Proceedings of The Computational Motor Control Workshop

May 25, 2005, the Senate Auditorium of Ben-Gurion University, Israel

Ben Gurion University of the Negev, Department of Biomedical Engineering,
The Zlotowski Center for Neuroscience at Ben Gurion University and
The Interdisciplinary Center for Neural Computation at The Hebrew University of Jerusalem

Program

8:20-8:50	Registration, Poster Placement and Coffee
8:50-9:00	Greetings - Amir Karniel, head of the organizing committee, BGU
9:00-9:10	Opening words - **President Avishay Braverman**, BGU

From Mathematical to Behavioral

Chairperson: Opher Donchin, BME, BGU

9:10-9:30	**Tamar Flash** - Dept. of Applied Math. and Computer Science, Weizmann. On the planning of complex movements
9:30-9:50	**Amir Karniel** - BME, BGU Optimal Motor Control: From minimum acceleration to minimum transitions
9:50-10:10	**Nachshon Meiran** - Department of Behavioral Science, BGU Task Switching and Cognitive Control

From Robots to Emotions

Chairperson: Amir Karniel, BME, BGU

11:00-11:40	**Sandro Mussa-Ivaldi** - Northwestern Medical School and the Rehabilitation Institute of Chicago. Remapping motor control
11:40-12:00	**Miriam Reiner** - Department of Education in Technology and Science, Technion. Communication through haptics -- a primitive haptic language?
12:00-12:20	**Mati Mintz** - Department of Psychology, TAU The Cerebellum and Emotions

From Human to Simple Invertebrates

Chairperson: Gideon Inbar, EE, Technion

13:50-14:30	**Claude Ghez** - Center for Neurobiology and Behavior, Columbia University. Parallel planning and learning of spatial vectors and final postures in reaching
14:30-14:50	**Opher Donchin** - BME, BGU Modeling learning process and finding the sources of noise
14:50-15:10	**Yair Manor** - Dept. of Life Sciences, BGU Mechanisms for phase constancy in central pattern generators

From PreMotor cortex to Spinal cord

Chairperson: David Golomb, Health Science & BME, BGU

15:50-16:10	**Moshe Abeles** - Gonda Brain Research Center, Bar-Ilan University. Dissociation between local population and single units properties in pre-motor cortex regarding both reaching and grasping
16:10-16:30	**Eilon Vaadia** - Department of Physiology, Hebrew U Learning induced modifications of internal representations in motor cortex
16:30-16:50	**Miriam Zacksenhouse** - Faculty of Mechanical Engineering, Technion. Rate-modulations of cortical neurons during arm movements and operation of a brain-machine interface
16:50-17:10	**Yifat Prut** - Department of Physiology, Hebrew U. Population-based corticospinal interactions during voluntary movements
17:10-17:30	The National Instrument Best Poster Award. The Alpha Omega Best Poster Award.

Foreword

The nervous system analyses sensory information and orchestrates motor commands. In so doing, it faces challenges that it shares with many artificially engineered systems. In the spirit of the classic field of cybernetics, the field of computational motor control makes scientific and technological progress simultaneously by exploring the differences between artificial control theory and biological motor control. Computational motor control is a multidisciplinary research program in which mathematics, engineering, biology, medicine and the cognitive neurosciences all play important roles. This workshop will bring together world leaders in the field of computational motor control including Israeli researchers and distinguished guests. The goal will be to learn about the current state of the field and to identify the directions that will provide the medical and scientific breakthroughs of the next decade.

Sponsors:

- The President, Ben-Gurion University
- The Rector, Ben-Gurion University
- The Dean of the Faculty of Health Sciences, BGU
- The Zlotowski Center for Neuroscience Research, BGU
- The Interdisciplinary Center for Neural Computation, HU

Organizing Committee:

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- Dorit Daloya doritd@bgu.ac.il
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Best Poster Award Committee:

- Dr. Opher Donchin
- Dr. Miriam Zacksenhouse
- Dr. Dana Cohen
- Prof. Gideon Inbar

Best Posters:

The finalists were:
Elizabeth Torres (Alpha Omega prize)
Ruthy Kaidar (National Instruments prize)
Nathaniel Leibowitz, Yevgeny Perelman, Felix Polyakov

On the planning of complex movements

Tamar Flash, Dept. of Computer Science and Applied Mathematics
Weizmann Institute of Science.

