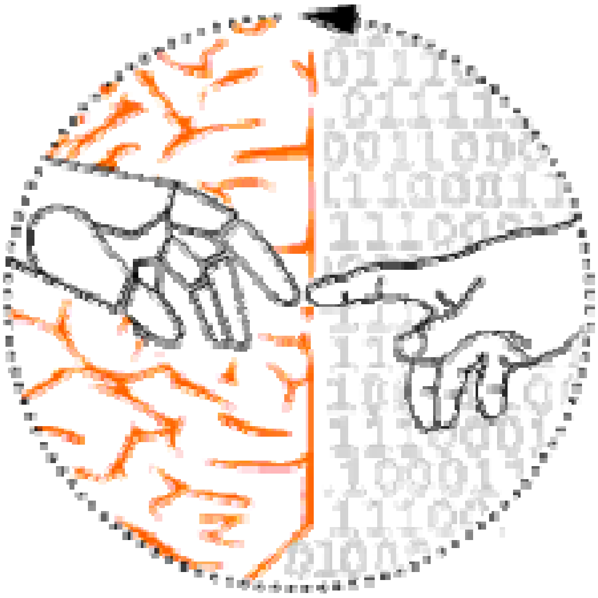

The Third Computational Motor Control Workshop at Ben-Gurion University of the Negev

June 13-14, 2007, W.A. Minkoff Senate Hall, BGU Marcus Family Campus, Beer-Sheva, Israel

http://www.bgu.ac.il/cmcw

Sponsors:

- The President, Ben-Gurion University
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- Opher Donchin, Ben-Gurion University
- Tamar Flash, Weizmann Institute
- Gideon Inbar, Technion
- Rich Ivry, Berkeley
- Amir Karniel, Ben-Gurion University
- Sandro Mussa-Ivaldi, Northwestern University
- Stefan Schaal, University of Southern California
- Eilon Vaadia, Hebrew University

Being in the desert leads us to ask questions about Origins of things, the timeless beauty and strength of Nature, the fragility and limits of human life and creativity

Dear friends:

On Wednesday the 13th of June right after the morning sessions, we are going for a trip to the Negev the Israeli desert.
We will begin with a beautiful viewpoint from the edge of Ramon's crater, which is a unique phenomenon in the desert.
Later, we are going to hike in the hart of the crater in river "Nikarot" approximately two and a half hours, then we will have a typical Bedouin dinner (the Bedouin are migrating desert men) full of desert tastes, with the desert sunset on the back round.

Meeting time: 12:30

Meeting place: At the Bus right outside the Senate Hall

What to bring: Back pack, sunscreen, a hat, comfortable clothes and shoes, and some snacks. Sandwiches for quick lunch and bottles of water would be available in the bus.

Cost: 150 NIS per person

We will be back in Beer-Sheva approximately at 9 p.m. at the Golden Tulip Negev Hotel

See you then
Eitan (the tour guide)

Wednesday, June 13, 2007

8:20-8:50 Registration, coffee

8:50-9:00 Greetings – **Dr. Amir Karniel**, head of the organizing committee, BGU

9:00-9:10 Opening remarks – **Prof. Rivka Carmi, BGU president**

Computation and Psychophysics

Chairperson: Prof. Anatol Feldman, Montreal

9:10-9:40 **Prof. Daniel Wolpert, Cambridge, UK**
Uncertainty in sensorimotor control

9:40-10:10 **Dr. Opher Donchin, BGU**
Learning by observation

10:10-10:40 **Prof. Philip Sabes, UCSF**
The eyes don't have it (all): Bayesian integration of motor plans across multiple reference frames predicts eye-centered reach errors

10:40-10:55 Discussion

10:55-11:20 Coffee

Basal Ganglia and Reinforcement

Chairperson: Dr. Opher Donchin, BGU

11:20-11:50 **Prof. Jim Houk, Northwestern University**
Agent-Based Models of the Motor System

11:50-12:20 **Prof. Hagai Bergman, Hebrew U.**
Motor repertoire is maintained by basal ganglia positive reinforcement learning

12:20-12:30 Discussion

12:40-20:00 Trip to the Negev and Dinner

Thursday, June 14, 2007

8:30-9:00 Registration, poster placement and coffee

Motor Cortex

Chairperson: Prof. Eilon Vaadia, Physiology, Hebrew U.

09:00-09:30 **Prof. Andy Schwartz, University of Pittsburgh**
Cortical Trajectory representation and Brain Machine Interfaces

09:30-10:00 **Prof. Ron Meir, Technion**
Control theory combined with a physiological plant model predict neural activity in motor cortex

10:00-10:30 **Dr. Nedialko Krouchev, CRNS, Montreal**
Neural computation for arm reaching: a realistic population model of interactions in the motor cortex with parallels to primate experiments

10:30-10:45 Discussion

10:45-11:40 Coffee and Posters

Spinal Cord

Chairperson: Prof. Gideon Inbar, Technion

11:40-12:10 **Prof. Uwe Windhorst, Goettingen, Germany**
Spinal recurrent inhibition: role in motor learning?

12:10-12:40 **Prof. Boris Prilutsky, GeorgiaTech, Atlanta**
Modeling the spinal CPG and neural control of locomotion

12:40-12:50 Discussion

12:50-13:20 Lunch

13:20-14:40 Posters

Neural basis of motor computations

Chairperson: Prof. Tamar Flash, Weizmann

14:40-15:10 **Prof. Pierre-Paul Vidal, LNRS, Paris**
Skeletal geometry and motor control

15:10-15:40 **Prof. Charles Capaday**, **CRULRG, Canada**
Linear summation of cat motor cortical outputs

15:40-16:10 **Prof. Natalia Dounskaia, Arizona State U.**
Optimization processes during arm movements revealed through directional biases

16:10-16:25 Discussion

16:25-16:30 **The ATI Industrial Automation,**
Alpha Omega and NanInstuments
Best poster and Travel Awards

16:30-17:00 Coffee and Posters

Cognitive Control

Chairperson: Dr. Amir Karniel, BGU

17:00-17:30 **Prof. Emanuel Donchin, U. of South Florida**
The Brain as a Finger: The P300 Based Brain Computer Interface

17:30-18:00 **Prof. Joseph Tzelgov**, **BGU & AAC**
Emergence of primitives in sequence learning

18:00-18:10 Discussion

Talks

Probabilistic learning in sensorimotor control

Daniel Wolpert

University of Cambridge, Department of Engineering

When we learn a new skill, from balancing a broom on our palm to riding a racing bicycle, the motor system adjusts its control parameters so as to achieve the task. However, once we have learned such skills we can rapidly generalize to balancing a walking stick or riding a mountain bike. This ability could arise through two distinct mechanisms. The controller could start from the control parameters of the first task and search for parameters appropriate for the new task. In such parametric learning the generalization relies on the closeness of the starting and final settings of the parameters. Alternatively, the controller could learn the structure of the task that is how the parameters co-vary. Generalization in such structural learning relies on preferential exploration in the restricted parameter space defined by the task structure. To test between these two classes of learning, subjects were exposed to visuomotor transformations of fixed structure whose parameters varied randomly. Although such randomly varying tasks are thought to prevent learning, we show that when subsequently presented with a novel task, subjects exhibit three key features of structural learning. First, we see facilitation for learning of tasks with the same structure. Second, the interference normally observed when switching between tasks which require opposite control strategies is strongly reduced if the two tasks have been experienced as part of a continuous structure. Third, subjects show preferential exploration of the parameter space conforming to the shape of the learned structure. These results suggest that adaptation takes place on a restricted region of the full parameter space allowing an efficient and rapid exploration that facilitates generalization. This suggests that structural leaning plays a cardinal role in skill acquisition.

Learning by observation

Opher Donchin

Department of Biomedical Engineering, Ben Gurion Universit

It is now quite well documented that humans are capable of improving their motor learning skills through observation of others engaged in the skill. However, we do not know how this actually happens. I will review some current thinking on this topic, presenting especially the currently popular notion that we learn through observation primarily because observation activates our own motor system creating an effect unlike actual practice. This hypothesis has specific predictions about the patterns of learning through observation. We tested two of these predictions in our laboratory using a well controlled experiment in observation of a complex motor skill. Our results do not support the claim that learning through observation is primarily the result of a practice-like effect. While these conclusions cannot be generalized beyond our specific paradigm, they do represent an important challenge to the currently popular thinking on the mechanisms of action observation.

