dot{q}, u(t)) = \sum_i A_i a_i(t + \tau_i) \Phi_i(q, \dot{q}) \quad (5)$$

Where q_i, \dot{q} , are joint angles and angular velocities, and t is time, F is the field expressed as joint torques, in general joint coordinates, $u(t)$ is the applied control and C is a (noninvertible) function transforming muscle activations to F . Spinal force-field motor primitives can provide a modular basis for constructing this potentially arbitrary field and designing $u(t)$ as on the right through selections of A_i and τ_i for basis fields Φ_i . Integration of this biologically plausible scheme with the purely kinematic acceleration-based fields used by Schaal and colleagues as a broader robot control and basis set remains as an area of active research. It is clear the mapping between these compositional frameworks is not 1:1 in biological systems, where we have observed that multiple sequence force-field primitives organize a single kinematic stroke, and circulating fields are avoided. Nonetheless, the framework of premotor drive/muscle synergy/force-field primitives can support a compact description of the optimal or near optimal control ‘affordances’ of a mechanism (e.g., see Berniker *et al.* 2009). Further, in biological systems it seems clear that switching of controls occurs to regulate interaction forces occurs at or before contact (Gorassini *et al.* 1994, Venkadesan and Valero-Cuevas 2008). Force-field and premotor drive /

synergy primitives can form a spanning basis set available to both types of controls by nature of their level of representation.

3.3 Extensions of primitives to contracting systems and temporal representation

Are biological systems really constrained in bases and controls, so as to always emulate passive systems? Likely in some instance this may not be the case. An alternative and broader notion of guaranteed stability is clearly possible. Lyapunov functions have been used to develop a biologically plausible compositional basis for coupling and superposition of modular controllers by Slotine and colleagues (Slotine and Lohmiller 2001, Wang and Slotine 2005). Drawing on dynamical system frameworks Slotine and colleagues show that a defined class of contracting systems, including both discrete and limit cycle modules can be combined appropriately with one another and with passive systems to guarantee contraction and thus long term stability. In studies of the frog limb it has been shown that muscle properties, acting as ‘reflexes’, provide trajectory stability properties which are consistent with behavior as contracting systems (Richardson *et al.* 2005a,b).

A major effort of engineering is often to remove the explicit representation of time in control system design. In the biological systems observed, the apparently explicit representation of time as part of a hierarchical rhythmic or timing system responsible for recruiting the constrained pulse durations primitives appear extremely prevalent and well supported. This is troubling, and raises questions of whether this biological structural organization and difference from many current engineering designs is an evolutionary accident, or a feature arising from exhaustive evolutionary search (e.g., see Zhao *et al.* 1996, Krishnamoorthy 2001, Huang and Xie 2010, Mirone 2009, Rajasekeran 2010 for application of evolutionary and GA search to solve non-linear structural engineering problems). One possibility is that perhaps this evolved biological hierarchy relates to stability issues, or is perhaps important to enable the system to syntactically, hierarchically and compositionally easily re-structure movements and sequences of movements for specific goals, or manage the inherent biological delays. It is clear that responding and adapting to temporally structured perturbations in the laboratory is difficult (Conditt and Mussa-Ivaldi 1996, Karniel and Mussa-Ivaldi 2004). The apparent role of rhythm generation and time representation in the biological design is thus currently still an open issue. Access to temporal information of CPGs may be limited, or sequence alone may be important. The possibility remains that the rhythmic hierarchical structures found in biology are simply a result of imperfect design constraints imposed by historical evolution, or else represent physical and computational limits on the biological control components’ ability to support particular computations and control algorithms.

3.4 Hierarchical schemes and nesting optimal controls

Motor behaviors that are flexibly constructed must usually then also be improved and adapted across contexts. Nested optimal feedback control frameworks (Todorov 2004, Todorov *et al.* 2005) have been proposed as a means to manage the degrees of freedom problem in such adaptation and optimization. It has also been argued that this type of scheme may eventually, at higher levels in the control hierarchy, develop many more contextual ‘primitives’ than there are muscles, for highly skilled optimal behaviors. These large libraries of primitives would support complex contextual learned skills. However, the need of the animal or robot system to bootstrap this hierarchy at a low level and to provide initial basis sets that allow rapid elaboration of useful actions without severe hazard remains

in this scheme, and is a point of discussion.

Working initially through low level bases that provide compositional support for anticipated basic operations of the agent and that guarantee stability when used in combination may be a very useful design feature for nested learning hierarchies to begin from.

4. Biological control design limits

Research in biological motor systems suggests that passive or contracting basis sets activated by limited temporal duration pulses may represent an ideal low level basis. Further, in the biological systems where visco-elastic force-field primitives derived from premotor drive pulses form this type of support, these drive pulses are chosen so as to be matched to the mechanism and derive many of their properties from the mechanical design of the effector limb. Evolution may have selected and co-adapted limb designs and compositional bases a priori in the biological system (Wagner *et al.* 2005, 2007, Welch and Waxman 2003, Callabetta *et al.* 2000, 2003, Callebaut and Raskin-Gutman 2005). This differs from most high degree of freedom robotics where there can be significant separation in time of the control design, from the design of the mechanical platform and properties of the limbs. In robotics there may possibly be very different design principles in each. Robot mechanisms may be general purpose mechanical designs aimed to support control scheme explorations. However, in the biological system the explicit matchings of the limb design and low-level neural control structures represent both a blessing and a curse. Some action is readily constructed and stability may be well supported in such biological matching. However, possible actions can be highly constrained both by the limb design and by the neural basis sets, and so they are limiting. Fullest use of the biological limb must circumvent or augment these mechanisms, and one task requirement of motor learning in biology may be to gradually transcend these constraints with more sophisticated layered controls (see Valero-Cuevas *et al.* 2007, 2009). For example in man this need may occur in order to support bipedal stepping in the infant (Pang *et al.* 2003, Yang *et al.* 2004, Dominici *et al.* 2007, Ivanenko *et al.* 2005) and then to learn fully individuated hand controls in limited contexts such as piano playing or fine manipulation (Valero-Cuevas, 2009, Valero-Cuevas *et al.* 2007). These processes can be lengthy and require specific nurturing environments. The level of plasticity in the low level biological control system and the degree to which low level control is structurally hardwired or can be plastic in such development is an open area of research in biology. The possibility of a fairly hardwired structure is very real (Hart and Giszter 2010) and the arguments for it from an evolutionary standpoint are fairly cogent (Giszter *et al.* 2010). Nonetheless, there are arguments on both sides (see Tresch and Jarc 2009 for discussion).

5. Conclusions

In the biological motor control system a major part of the structure of control and stability is embedded in the physical plant design and actuator dynamics. The neural controls match this structure and are clearly modular at lower levels in the control hierarchy. In part this is a means to deal with the slow transmission times, computation times and delay inherent in implementing controls with biological components. However, these biological systems and controls still surpass most robotic designs in performance, flexibility, generalization and robustness. We need a better

integration of both the results of robotics and control engineering with the biological research. Likely, continuing open dialogue will benefit both fields. The importance of the low level mechanical structure and its modular control in robust function is underscored in biology. The biological ‘design’ apparently involves a meshing of materials, dynamics and design non-linearities in the limb construction, that are matched to, and enable low dimensional robust and flexible controls. The problem which would be faced by the highly principled roboticist, following this biomimetic perspective to design robots from first principles, would be the exploration, utilization and management of this complex and open material and mechanical design space. The matching need to also understand better how this design space is explored and managed by evolutionary mechanisms in biology may be good note on which to end our review.

Acknowledgments

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