In my talk I will discuss several open questions with respect to the planning and representation of complex, i.e., multi-joint and/or sequential movements and review the relations that exist between several mathematical models that were used to investigate the principles that underlie their generation. One open question concerns the level at which such movements are planned. I will discuss differences between the kinematic features of arm movements in 2D (pointing and drawing) and pointing movements in 3D. For the former, motion invariants were observed mostly in trajectories expressed in hand coordinates while in the latter they were found mostly in joint trajectories. Thus, optimization principles based on objective functions expressed in hand space were found to provide the most successful descriptions for the former, while for the latter recently an objective function based on geodesic distances in joint space was used to model the movements (joint work with Biess, Liebermann and Nagurka). The second issue is the separation between geometrical and temporal aspects of the movements. This was demonstrated in two recent studies: one of 3D pointing and the other investigating the effect of practice on co-articulation and transfer for a task involving the generation of a sequence of movements through a series of targets (joint work with Sosnik, Hauptamann and Karni). Finally, I will discuss the open problem of motion segmentation and the application of new geometrical perspectives with the objective unraveling what is the nature of the underlying motion primitives and the metrics subserving motion planning and representation (joint works with Handzel, Polyakov, Maoz and Abeles).

Optimal Motor Control: From Minimum Acceleration to Minimum Transitions

Amir Karniel

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> "*Nature sets in motion by signs and watchwords, which are made with little momentum…Just as in the army the soldiers are set in motion by one word as if by a given signal and continue to move until they receive another signal to stop, so the muscles move in order and harmony from established custom.*"
> William Harvey (1578-1657)

Following the cybernetics tradition we consider successful engineering tools as models for the biological system. In this study we consider the bang-bang control method. We assume that the central nervous system issues piecewise constant signals as motor commands (i.e., piecewise constant firing rates) and determine the timing and amplitude of each burst. The spinal cord and the muscloskeletal dynamics generate the details of the movement profile. The muscle properties were shown to be capable of generating smooth movement with such rectangular control signals and we assume that the synergies evolved to minimize the effort of the central nervous system as measured by the number of transitions between constant neural activities - namely the minimum transition hypothesis.

We consider the well studied point to point reaching movement and review the possible optimization criteria that were proposed in order to account for the observed bell shaped speed profile of fast reaching movements. Among the end-point related criteria, the possible minimum acceleration criterion was rejected due to the predicted jump in acceleration at the initiation of the movement and the minimum Jerk was found to best fit the experimental observations. However, the limitation of the minimum acceleration profile was a consequence of the method used to find the optimal solution – a method that did not include any assumptions on the boundary conditions. Applying the minimum principle with the natural boundary conditions and an assumption about maximum and minimum values for the control signal, we show that the minimum acceleration criterion generates smooth bell shaped speed profile. Furthermore, our analytical derivation of the optimal control signal predicts two transitions, i.e., three phase control signal which can be interpreted as activation of flexor and then of extensor - a well observed biologically plausible control strategy.

The minimum transition hypothesis was developed with Sandro Mussa-Ivaldi, Andrea d'Avella and Emilio Bizzi (NCM2002). The minimum acceleration with constraints is developed with Shay Ben-Itzhak (see Poster in this workshop). Part of this research was supported by Grant No. 2003021 from the United States-Israel Binational Science Foundation (BSF), Jerusalem, Israel.

Task switching and cognitive control

Nachshon Meiran
Department of Behavioral Science,
Ben Gurion University of the Negev

Executive processes control cognition, action, and emotional responses.
The task switching paradigm is among the most popular paradigms to study cognitive control. It involves frequent switches between simple choice reaction-time tasks. The talk will present the main findings from research on task switching and a model which accounts for them. The model assumes that response selection is based on matching stimulus representations to response representation. Selective attention serves for response selection by letting only relevant stimulus information enter response selection. Task switching involves changes in the direction of selective attention to stimulus information as well as retroactive adjustment in the selective attention which applies to response representation.