The eyes don't have it (all): Bayesian integration of motor plans across multiple reference frames predicts eye-centered reach errors

Philip N. Sabes

Keck Center for Integrative Neuroscience and the Department of Physiology, University of California, San Francisco

The search for the neural representation of movement plans in primate cortex has revealed that a wide range of putative "reference frames" are used across sensorimotor circuits. This finding appears difficult to reconcile with psychophysical studies showing that a single reference frame can often explain the spatial patterns of movement error. Here we show how a model that uses multiple weighted representations of the planned movement vector can explain a widely-observed retinotopic pattern of reach errors, the "peripheral exaggeration effect" in pointing to non-foveated visual targets. This effect has been used by many researchers to argue that reach planning is retinotopic. We show that a similar but reversed pattern is observed when reaching to peripheral proprioceptive targets. We argue that both of these error patterns can be explained by the Bayesian integration of neural representations in multiple reference frames and by the presence of biases in the transformations between them.

Our model is based on two main ideas: there are multiple simultaneous representations of a planned movement vector, and uncertainty in coordinate transformations introduces biases in movement plan. The model supposes that the spatial location of reach targets and effectors are represented in multiple reference frames regardless of the sensory modality in which they are perceived. Computing these representations requires transforming visual and proprioceptive signals into each coordinate frame.

These transformations are assumed to inject both bias and variance into the transformed signals. Optimal integration occurs at two levels: for each representation, vision and proprioception are optimally combined, taking into account the transformation-derived variance, and the multiple resulting movement vector plans are similarly combined. In order to explain the "peripheral exaggeration effect", the model must include a bias in the transformation between body-centered and retinotopic transformations. This is implemented as a shift in the estimated eye position towards the reach target. The model predicts a (nearly) retinotopic pattern of reaching errors that qualitatively matches those observed for pointing to visual and proprioceptive targets in both the presence and absence of visual feedback from the hand. The model predictions are compared to human and primate psychophysical results and neurons recorded from the parietal cortex during reaches to visual and proprioceptive targets.

<u>Agent-Based Models of the Motor System</u>

Jim Houk and Jun Wang

Northwestern University

Subcortical loops through the basal ganglia (BG) and through the cerebellum (CB) form computationally powerful distributed processing modules (DPMs; Houk 2005). The computational features of a DPM's loop through BG are well suited for a motivationally modulated selection of a ballpark, approximate action, and the computational features of a DPM's loop through CB are well suited for the amplification and refinement of the selected approximation. These loop actions nicely complement each other.

The above assessment is based on the operations performed in the DPM that regulates the voluntary motor commands generated in the primary motor cortex (the M1-DPM). However, the neuronal architecture of the DPMs subserving premotor, prefrontal and parietal areas of cortex is essentially the same as the the arcitecture of the M1-DPM. On the basis of analogy, I posit that the same signal processing operations implement the selection of ballpark motor plans and ballpark thoughts, via the BG. and that the amplification and refinement of these tentative planning and thinking signals via CB yields improved accuracy and timing of plans and thoughts. If so, a network of DPM agents should provide a useful framework for exploring the dynamics of the mind. This would be along the lines that others have pursued with the technique of agent-based modeling (Riolo, Cohen & Axelrod, 2001; Wilensky & Reisman, 1998).

Motivated by this hypothesis, my colleagues and I are in the process of developing a minimal model of the M1-DPM. Anatomical and physiological data suggest that the M1-DPM is comprised of a large array of microscopic modules that individually possess essentially the same neuronal architecture as the macroscopic M1-DPM module. I will describe our use of nonlinear dynamics to model the operational features of individual microscopic modules and of small arrays of microscopic modules. I will also speculate about how larger arrays of microscopic modules comprising the M1-DPM serve to generate the composite motor commands that control voluntary movements.

The learning rules used by planning and thinking DPMs should be essentially the same as those used by the M1-DPM. The loop through BG relies on reinforcement learning to discover approximations of salient actions and the loop through CB relies on a simple form of supervised learning to amplify and refine the selected approximations. With practice shaped by input from BG and CB, Hebbian learning in the cerebral cortex shapes intracortical connectivity so that M1 can implement actions automatically. We are using these concepts to investigate motor learning and consolidation in M1.

References:

Houk JC (2005) Agents of the mind. *Biological Cybernetics* 92: 427-437.

Riolo RL Cohen MD, Axelrod R (2001). Evolution of cooperation without reciprocity. <u>Nature</u> 414:441-3.

Wilensky U & Reisman K (1998). Learning Biology through Constructing and Testing Computational Theories -- an Embodied Modeling Approach. In Y. Bar-Yam (Ed.), <u>Proceedings of the Second International Conference on Complex Systems</u>. Nashua, NH: New England Complex Systems Institute.

Motor repertoire is maintained by basal ganglia positive reinforcement learning

Mati Joshua, Avital Adler and Hagai Bergman

Hebrew University

Experimental and theoretical studies depict the basal ganglia as a reinforcement learning system. The dopaminergic neurons provide the reinforcement error signal and control cellular plasticity at the cortico-striatal synapses, therefore reshaping the mapping between states and actions. However, the low tonic discharge rate of dopaminergic neurons impedes their capability to suppress their firing rate and to encode negative events.

We recorded the activity of neurons (n=475) and field potentials (n=650 sites) in five distinct areas of the basal ganglia (GPe, GPi and SNr of the main axis of the basal ganglia, and striatal TANs and SNc dopaminergic neurons of the basal ganglia modulation sub-system). The recordings were done during the performance of a probabilistic classical conditioning task with food or an air puff as the rewarding and aversive outcomes, respectively. A neutral cue provides control for sensory and arousal related responses.

We found that basal ganglia activity is strongly modulated by expectation of reward but only slightly by expectation of an aversive event. Furthermore, the activity of the basal ganglia neurons reflects the probability of future reward, but does not reflect the probability of future aversive outcome.

The asymmetric encoding of reward versus aversion suggests that the basal ganglia system is biased toward the processing of rewarding events and might provide the neural basis of asymmetric human motor responses to risk vs. appetitive predicting cues.

Cortical Trajectory representation and Brain Machine Interfaces

Andy Schwartz

University of Pittsburgh

Over the years, we have shown that detailed predictive information of the arm's trajectory can be extracted from populations composed of single unit recordings from motor cortex. By developing techniques to record these populations and process the signal in real-time, we have been successful in demonstrating the efficacy of these recordings as a control signal for intended movements in 3D space. Having shown that closed-loop control of a cortical prosthesis can produce very good brain-controlled movements in virtual reality, we have been extending this work to robot control. By introducing an anthropomorphic robot arm into our closed-loop system, we have shown that a monkey can easily control the robot's movement with direct brain-control while watching the movement in virtual-reality. We now have monkeys using their cortical output to operate the prosthetic arm to reach out and grasp food in a self-feeding task.

Control theory combined with a physiological plant model predicts neural activity in motor cortex

Ron Meir[1], Ehud Trainin[1], Amir Karniel[2]

[1]*Department of Electrical Engineering, Technion*
[2]*Department of Biomedical Engineering, Ben-Gurion University of the Negev*

What determines the specific pattern of activation of primary motor cortex (M1) neurons in the context of a given motor task? We present a systems level physiological model describing the transformation from the neural activity in M1, through the muscle control signal, into joint torques and down to endpoint forces and movements. The redundancy of the system is resolved by biologically plausible optimization criteria. The model explains neural activity at both the population, and single neuron, levels.

Due to the model's relative simplicity and analytic tractability, it provides intuition as to the most salient features of the system, as well as a possible causal explanation of how these determine the overall behavior. Moreover, it explains a large number of recent observations, including the temporal patterns of single-neuron and population firing rates during isometric and movement tasks, narrow tuning curves, non-cosine tuning curves, changes of preferred directions during a task, and changes of preferred directions due to different experimental conditions. The model deals mainly with a subset of M1 neurons which are highly correlated with muscle activity. We view our results as but a first step in providing a more comprehensive functional interpretation of the heterogeneous activities observed in motor cortex.

Neural computation for arm reaching: A realistic population model of interactions in the motor cortex with parallels to primate experiments

Nedialko Krouchev

Université de Montréal

Key words: reaching movements, system dynamics and modeling, arm biomechanics, primate cortical electrophysiology, muscle synergies

When monkeys make movements with or without external force perturbations, or generate isometric forces in different directions while the arm is in different workspace positions, primary motor cortex (MI) cell activity shows systematic changes in directional tuning and in force-generation gains as a function of arm posture (Krouchev & Kalaska 2003), (Sergio & Kalaska 2003), (Sergio & al. 2005).