Remapping motor control

Sandro Mussa-Ivaldi
Northwestern Medical School and the Rehabilitation Institute of Chicago

The issue of how the Euclidean properties of space are represented in the nervous system is a main focus in the study of visual perception, but is equally relevant to motor learning. The goal the studies that I will present is to investigate how the properties of space guide the remapping of motor coordination. Subjects wore an instrumented data glove that recorded the motions of the fingers. Signals generated by the glove operated a remotely-controlled endpoint: a cursor on a computer monitor. The subjects were instructed to execute movements of this endpoint with controlled motions of the fingers. This required inverting a highly redundant map from fingers to cursor motions. We found that 1) after training with visual feedback of the final error (but not of the ongoing cursor motion), subjects learned to map cursor locations into configurations of the fingers; 2) extended practice of movement led to more rectilinear cursor movement, a trend facilitated by training under continuous visual feedback of cursor motions; 3) with practice, subjects reduced motion in the degrees of freedom that did not contribute to the movements of the cursor; 4) with practice, subjects reduced variability of both cursor and hand movements; and 5) the reduction of errors and the increase in linearity generalized beyond the set of movements used for training.

These findings suggest that subjects not only learned to produce novel coordinated movement to control the placement of the cursor, but they also developed a representation of the Euclidean space upon which hand movements were remapped.

Communication through haptics – a primitive haptic language?

Miriam Reiner

Department of Education in Technology and Science
Technion – Israel Institute of Technology

We will present three studies that explore the mechanism of touch as an information system, and its implications for 'presence'. The first looks at a haptic primitive 'language' used in surgery. Furthermore, 'touch language' is central in expertise in surgery. The second study looks at brain correlates of haptics – what is activated in the brain while touching, without vision? How come we learn shapes without vision through touch only? The third study relates semantics with haptics. It looks at what happens when semantic and haptic information are inconsistent - how is performance, learning, and manipulation affected by inconsistency?
Results of these studies suggest a model for a somato-conceptual kind of intelligence used in action-reaction through touch, and provide a framework for designing VR for 'presence'. The last part will describe an ongoing project on the sense of presence, titled 'Presencia', and funded by the European Union, under the section of FET (Future Emerging Technologies).

From motor learning to emotional control

Matti Mintz[1], Constanze Hofstotter[2], Paul F.M.J. Verschure[2].
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Classical aversive conditioning proceeds through two successive stages: amygdala-related fast acquisition of fear CRs (Conditioned Responses), followed by cerebellum-related slow acquisition of protective motor CRs. We hypothesized a third stage during which an adaptive level of motor performance helps in extinction of fear CRs. To support this hypothesis we have studied the cerebellar involvement in the timing of the motor CRs and the effect of the cerebellar output on fear CRs.

Timing of the motor CRs was studied in a neuromorphic simulation of the cerebellar circuitry. In the simulation, prolonged IPSPs in the deep nucleus give rise to a rebound excitation, which models the peripheral motor CRs. IPSPs in the deep n. are generated by synchronized GABAegic input from cortical Purkinje neurons activated by the CS event. At the first stage of conditioning, the Purkinje response to the CS and the associated IPSPs in the deep n. are long, so that the rebound excitation emerges after the US onset; too late to generate protective motor CRs. During the second stage of conditioning, cortical Long-Term Depression (LTD) shortens the Purkinje response and the IPSPs in the deep n., and consequently shortens the latency to the rebound excitation in the deep n. Eventually, the rebound arrives ahead of the US onset and triggers adaptive motor CRs. These results indicate that *cortical LTD is essential for advancing the cerebellar output ahead of the onset of the US.*