At least three competing views have been around to address how the brain may control skilled motor behavior. One is the equilibrium point (EP) hypothesis, the second is known by control engineers as model-reference adaptive control (MRAC) and in neuroscience has been called various names and acronyms - from MOSAIC to optimal control, often with a flavor of rediscovery. EP is in essence a succinct description of muscle dynamic properties. It has been instrumental for several elegantly simple models (e.g. Gribble et al. 1998). On the other hand, many control-theoretic results imported to neuroscience come from engineering systems with very different dynamics from either the brain or its musculo-skeletal plant. Both approaches have problems finding their correlates in the living brain. A third perspective gets inspiration from biomechanics. Considerable insight into cell discharge properties can be gained by modeling the biophysics of the limb at different levels of complexity. The external environment and musculo-skeletal plant are a major source of functional correlations between MI neural activity and other purely physical quantities.

We had previously (Krouchev & al. SfN 2001, 2005) used a 2 d.o.f. model of arm kinematics and dynamics with few parameters and assumptions (Lukashin et al. 1996) that we modified to capture essential aspects of muscle moment arms (Gribble et al. 1998). We did not assume any particular muscle model and computed only the required muscle force profiles which are known to be closely coupled to EMG activity. The model was tuned using experimental data from human psychophysics and then scaled down using morphometric data from the macaque monkey (Graham and Scott 2003) and validated by demonstrating sufficient parallels between actually recorded and modeled EMG profiles. The key result of this work was demonstrating essential reasons why linear regression models (Krouchev & al. SfN2000) failed to produce generalizing predictions.

Some systematic changes in directionality of MI cell and limb muscle EMG activity and the gain-field like properties of tuning depth may stem from the physical properties of limb biomechanics, muscle anisotropy and force production nonlinearities and their interplay with task conditions. However, it would be too simplistic to assume all control intelligence is in the cortex and too little in the brainstem, and especially too little in the spinal cord (De Luca et al. 2006). With very few known exceptions, mostly in the human, cortex does not manage single motor units.

If you were the MI and knew about the reliable ways to specify joint torques (via already existing subcortical and spinal mechanisms), it is the robustness of the motor controller that may be your top priority. Rather than having to learn a detailed model of every single new task before you could perform well in it, you'd have a definite competitive advantage in natural selection if you implemented control principles that would perform reasonably well in a wide range of tasks and external dynamic conditions at the very first encounter with them.

I will present control principles and a computational model implementing them, that contain elements from all three approaches described above. Moreover, I can and will demonstrate a multitude of correlates in the living brain. Finally, the computed PCA and NNMF factors of EMG and cell activity will be used to support a thesis that MI may be part of a distributed neural circuit coding for muscle synergies (Krouchev & al. 2006).

Spinal recurrent inhibition: role in motor learning?

Uwe Windhorst

Goettingen, Germany

Here the hypothesis is propounded that spinal recurrent inhibition exerts, beyond its moment-to-moment functions, longer-term functions in regulating the strength of synaptic connections from input systems to moto- and interneurons (review: Windhorst 2007). This idea is based on the following facts and assumptions. (i) In mammals, spinal recurrent inhibition via Renshaw cells is prevalent in motor output systems controlling the force of anti-gravity extensor muscles during postural stance and the locomotor stance phase. (ii) During the stance phase, anti-gravity extensor α-motoneurons receive supportive sensory feedback from force-related sensory receptors, including Golgi tendon organs, muscle spindles and cutaneous mechano-receptors in the footpad. (iii) The sensory afferent-to-motoneuron connections must be finely tuned to provide for proper stability. (iv) Proper tuning of sensory-motoneuron connections requires them to be plastic, which has been shown to be the case. (v) The core hypothesis is that recurrent inhibition assists in calibrating and adapting the synaptic connections to motoneurons. It does so by modulating the degree of retrograde invasion of the motoneuron dendritic trees by back-propagating action potentials (APs), which are assumed to serve as postsynaptic signals to be correlated with presynaptic signals for Hebbian synaptic plasticity. Since the degree of back-propagation depends on prevailing inhibition, recurrent inhibition is implicated in regulating these processes. (vi) The hypothesis has several important corollaries. 1) Since most of the excitatory inputs arrive in the α-motoneuron dendritic tree, recurrent inhibition should also act dendritically. This is the case. 2) Since γ-motoneurons contribute to the afferent inputs to α-motoneurons (via muscle spindles) in an ordered and adjustable way, they too should be subject to recurrent inhibition. This is the case. 3) Since the connections of group Ia muscle spindle afferents to reciprocal Ia inhibitory interneurons should obey an ordered and adjustable spatial pattern, these interneurons should also be subject to recurrent inhibition. This is the case. 4) All neuronal elements involved in the above adaptation processes (sensory inputs, α-motoneurons, γ-motoneurons, reciprocal Ia inhibitory interneurons, and Renshaw cells) should be active concurrently during the relevant stance phase. This is the case. – A crude illustration of how this mechanism might work is as follows. Severance of cat hindlimb nerves to synergist muscles of the medial gastrocnemius (MG) causes, in the acute phase, ankle yielding and extensive extensor muscle stretch during the stance phase, accompanied by a lack of proprioceptive support from synergists to the MG. Over several days and weeks, these initial deficits are overcome by plastic processes, to which recurrent inhibition might contribute as follows. The initial lack of proprioceptive support would reduce the excitatory input to MG and synergistic α-motoneurons, which in turn would reduce their recruitment and firing rates, which in turn would reduce recurrent inhibition, which would reduce the inhibition of AP back-propagation, this promotion of AP back-propagation enhancing the potentiation of excitatory inputs to compensate for the lack of such inputs to ankle extensors.

Reference:

Windhorst U (2007) Muscle proprioceptive feedback and spinal networks. Brain Res Bull (in press)

Modeling the spinal CPG and neural control of locomotion

Ilya A. Rybak[1], Boris I. Prilutsky[2], and David A. McCrea[3]

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[3]*Department of Physiology & Spinal Cord Research Center, University of Manitoba, Winnipeg, CANADA*

The ultimate goal of our study is to develop a comprehensive, realistic neuro-biomechanical model of limb movement control that can provide an understanding of the functional organization and complex neural mechanisms operating at the level of spinal cord and responsible for neural control of locomotion. Our previous neuro-biomechanical model of hindlimb locomotion in the cat (Ivashko et al., 2003), while demonstrating a relatively realistic and stable walking, was based on an abstract model of the locomotor central pattern generator (CPG) and could not provide testable predictions on the organization of spinal circuits involved in control of locomotion.

A new model of the spinal locomotor CPG integrated with circuits of spinal reflexes has been developed using data from studies of fictive locomotion – the locomotor activity in the decerebrate, immobilized cat preparation evoked by a continuous stimulation of the midbrain locomotor region. It was suggested that this activity (generated without sensory feedback and supra-spinal control) represents the inherent CPG operation. The following data sets were taking into account during the development of this model: (1) coordinated activities of synergist motoneuron pools (e.g., the strict alternation of flexor and extensor activities), (2) activities of different synergist motoneuron pools during deletions (spontaneous errors in alternating rhythmic activity, i.e., missing series of bursts), and (3) effects of phase-dependent stimulations applied to selected extensor and flexor afferents on the locomotor pattern generated and the activity of different synergist motoneuron groups. As a result, a two-level model of the locomotor CPG has been developed (Rybak et al., 2006) that was able to reproduce and explain most of the experimental data obtained in the fictive locomotion studies.

On the biomechanical side, a new musculoskeletal model of cat hindlimbs with the trunk has been developed. Each hindlimb was actuated by nine muscles with the force-length-velocity properties and pennation of the muscle fibers and the force-length properties of the tendon. Muscle dynamics was described by a Hill-type model. Each muscle force was computed as a function of muscle activation, fiber length, velocity, acceleration, and pennation angle. The ground reaction forces were computed from horizontal and vertical displacements of the foot contact point on the ground. The EMG profiles of nine muscles were taken (at this stage) from experimental recordings in walking cats and/or adapted from the literature and used as an input to the model. The equations of hindlimb motion were solved using the second-order Runge-Kutta method. A simulated annealing optimization algorithm was used to adjust model parameters so that the difference between the simulated and experimentally measured kinematics and ground reaction forces would be minimal. The musculoskeletal model was than used to compute the activity of group I (Ia and Ib) and II afferents from each muscle. Their activity was similar to that reported in the literature for walking cats.

The pattern activity of sensory afferents obtained from musculoskeletal will be used as an input to the spinal cord model incorporating the locomotor CPG (see above), and the weights and architecture of afferent connections will be adjusted to convert the fictive locomotor pattern to the output EMG pattern used as the input to the biomechanical model. The resultant closed loop neuro-biomechanical model for control of cat hindlimb locomotion will be investigated in detail under different conditions. We believe that this comprehensive model will provide a powerful tool for investigating neural control of locomotion at the spinal cord level.

Skeletal geometry and motor control

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[2]*Adaptations et Evolution des Systèmes Ostéomusculaires, UMR 8570, CNRS-MNHN*

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We first demonstrated a stereotyped resting posture in a number of vertebrates: the cervical vertebral column is oriented vertically to form one portion of the partial S-shaped configuration of the entire spine. The resulting biomechanical constraints limited the number of possible solutions of how these species can perform orienting movements. At one end of the spectrum, rabbit used the head-neck structure in a parallelogram fashion, which resulted in head posture being independent of cervical vertebral column orientation. In monkeys and humans, however, orientation of the head depended almost entirely on the orientation of the cervical vertebral column. These different strategies correlated with the different ranges of motion of the atlanto-occipital articulation. During forward locomotion, quadrupeds adopted a posture as stereotyped as at rest. The whole extend of the vertebral column was extended, parallel to the earth horizontal plane. These results support the hypothesis that, in Mammals, gaze and postural control would be simplified by the adoption of a limited number of skeletal configurations. They would be optimized for energy saving, biomechanical efficacy and limitation of the number of degree of freedom of the skeletal apparatus.

Three later studies investigated the vestibular control of posture. First, X-ray methods were used to describe the postural syndromes following vestibular lesions. Unilateral utricular lesion induced a bascule of the head-neck ensemble about the cervico-thoracic junction whereas those of the horizontal semicircular canal induced its rotation about the cervical column. Hence, the functional segmentation of the cervical column corresponds to a differential distribution of vestibular afferents. Second, in vivo and in vitro studies suggested that the mass discharge of the vestibular nuclei neurons and their NMDA receptors were essential for the maintenance of symmetric posture and normal eye position at rest. Third, resting posture and locomotion were compared in wild type and vestibularly deficient mice (IsK -/- mutant) using cineradiography at 250 frame/sec. Postural control and locomotion in IsK -/- mice were characterized by a continuous circling at 1000 deg/sec and permanent head bobbing. It showed that vestibular information was mandatory during an in utero critical period for providing stable references for motor control.

Finally, we carried out a study in unrestrained rats from birth (P0) until postnatal day 23 (P23) to study the temporal pattern of emergence of these skeletal configurations. Many of them were already present at birth. By contrast, limb placement changed abruptly at around P10. We suggest that a few innate skeletal configurations provide the necessary frames of reference for the gradual construction of an adult motor repertoire in altricial mammals, such as the rat.

Operational principles of motor cortical function: Linear summation of motor cortical outputs.

C. Capaday,

Dept. Of Anatomy and Physiology, Brain and Movement lab. Université Laval, Québec City, Canada.

Recent studies on the functional organization and operational principles of motor cortical function, taken together, strongly support the notion that the motor cortex controls the muscle activities subserving movements in an integrated manner. For example, during pointing the shoulder, elbow and wrist muscles appear to be controlled as a coupled functional system, rather than individually and separately. The pattern of intrinsic connections between motor cortical points, identified by light and electron microscopic methods, is likely part of the explanation of this operational principle. So too is the manner in which muscles and muscle synergies are represented in the motor cortex. However, selection of movement related muscle synergies is likely a dynamic process involving the functional linking of a variety of motor cortical points, rather than the selection of fixed patterns embedded in the motor cortical circuitry. One of the mechanisms that may be involved in the functional linking of motor cortical points is disinhibition. Thus, motor cortical points are recruited into action by selected excitation as well as by selected release from inhibition. The in-coordination of limb movements in patients after a stroke may be understood, at least in part, as a disruption of the connections between motor cortical points and of the neural mechanisms involved in their functional linking. Finally, I will present results of experiments demonstrating that separate corticospinal outputs sum linearly and lead to blending of the movements evoked by the activated cortical points. Thus, cortico-cortical and corticospinal interactions insure a near linear output, an operational principle that may simplify the synthesis of motor commands. Another implication of this result is that not all movements need be represented in the motor cortex, but may be synthesized from a smaller repertoire.

Optimization Processes during Arm Movements Revealed through Directional Biases

Natalia Dounskaia

Arizona State University

Strategies used by the central nervous system (CNS) to optimize arm movements in terms of speed, accuracy, and resistance to fatigue remain largely unknown. A hypothesis is investigated here that the CNS exploits biomechanical properties of multijoint limbs to decrease muscular effort for movement production. To test this notion, a novel free-stroke drawing task was employed that instructs subjects to make straight strokes in as many different directions as possible in the horizontal plane via rotations of the elbow and shoulder joints. In spite of explicit instructions to distribute strokes uniformly, subjects demonstrated biases to move in specific directions. Major directional biases were associated with a minimization of interaction torque regulation by muscle torque at either the shoulder or elbow joint, resulting in largely passive motion at this joint. Other biomechanical factors, such as inertial resistance and kinematic manipulability, were unable to adequately account for major directional biases. Also, minimizations of jerk, torque change, and sum of squared torque were analyzed; however these cost functions provide generalized descriptions of all strokes regardless of movement direction. Thus, each failed to explain the emergence of specific biases. These results suggest that knowledge of biomechanical cost functions regarding IT regulation is available to the control system. This knowledge may be used to evaluate potential movements and to select movement of "low cost". The preference to reduce active regulation of interaction torque suggests that, in addition to muscle energy, the criterion for movement cost includes neural activity required for movement control.

Emergence of Primitive in Sequence Learning

Joseph Tzelgov[1], Amotz Perlman[2], Emmanuel Pothos[3], Daniel Millar[4]

[1] Ben Gurion University and Achva Academic College, [2,4] Ben Gurion University,
[3] Swansea University

In this study participants were trained to respond to one of two sequences of four visual stimuli, each requiring a finger keypress. Each sequence was preceded by a specific cue. Before training, latencies of the keypresses were a monotonously decreasing function of the location of the stimuli in the sequence. Training resulted in an increased waiting time before responding to the first stimulus in each sequence, and in fast and equal latency responses to the remaining three in the sequence. We believe that this pattern is a marker of an emergence of a unitized behavioral unit that is computed in advance and performed as a unit.

The Brain as a Finger: The P300 Based Brain Computer Interface

Emanuel Donchin

Department of Psychology, University of South Florida

Brain-Computer Interfaces (BCI), that allow a person to use the electrical activity of the brain as a substitute for lost motor control, exist in two flavors, one mimicking the Joystick and the other mimicking the Keyboard. In the Joystick model the user gains control over some aspect of brain activity, e.g. the spectrum, and by choosing among spectra the subject indicates the action desired. This approach requires lengthy biofeedback training. The P300-BCI described in this report requires virtually no prior training of the user but it allows only, as does a keyboard, a choice among a limited set of "keys". This allows, as does the keyboard, the "typing" of arbitrary text, the choice among menu items, and as I will report in this presentation, the control of a robotic arm.

The approach utilizes the so called "Oddball Paradigm" (OP), in which a person is presented with a sequence of events, each of which can be classified in one of two categories. If the subject is assigned a task that can not be performed without properly categorizing each event, and if one of the categories appears rarely, events in the rare category elicit the P300 component of the Event Related Brain Response (ERP). The P300 is a positive going component that peaks about 300 msec after the rare event has been identified and which is largest in the parietal area. There is considerable controversy regarding the functional significance of the P300, and regarding its intra-cranial sources, but the conditions under which it is elicited, and the variables that control its amplitude and latency has been very well established. It is the latter well established data that are critical for the application of the P300, and the OP, in a BCI.

The P300 BCI has been first described by Farwell and Donchin (1988) who presented subjects with a 6 bt 6 matrix each cell of which contains a character. The subject chooses the character to be typed. The rows and the columns of the matrix are intensified for 100msec each, at the rate of 8 elements per second. This procedure creates an OP as the row and column containing the category elicit a P300 as they are the rare events. The BCI system need only identify the row and the column that elicited the largest P300s to determine the character which the user wished to type, thus the Brain is used as a Finger.