An implication of this learning mechanism is that LTD must be stopped to prevent further shortening of the rebound latency. This could be achieved by blocking of the US input to Purkinje neurons. The US is conveyed to the cerebellum through the inferior olive (IO) and can be blocked there by the inhibitory afferents from the deep n. However, the blocking may be effective only at the second stage of conditioning, when the inhibitory drive triggered by the deep n. rebound excitation precedes reliably the US onset. This marks a third stage of conditioning during which, only the CS signal excites the Purkinje neurons. This in turn stops the LTD process and stabilizes the latency of the rebound in the deep n. These results indicate that *blocking of the US signal stabilizes the cerebellar output just ahead of the US onset.*

In line with these studies we suggest that blocking of the US input to the amygdala may initiate the extinction of the amygdala-based fear CRs during the third stage of conditioning. In experimental animals we have shown extinction of the fear CRs after massive conditioning trials. Lesion of the cerebellar deep n. abolished the motor conditioning and prevented the extinction of the fear CRs.

These findings define the third stage of conditioning. Well timed rebound excitation generates motor CRs just preceding the US onset. At the same time, the cerebellar output effectively blocks the US afferents to the cerebellum but also to the amygdala. The latter may be responsible for the extinction of the fear responses after massive motor conditioning.

Posture and movement invoke separate adaptive mechanisms and represented in different coordinate systems.

C Ghez[1], RA Scheidt[2,3,4] and FA Mussa-Ivaldi[5]. *Columbia Univ Medical Center, New York, NY, [2]Marquette Univ, Milwaukee, WI, [3]Northwestern Univ Medical School, Chicago, IL.*

Reaching straight for a target requires planning a movement trajectory and stabilizing the hand at the desired endpoint. In order to determine whether these two functions share adaptive controllers we examined the transfer of adaptation to 30° visuomotor rotations between two tasks requiring specific control either of their trajectory (*slicing task*) or of their final position (*reaching task*). In *slicing* subjects moved the handle of a robotic manipulator out-and-back, reversing within a visual target with continuous visual feedback. In *reaching*, subjects moved at the same peak speed but stabilized their hand in the target with feedback only of their final position. Unpredictable forces were applied to the handle after movement termination forcing subjects to co-contract shoulder and elbow muscles to maintain alignment. Both experiments compared two groups of subjects, those trained with the visuomotor rotation while *slicing* and those trained while *reaching*. Transfer was tested with periodic catch trials performed without any visual feedback.

The first experiment examined transfer of adaptation across tasks with reaching to 8 concentric visual targets. With *slicing*, paths remained straight during adaptation but became curved with *reaching*. Endpoints of catch trials showed little transfer of adaptation from learned slicing to reaching or from learned reaching to slicing. However, earlier in the movements, at peak velocity, there was greater transfer, but only from slicing to reaching. Transfer did not depend on hand speed. Thus, trajectory and posture invoke separate learned adaptive controllers, which dominate early vs. late in movement (i.e. near the final position); moreover, specification of posture does not obligate rectilinear hand trajectories in task space.

The second experiment asked whether adaptation achieved with a single target generalizes differentially for slice and reach training when initial position or target direction (45°) are altered. The slice task was modified requiring subjects to terminate movement in a final target which was located equidistant from the starting location, but 180° away from the target for movement reversal. In this way it was possible to reposition the hand at specific starting locations for both slices and reaches and to better characterize transfer of adaptation from one task to the other. As in experiment 1, there was only modest transfer of learning across tasks. However, with shifts in initial position, movement direction to the reversal point remained unchanged with *slicing* but changed with *reaching* direction so that similar final positions were achieved both before and after adaptation. Generalization of slice adaptation to targets at 45° was minimal (as per Krakauer et al. 2000) but was greater following reach adaptation. Moreover, when tested after reach adaptation, the final positions of return phases after slicing movements were rotated in the opposite direction relative to baseline. We hypothesized that since subjects did not have explicit information about the visual location of their initial position, movement errors could have been coded in reference to the shoulder rather than the hand. Consistent with this, repeated measures ANOVA showed no significant difference in the angular deviations of final positions relative to the shoulder of reaches to the adapted target, the 45° target and the final position of the slice following reach adaptation. We conclude that reaching is governed by separate learned visuomotor transformations that specify transport and final position, corresponding to “pulse” and “step” phases of a compound command, which can be dissociated by manipulating feedback information and terminal stability. Whereas trajectory is represented as a vector, relative to the initial position of the hand, endpoint is represented relative to the shoulder, which remains fixed throughout the movement. (1) NS022715, (2)HD39627, (3)Whitaker RG010157, (4) NSF 0238442, (5)NINDS NS35673.