Following an extended period during which this BCI has been tested by able bodied users while improving the operating characteristics of the system, we began in 2003 to test the system with ALS patients with considerable success. More recently we adapted the system to allow a user to control a wheelchair-mounted robotic arm (WMRA) developed by Redwan Alqasemi and Rajiv Dubey of the Department of Mechanical Engineering at USF. In this case the user is selecting from a smaller matrix that displays directional symbols. This application will be presented in some detail.

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For relevant papers see http://www.cas.usf.edu/psychology/publications_donchin.htm Items 125, 154,158,166, 178 (PDF files available through the site)

Posters

Simple spike pauses in Purkinje cells of the awake cat: relation to behavioral events and complex spike activity

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A debate has emerged recently regarding reported bistability of cerebellar Purkinje cells (PC). The existence of membrane bistability in vitro and in anaesthetized animals is not contested and has been confirmed by different laboratories. However, the functional relevance of this bistability has been questioned following reports that simple spikes (SS) extracellularly recorded in awake rats do not exhibit long pauses in firing that would be predicted by a bistable membrane potential. We recorded extracellular action potentials from the vermal lobule VI of the cerebellar cortex in awake cats engaged in feeding. Approximately half of the SS showed clear bimodal firing patterns and were characterized by long and distinctive pauses. Statistics show the existence of two separate populations of neurons. Different methods of characterization yielded identical categorization of the population. Functional significance of bimodal activation was explored by testing for a relationship between SS pauses and behavioral events and between SS pauses and complex spike (CS) activity. Despite the fact that all PCs we recorded in nearby sites, all of the non-bimodal neurons in our population showed a significant response to orofacial stimulation whereas none of the bimodal neurons had such a response. Interestingly, initiation and end of pauses in some bimodal cells were associated with CS, suggesting some functional role for the CS in driving transitions between two states of SS activity. Taken together, our results suggest that the bistability of the membrane potential of PC cells effects the firing patterns of these cells in awake animals and point towards important directions for further exploration of their functional role.

A musculoskeletal model of the cat hindlimbs for computing proprioceptive signals during cat locomotion

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The ultimate goal of our study is to develop a comprehensive neuromusculoskeletal model that could be used for simulating the complex mechanisms of neural control of locomotion. Such a model should incorporate and reproduce the complex interactions between the central pattern generator (CPG), circuits of spinal reflexes, limb and muscle dynamics, and the motion dependent afferent input to the CPG. Here we present a preliminary musculoskeletal model of the cat hindlimbs, which is considered an important part of the full neuromusculoskeletal model and will be used for deriving the motion dependent afferent signals similar to those generated by the spindles and the Golgi tendon organs in cat hindlimb muscles during walking.The mechanical description of cat hindlimb dynamics is based on the Lagrange equations for a 2D, 10-DOF model of two hindlimbs with the pelvis and trunk. The ground is modeled as a viscoelastic material. Each limb is actuated by 9 muscles with the realistic force-length-velocity properties and geometry (pennation angle) of muscle fibers, the force-length properties of the tendon and the parallel elastic component. The muscle dynamics is described by a Hill-type model with the muscle mass. In order to simulate cat locomotion, we used as input averaged low-pass filtered EMG profiles of the 9 hindlimb muscles recorded during walking. The equations describing hindlimb motion and muscle dynamics were integrated over one complete walking cycle. Numeric optimization was used to adjust a subset of parameters of the muscle model and the ground within realistic limits to minimize the difference between the simulated and experimentally recorded walking kinematics and kinetics. As a result of optimization, the difference between the simulated movement and the experiment was drastically reduced but remained substantial.

This could be explained by the fact that many other model parameters were not optimized or/and the input to the model (averaged EMG patterns) differed from the actual EMG patterns of the particular cat the movement of which was used to identify the model parameters. In an attempt to further improve the match between the experiment and simulations, we allowed the optimization algorithm to change the muscle activity patterns within limited ranges. This decreased the simulation error to about 10% for the kinematics. Despite this close match, the simulated muscle velocities and forces demonstrated unrealistic behavior at the swing-stance transitions. Thus our simulation model reproduced well the experimental kinematics (i.e., joint angles), but this was insufficient to calculate smooth feedback signals. Using a simplified version of our hindlimb model and the experimental kinematics and kinetics we computed lengths, velocities and forces of hindlimb muscles and subsequently calculated the firing rates of Ia, Ib, and II hindlimb afferents during cat walking as functions of these mechanical variables (Prochazka, Gorassini, 1998). There was a good qualitative agreement between the computed and recorded afferent activity which we found in the literature for selected muscles. To improve the forward dynamics simulation model, we plan to record forces and fascicle lengths of selected muscles in cat locomotion and adjust muscle model parameters using these measurements.

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Reducing errors in inverse dynamics joint torques calculation through optimized segment motion profiles

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Inverse dynamics is commonly applied to the biomechanical analysis of human movement in order to estimate the net muscular torques generated in various limb joints. Past research has shown that errors in these torque estimates can be relatively large. Errors in inverse dynamics calculations strongly depend on errors in the body segment motion profiles, which arise from two main sources: noise in the motion capture system and skin movement artifacts of skin-mounted markers. Kuo (1998) and Cahouet et al. (2002) exploited the ''overdetermined'' nature of inverse dynamics; they proposed static optimization to reduce the effect of noise in ground reaction forces (GRF) and segment motion measurements. Their methods, however, were not designed to deal with the effect of the skin movement artifacts. This study presents a method that deals with both sources of motion errors to increase the accuracy of joint torque calculations through optimization of segment motion profiles.
We formulated a constrained (on motion) nonlinear optimization with a cost function that minimizes the difference between the measured GRF and the GRF calculated via a top-down inverse dynamics. To assess this approach, we conducted a series of studies using simulated movements of either squatting or lifting with strait arms. The human models for these movements assumed a rigid body, and were represented by a three- or four-link system (2D). The GRFs were calculated with respect to the ankle joint. The simulated movements were considered to produce a set of "true" motions, joint torques, and GRF. To simulate real-world inaccuracies in motion data, ten noise conditions were applied to these true motions (Lu and O'Connor 1999). From these noise-induced conditions, optimized motions and related joint torques were determined. For each condition, the root mean square errors (RMSE) for the joint torques between the "true" and optimized values were computed. These RMSE values were then compared to RMSE values computed between the "true" and traditional inverse dynamics joint torques.
In both the bottom-up and the optimization approaches the error in the ankle was practically zero. For the squatting, the relative reductions in the joint torque errors after optimization were 66% and 79% for the knee and hip, respectively. The bottom-up approach had lower RMSE than the top-down. A similar analysis was performed for lifting; here, however, the shoulder joint torque was compared to the top-down values, while the ankle, knee and hip were compared to the bottom-up values. This enabled to compare the optimization-based solutions to the best values obtained from the traditional approaches. For lifting, the comparisons showed reduction in the torque RMSE by an average of 63% for the knee, 59% for the hip, and 58% for the shoulder. Thus, the average reduction due to our method was 65%. This is an improvement compared to previous results by Kou (1998) who achieved an overall reduction of 30%.

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Planning three-dimensional hand movements constrained to curved planes

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Background: An important question in motor control research is whether the spatial and temporal features of movements are planned separately, or whether they are inseparable aspects of one motor planning scheme. Different rules may prescribe the geometric characteristics of the hand paths in a 3D workspace (e.g., functional needs or unexpected environmental constraints). A relevant question regarding 3D movements is if the hand follows maximal smoothness and minimal amplitude paths, as suggested by the minimum-jerk model for planar motion (Flash & Hogan, 1985). Alternatively, the constrained minimum-jerk model (Todorov & Jordan, 1998) assumes that path and speed are planned independently. The spatial features of the hand path may follow many and different optimization rules, but in theory, maximal smoothness is invariantly followed regardless of the path geometry. This study characterized paths and speeds during hand movements on a hemispheric workspace. It was hypothesized that the hand movement follows maximally smooth paths. The project tried to verify if control of path is separated from control of speed.

Methods: Ten right-handed subjects (mean age =27.4 ±3.5 years) performed back and forth reaching movements towards 3 visual targets at a comfortable pace, in a repeated measures (RM) design. Multiple two-way ANOVAs with repeated measures were used (α-level ≤ 0.05), using several spatial and temporal measures.

Results: Regardless of the dependent variable used, the fit of the tangential velocity profile to the maximally smooth profile remained the same. This suggests that the maximal smoothness criterion is a robust principle during hand reaching in different directions and under different degrees of workspace curvature. However, there were significant interactions between the curvature and movement direction for two of the temporal measures, suggesting that the fit to maximal smoothness is somewhat influenced by a combination of the two factors. The fit to the geodesic path was affected by the curvature of the workspace as well as by movement direction.

Conclusions: Smoothness control, as a general principle, is supported by results obtained in our specific subset of 3D movement but minimal amplitude movements (geodesics on the surface of the hemisphere) were not followed. Such results argue in favor for a separate planning of hand path from the control of hand speed, as suggested by the constrained minimum-jerk model (Todorov & Jordan, 1998). The current study is regarded as a preliminary step for constructing a complete mathematical model, where geodesic hand-paths within a curved workspace may be hypothesized to be an outcome of minimization of jerk at the endpoint level.

Moving with the beat: Effects of rhythmical cueing on kinematics of arm movements

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Background: Empirical evidence shows that rhythmical (temporal) constraints provide accurate boundaries for movement. This translates into an increase in smoothness of movement of the end-effector (e.g., the hand while reaching [Balasubramaniam, Wing, and Daffertshofer, 2004] or the feet during gait [Thaut, Kenyon, Schauer, & McIntosh, 1999]). People find it easy to keep time during motion even without intention (Liebermann, Raz and Dickinson 1988), and this enables a better control of spatial features; i.e., performing within well-defined rhythmical structures may simplify motor planning and execution.

The current study investigated what aspects of a hand movement does auditory cueing affect when the rhythmical structure is modified during motor performance. Hand paths that followed smooth and shortest amplitudes (i.e., geodesics that comply with the minimum-jerk criterion) were modeled for comparisons with experimental movements performed on the surface of a virtual hemisphere (i.e., a subset of constrained 3D hand reaching movements).

Method: Ten subjects performed continuous point-to-point movements towards visual targets under two beat frequencies (1 Hz and 2 Hz) and two metrical structures (Duple and Triple).

Analysis: Differences between experimental movements and modeled geodesic paths and tangential velocities were evaluated using different dependent variables that described spatial and temporal features. These variables were introduced in multiple two-way ANOVAs with repeated measures.

Results: Beat frequency changed significantly the movement kinematics. Both the spatial (path geometry) and the temporal (velocity profile) features were affected, whereas faster movements displayed straighter trajectories and smoother velocity profiles. However, meter only affected the spatial characteristics and not the temporal evolution of movement.

Conclusions: Pacing movements to a cue as well as altering the type of rhythmical constraint (different meter) may require different attention resources to comply with the task goal. Attention towards an unusual rhythmical cue changes motor control from a feedback-dependent mode to a pre-programmed feed-forward mode.

Keywords: Attention, Rhythm, Hand Kinematic Features

Using a Joystick to Study Hand Movements

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Robotic therapy has been found to significantly improve the movement ability of the affected upper limb in stroke patients. In addition to providing a platform for intensive, repetitive movement therapy, the use of robots and other computerized mechanical devices also provides the opportunity for detailed kinematic analysis of patient movement. Quantitative information about movement (timing, joint angular and segmental paths, velocities and accelerations) can be used for diagnosis, evaluation and monitoring of patient progress and would, therefore, be a useful tool for therapists in a clinical setting. Despite the important information that can be derived from kinematic analysis, use of this type of analysis is not a routine part of treatment in most therapeutic settings. The reason is that most of the computerized systems that have been used for such analysis are complicated and expensive and, therefore, not suitable for ordinary clinic or home use.

This research tested the ability of a low cost, commercial, off the shelf system to generate and analyze the kinematic data necessary to produce movement quality measurement. Our system includes a joystick, an ordinary home computer and software programs written specifically for this research. An experiment was designed in order to test the ability of our system to identify and group healthy subjects according to their age, gender and dominant hand. In the experiment the volunteers used a joystick to move a marker on the screen through several targets, their movements were recorded and later analyzed. From the analysis, it was concluded that this system was successful as a measurement device for movement quality.

The system was found to be able to distinguish between older and younger users with an accuracy of 97%. The data show that older users were slower in reaching the targets, initiating the movement, and reaching maximum acceleration. Older users' paths were longer, they needed more corrective movements after missing the targets, and their movements were consisted of more submovements than the younger users. In the younger group, the system found a significant difference between the hands in the kinematic parameter straightness of path, but not in movement time or path length. In the younger group, significant differences between genders in movement time and the number of submovements were found. For the younger users, the system was able to distinguish between men and women with an accuracy of 76%. No significant differences between the hands or between genders were found in the older group.

Regression based model for human perception of delayed stiffness

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The nervous system as well as many artificial tele-operation systems includes unavoidable relatively large delays between motor command and resultant sensation in the first case, and between position and resultant force in the second. In both cases, the presence of delays is likely to affect the estimation of the mechanical impedance at the interface of the environment, because impedance describes the relation between state of motion and force. In this study we investigated how the presence of delays influences the human perception of stiffness. We used a Virtual Reality with haptics system (Reachin® system) to experimentally test the perception of delayed stiffness by human subjects. We employed a forced choice paradigm in which subjects were asked to identify the stiffer between two virtual surfaces presented to them, after probing the surfaces with PHANTOM® Desktop™ haptic device. We found that subjects tend to underestimate the stiffness of spring-like surfaces without boundary and overestimate the stiffness of spring-like surfaces with boundary when the force feedback is delayed. We found that even in the case of spring-like surface with boundary subjects tend to underestimate the delayed stiffness when most of probing movements are inside the spring-like surface. We propose a unified model for the underlying computational process. The proposed model combines force over position and position over force regression, weighted by the fraction of movements completed outside the surface. The unified model yields an estimation of stiffness and outperforms each one of the separate models in all conditions without overfitting the data. We hypothesize that the stiffness estimation strategy is coupled with a combined force and position control strategy. Finally we present a testable prediction for future transcaranial magnetical stimulation study.

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A computational model of Body expression of emotion in Human Computer Interaction

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Research on body expression of emotion (BEE) is rapidly emerging as a new field in human computer interaction (HCI) and affective computing. The present research focuses on this topic and in particular on the development of a computational model of BEE for static postures. Four basic emotions were considered: joy, sadness, anger, and fear.
The input material consisted of still images derived from video films in which professional actors and ordinary subjects freely portrayed body postures expressing different emotions. Our experimental data were derived from 127 subjects. The photographs were subjected to different image processing procedures which included body segmentation from the background; labeling body parts; building a multi-joint human body model; estimating head position and gesture. Since some of these image processing steps are very complicated to be automatically performed, part of the analysis was performed manually.
We use a heuristic approach to the modeling of BEE based on the assumption that BEE can be considered as being built of a set of the primitives using a combinatorial syntax. To investigate the nature of these primitives several features were extracted.
We determined emotion-specific overall body configuration as synergies among simpler components (primitives). Primitives encompass only a limited number of features.
The extracted features, i.e., head posture, hand posture and configuration, joint positions of different body segments, were extracted from the input data and an algorithm allowing finding the maximum mutual information between the different features and emotions was developed. Features with highest mutual information scores were defined as primitives. Then, for all possible sets of primitives the mutual information of the sets with the different emotions was found. The set/s (one or many) with highest mutual information was defined as emotion-specific overall body configuration.
Human subjects were then tested to assess their ability to recognize particular emotions using the above data set. For each individual picture the subjects were asked to categorize the emotion and to rate its intensity. The images with the highest recognition rates were defined as “representative images”. For each emotion, overall body configuration of “representative images” was compared with set/s (one or many) emotion-specific overall body configuration that was obtained by the automatic procedure. The results show that the emotion-specific overall body configurations extracted by the automatic procedure are similar to the overall body configurations in the “representative images”, and vice versa. When sets of primitives extracted by the automatic procedure were not present in the images, the ability to recognize particular emotions by subjects was low.
Our future goal is to determine the intensity of the affective response to the overall body configuration using a similar automatic algorithm by breaking the classes of each emotion into a number of sub-classes according to the intensity values.

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The KARMA of Hand Tracking

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In this work we propose and test a machine learning method, called Kernel Auto Regressive Moving Average, or KARMA in short, for the task of tracking hand movements, executed by a monkey in a standard motor control task, from neural spiking activity in primary motor cortex.

KARMA uses both past observations (neural activities) and past predictions (movement parameters) to make the next prediction. In the model used by KARMA one may learn to predict not only target values (hand positions) but also auxiliary features, which can be used to improve modeling of the dynamics and the prediction of the target values. For example, we predict hand velocity and acceleration and use them to better predict hand position. Unlike the standard ARMA model which is a linear model, KARMA uses non-linear similarity functions (termed kernels) to compare between (observed) eural activities and (previously predicted) motor task parameters.

In this work we compare KARMA to several state-of-the-art methods. We used correlation coefficients between true and predicted hand positions as the measure of success. We explain the differences between the methods and interpret the demonstrated superiority of KARMA as an indication that the algorithmic differences are important for understanding the motor control task.

Our main conclusion is that both the nonlinear dynamics and interpretation of neural activity are key elements in the hand tracking task.

Markerless motion capture for octopus arm movements in 3D space

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Tracking the movements of animals in 3D space is useful in many biomechanical studies. The most popular technique for human motion capture uses markers placed on the skin that are tracked by a computerized system. However, this technique is inadequate for the purpose of tracking animal movements especially when it is impossible to attach markers to the animal body, either because of its size or shape or because of the environment in which it performs its movements. Even when these technical issues can be resolved, attaching markers to an animal body may cause unnatural motor behavior. Here we present an automatic markerless motion capture system together with the motion tracking results for octopus arm movements in 3D space. The system is based on three successive tracking and processing stages. The first stage involves the detection of the movement in a pair of video sequences recorded by two cameras placed in different angles with respect to the animal body which utilizes a novel segmentation algorithm. Second, the video sequences are further processed to produce a skeletal representation of the moving arm. Finally the third stage involves the reconstruction of the octopus arm as a 3D curve using a computerized system. The segmentation process adaptively identifies the shape of texture elements and characterizes them according to their size, aspect ratio, orientation, brightness etc., and then uses the statistics of these properties to distinguish between different textures. A bottom-up aggregation framework starts from the pixels level and combines pieces with similar characteristics into meaningful segments at the higher levels. The ability of the algorithm to process a sequence of frames simultaneously as one 3D structure is a significant advantage in the detection of dynamic behaviors. This procedure gave quite satisfactory results. Motion tracking, segmentation and construction in the case of octopus arm movements is considered an especially difficult problem because of the deformable non-rigid structure of the octopus arm and the underwater environment in which it performs its movements. Yet, given the success of the new automatic motion tracking system, it may be of a general use both for the tracking of the movements of non-rigid objects as well as for the tracking of human and animal movements.

The Hybrid Kalman Filter: A model for exploring hidden states

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Neurons may encode variables which are “hidden” from the experimenter. Such hidden variables may be either: (i) sensory/behavioral parameters which the experimenter does not control or ignores, as well as, (ii) signals that are intrinsic to the brain’s processing. Such hidden variables may, in addition, be state dependent.

We developed a state-based model that includes hidden states, in addition to the observed state variables—the *Hybrid Kalman Filter*. In order to train the model, we extended the classical EM algorithm for Linear Dynamical Systems (LDS).

The model was tested both on simulated LDS data, as well as, used to predict movement kinematics by decoding neuronal responses from the primary motor cortex of behaving monkeys. In the future, we plan to use the model to try to capture the dynamics of motor learning, as well.

Possible advantages of the model include comparing the *complexity*, i.e. the optimal number of hidden states, of the neural signal during different epochs (e.g. standard movements versus learning periods). A second advantage involves discriminating between a set of possible parameters encoded by the neural data.

Time representation for perception of simultaneity during slicing movement

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Many studies suggest that the human nervous system incorporate time representation. In adaptation to force perturbations, however, the nervous system clearly favor state representation (i.e., position, velocity acceleration based representation), and therefore it was suggested that a time representation may not be available to the control system responsible for motor adaptation to force perturbations. In this study we explored the neural mechanisms underlying the perception of simultaneous events during motor behaviors. Does the nervous system employ time or state representation in order to recognize the simultaneity of two or more movement related events.

We examined the perception of simultaneity between the action of tapping a surface and the resulting force impulse. Subjects were asked to hold the robotic manipulandum as it actively guided them through a slicing movement forward and back. During this movement they experienced a tap. To understand the perception of simultaneity we used a virtual environment in which the timing between the point of movement reversal and the instant of force reflection where disassociated. Time and position are closely associated to one another (i.e., $X = V \cdot T$). In order to disassociate the two, subjects' were moved at two different velocities during the experiment. They were queried in a forced choice paradigm to state which came first: the tapping event or maximum protraction.

During each trial, location of the arm was registered along with time and state information regarding the tap and reversal points. This information served as input for two models (time and state) which were used to predict the responses provided by subjects. The first used the time between the tapping and the reversal point, while the second used state information (position and velocity between the two events). Data collected at each velocity was considered to be a separate data set used for cross validation.

Comparing the performance of the time model across both data sets does not shows any significant change. On the other hand, the state model showed a significant drop in performance when evaluated on one data set. These results support the hypothesis that true coincidence in time, rather than correspondence of states, was employed to evaluate simultaneity.

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Dual Task Reduces Magnitude of Upper Extremity Kinematics during a Pendulum Tracking Task in Adults with Parkinson's Disease

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Aim. Automatic action of individuals with Parkinson's disease (PD) is distinctively interrupted by a concurrent cognitive task (dual-task). Such interferences were illustrated during walking, serial sequencing of the fingers and while tracking sinusoidal motion with the distal joints of the upper extremity. However, the effect of a dual task on the tracking performance of the whole upper extremity in individuals with PD was not investigated. The main goal of the present pilot study was to compare the effect of a cognitive concurrent task on the ability of individuals with PD and healthy adults to track a pendulum oscillating at a frequency of 0.5 Hz and visible peripherally slightly above the subjects' shoulder height.
Methods. Three healthy adults (mean age 55) and five patients with PD (mean age 58) at stages 2-3 according to the Hoehn & Yahr scale. The PD subjects were evaluated by the Unified Parkinson's Disease Rating Scale (UPDRS), range of motion test, Berg balance test (BBS) and Time Up & Go test (TUG). Reflective markers were attached to the pendulum, as well as the ulnar styloid process, lateral epicondyle and acromion of the more affected arm of the PD subjects and the non-dominant arm of the healthy subjects. All subjects were instructed to sit on a chair with their arm beside the suspended pendulum and, after a short practice session, to perform two types of tracking tasks. The first task included three trials of swinging the arm loosely forward and backward, following the rhythm of the swinging pendulum. After five minutes rest they had to repeat the tracking task while counting backward out loud, from one hundred and down, in steps of three (dual task). For both tasks, the subjects were instructed to look straight ahead at a target while simultaneously able to see, via peripheral vision, the bobbing of the pendulum during the anterior part of its path. The angular velocities of the total path of the pendulum and the swinging extremity were calculated using a video-based computerized system.
Results. During dual task performance, there was a significant group-by-task interaction ($p < 0.05$), as manifested by the decreased path and angular velocity of the shoulder parameters in subjects with PD. Both the pendulum's path and the angular velocity of the swinging extremity were invariant among the healthy subjects. The elbow kinematics did not exhibit similar interaction and, in both tasks, the elbow path of healthy individuals tended to be larger than those of the PD group.
Conclusions. It appears that adults with PD respond differently from healthy subjects in dual-task tracking. The systematic reduction in the path and angular velocity may represent a compensatory strategy for improving tracking performance, given the inherent motor deficit. The different variation of the shoulder and elbow kinematics suggests that the shoulder might have served as the "leading joint," and that the elbow-shoulder movement was modulated by a different control mechanism from that of the healthy subjects.

Performance in a paced balance training task in developmental dyslexia

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Introduction. Although several theoretical models and intervention techniques address the notion of a deficit in balance, timing and skilled motor behavior in children with developmental dyslexia (DD), there is an ongoing debate whether these motor deficits constitute part of the core deficit in DD and perhaps a target for remediation intervention.
Aim. To determine if any differences exist between dyslectic to non dyslectic teenagers during the acquisition of a paced balance task.
Methods. Ten children between the ages of 14 and 15 (mean 14.85) with a diagnosis of DD from special education school and 10 peers with normal reading abilities (mean age 14.56) from a regular school participated in the study, after parental consent. All participants performed a standard reading test to confirm the reading ability prior to Day1 of the practice. The paced-balance task constituted alternating one legged stance, with switching between legs every 6 seconds paced by a metronome. Each trial lasted one minute of the task. On Day 1 each participant underwent 6 trials with eyes open (EO), 2 trials with eyes closed (EC), and two trials performing dual task (DT). On Day 2 participants followed the same protocol as in Day 1 but with only 4 EO trials.
Data from two flat switches located under the ball of the foot, synchronized with the beat of metronome, were recorded into a data logger. The data was analyzed, off-line, and the time deference between the actual stepping (switching) rate and the beat of the metronome was computed with ms accuracy. A video camera was used to confirm the online observations. The variables of interest were **number of double support** (NDS) intervals - touching the floor with the free leg, **Timing error** (TE) - the average time between the metronome beat and the actual foot contact with the floor, and the level of variability across the trial in TE, within and between groups, control and test (DD).
Results. The DD group did significantly poorer in the reading test. Both the TE and NDS differed significantly between the groups. There were significant performance gains within session (Day 1) across trials, and in the levels of performance between Day1 and Day2 in all three conditions (EO, EC, DT) in both groups. The control group's performance was better throughout in both days, but the test group's learning was higher relative to their initial performance. The DT trials challenged both groups, especially the test group, where significant improvements were observed in Day 2.
Conclusions. Individuals recruited because of a reading disability had significant difficulties in the paced-balance task, both in terms of their ability to keep the required movement rhythm and in their ability to keep balance in leg switching. Nevertheless, these preliminary data suggest that with practice the youngsters with DD may be able to close this gap in pace keeping and balancing. It is not clear whether such an intervention can alleviate any of the reading difficulties.

Motor Memory – does it address the past or the future?

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In an essay presented in Nature, Yadin Dudai and Mary Carruthers suggested that memory is better equipped to handle the future than **the** past. In this study we explored this distinction in the context of motor memory.

The human motor control system deals with dynamic and time varying environment and plant. It was suggested that it is adaptive, and composed of internal models, such as forward model and inverse model. The internal models that are used for motor control constitute the motor memory. Can this motor memory predict the future element in a sequence of movements or would it use the average of its past experience?

We used an adaptation task consisting of slicing movements into a spring-like surface, emulated by Reachin™, a virtual reality with haptics system. We looked for a sequence where handling the past will be significantly different than preparing for the future and selected two such series. In the first experiment, the stiffness levels of these SLS's were repeated series of increasing magnitude. In a second experiment, the increasing part of the series was followed by a decrease back to the initial stiffness level, and only then repeated.

If the motor memory is used to store the past the controller is incapable to predict larger stiffness than one that was previously experienced. Catch trials in which the stiffness was equal to the mean stiffness level were integrated, in order to reveal the movement plan. In addition we examined whether mental practice helps adaptation. Subjects first performed the experiment task and then were asked to mentally practice the task for ten minutes. Subjects were instructed either to mentally practice in order to perform the task again (Group 1), to mentally practice in order to remember the experienced surfaces and describe them later (Group 2), or to rest and at the end of the ten minutes they were told what stiffness levels they experienced (Group 3). Then subjects in all three groups performed the task again.

All subjects failed to predict the next stiffness in the first experiment, and instead improved by adapting to a stiffness typical for each subject. In the second experiment, four out of thirteen subjects could predict the next stiffness. Preliminary analysis of the data indicates the value of mental practice in improving the predicting learning process.

We are currently planning further studies with various stiffness level series in order to gain more insight as to how motor memory is used in order to predict the future.

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Adaptation to delayed visual feedback during virtual reality goal directed interception task

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When intercepting a moving ball, such as in a tennis game, we have to estimate the instant of impact in order to accurately control the ball's trajectory. The estimated interception time could be calculated based on the visual cues about the target trajectory before the impact as well as multisensory information about the actual interception event, mainly properception and vision. In order to study the ability of the brain to fuse such multi-sensory cues and adapt to varying delays between vision and haptics we devised an experimental setup consisting of an augmented reality system with force feedback. The task was designed to implicitly include spatio-temporal precision requirements while enabling cross modalities time delays manipulations.

***Experimental Setup*:** The experimental setup included virtual reality system and force feedback device intended to mimic end-effector collision forces at impact and to continuously measure the hand position. The experiment task was to hit a virtual horizontally moving ball (the target) with virtual vertically moving ball and to provide enough momentum for the target to arrive at a predefined location. The vertically moving ball followed the hand true position while its visual representation could be either delayed or non-delayed. In addition whenever the visual representation of the hand was delayed, the target visual representation was also delayed.

Experimental Protocol: Eleven paid subjects performed the goal directed interception task in two sessions on two consecutive days under two conditions. In the first condition no delay (ND) was introduced between vision and haptic, in the second condition a constant visual feedback delay (D) of 50ms was added.

Results: Subjects were able to master the task and reduced the mean distance error to zero. When a visual delay session was introduced subjects score was initially degraded and on average the target was struck too late causing it to move in oblique path ($p<0.001$). After additional training the mean error fell back to zero. An after effects of learning were observed when the delay was eliminated in the last session ($p<0.01$) suggesting adaptation to the delay.

We've analyzed the motor adaptation by analyzing trial by trial trajectory modification. Our initial results revealed that subjects modify the onset time (OT) and movement time (MT) from trial to trial in attempt to improve the results of the task. By analyzing pure range errors and pure angle errors independently we concluded that when subjects hit the ball with the correct velocity but with a wrong timing they modify the onset time of the next movement and do not modify the trajectory. On the other hand when subjects hit the ball with wrong velocity and correct timing they on average maintain the same impact time on the next trial but readjust the OT and the MT.

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Measure of Unaware Haptic Perception (Subliminal Perception) using a Virtual Reality Environment

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It is well known that unaware exposure to a visual stimulus increases the preferability of the associated object. We found that in a preference test, people exposed to surfaces with imperceptible differences in roughness tend to choose rougher or smoother surfaces, in accordance to their natural tendency. The experiment was performed using the virtual reality hapto-visual device in our laboratory (Reachin & Sensable Technologies) by the following method: We performed a preference test between surfaces with roughness differences **above** the aware perception limit. Only subjects with a clear preference toward one kind of surface roughness were taken into account. Using the relative sensitivity experimental paradigm, we performed a preference test between surfaces with roughness differences **below** the aware perception limit, and then a recognition test, where subjects were instructed to choose the smoother surface. Finally we measured the applied forces to validate that an unaware change in roughness was followed by an unaware (but measurable) change in the applied normal force. The results of the study showed that in the unaware preference test, the participants selected the surface in accordance to their aware choice in ~ 57 % of the trials ($p < 0.01$). Recognition test was used to cut out aware effects. The results suggests that subliminal roughness perception affects texture preferences, in addition to motor behavioral effects of magnitude of force applied by the subjects on the surface.

Adaptive motor control during experiments with Brain Machine Interfaces

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Recent experiments with Brain Machine Interfaces indicate that the extent of neural modulations increases abruptly upon starting to operate the interface. In contrast, neural modulations due to the trajectory profile remain relatively unchanged. Furthermore, the enhanced modulations subside with further training, mirroring the trend in task performance, which degraded upon starting to operate the interface and improved gradually with training. Here we investigate the hypothesis that the enhanced modulations reflect internal representation of trajectory errors, which results in corrective commands in the short term and adaptive modifications of internal models in the long term. A simplified uni-dimensional model is analyzed to demonstrate the observed transient enhancement in neural modulations during the operation of Brain machine Interfaces. Identifying the source of the transient enhancement in neural modulation would provide insight into adaptive motor control and facilitate the improvement of future Brain Machine Interfaces.

Analysis of the model yields the conditions under which it is stable, reduces the motor error and acquires the correct inverse internal model/feedforward controller. Simulations of both skilled and BMI operations, using parameters and signals from experiments, yield results with similar characteristics as those observed in experiments in regards to both tracking performance and to neuronal modulation levels. Our model gives rise to the hypothesis that motor neurons are tuned both to preferred desired directions and preferred error directions, further more, it stresses the importance of adequate tuning to error directions without which the model is not stable and unable to reduce the motor error by feedback control or to adapt the correct internal inverse model that will perform as feedforward controller.

Analyzing movement trajectories using a Markov bi-clustering method

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In this study we treat scribbling motion as a compositional system in which a limited set of elementary strokes are capable of concatenating amongst them selves in endless amount of combinations thus producing an unlimited repertoire of complex constructs. We broke the continuous scribblings into small pieces. Next, after grouping the pieces based on trajectory similarity, the Markovian transition matrix between the trajectory-clusters is computed. Finally, the Markov states are grouped in a way that minimizes the loss of mutual-information between adjacent strokes. The grouping algorithm is based on a simultaneous bi-clustering version of the Information-Bottleneck principle. We illustrate the usefulness of this approach by applying it to human scribbling. Further we show how the scribbling may be hierarchically decomposed into finer and finer elements which may be regarded as ‘sentences’, ‘words’, and ‘phonemes’.

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