Modeling learning process and finding the sources of noise

Opher Donchin, BME, BGU

State space models are an increasingly popular tool in the study of motor adaptation. For instance, the progression of errors from movement to movement during reaching movements in force fields can be described as a state space model (Donchin et al., 2003). In this case, the hidden state represents the internal model used by the subject to predict the force field, and the state update captures the subject's tendency to update this model in the face of error. We have now developed our model to incorporate explicit representation of noise. Two different sources of noise are represented: state noise and output noise. State noise reflects lack of stability in the internal model presumably caused by that the representation is built using noisy neurons noise but also potentially reflecting unmodeled influences on the internal model. State noise necessarily propagates forward in time, affecting all subsequent movements. Output noise reflects noise in descending pathways that implement the movement. Output noise may or may not propogate to subsequent movements. Whether or not it does depends on whether the update uses a measure of error derived from the intended movement (uncorrupted by error) or the actual movement (corrupted by error). We fit our model to data collected under different patterns of force in an effort to distinguish which of these two models better describes human behavior and to determine the relative size of output error and state error. We found that in practice it is very difficult to distinguish the two models. Tentatively, it is possible to say that the model which uses an uncorrupted measure of error describes the data somewhat better than the model which propogates the output error forward to subsequent movements. Interestingly, regardless of the model used to describe the data, we found that output error is approximately 20 times larger than state error. This finding has important implications for models of learning and adaptation.

Synaptic depression in conjunction with A-current channels promote phase constancy in a rhythmic network.

Yair Manor
Dept. of Life Sciences, Ben Gurion University of the Negev

In many central pattern generators, pairs of neurons maintain an approximately fixed phase despite large changes in the frequency. The mechanisms underlying phase maintenance are not clear. Previous theoretical work suggested that inhibitory synapses that show short-term depression could play a critical role in this respect. In this work we examine how the interaction between synaptic depression and the kinetics of a transient potassium (A-like) current could be advantageous for phase constancy in a rhythmic network. To demonstrate the mechanism in the context of a realistic central pattern generator, we constructed a detailed model of the crustacean pyloric circuit. The frequency of the rhythm was modified by changing the level of a ligand-activated current in one of the pyloric neurons. We examined how the time difference of firing activities between two selected neurons in this circuit is affected by synaptic depression, A-current, and a combination of the two. We tuned the parameters of the model such that with synaptic depression alone, or A-current alone, phase was not maintained between these two neurons. However, when these two components came together, they acted synergistically to maintain the phase across a wide range of cycle periods. This suggests that synaptic depression may be necessary to allow an A-current to delay a postsynaptic neuron in a frequency-dependent manner, such that phase invariance is ensured.

Dissociation between local population and single units properties in pre-motor cortex regarding both reaching and grasping

Eran Stark, Itay Asher, Rotem Drori, and Moshe Abeles
The Hebrew University of Jerusalem, and Bar Ilan University, Israel

Reaching and grasping are fundamental activities in primate behavior. Psychophysical studies have demonstrated that when these elements are performed during prehension, they are highly coordinated. This implies that neuronal representations must somehow be coordinated. However, classical mapping studies of frontal motor fields indicate spatially segregated representations of proximal and distal movements. Therefore, the neuronal substrate of the well-coordinated composite movement is not yet understood.

To address this issue, we used a prehension task in which the subject has to perform one out of 3 types of grasps in one out of 6 locations and recorded neuronal activity from premotor areas of behaving Macaques.

We used a combination of micro-stimulations and detailed sensorimotor mappings to characterize properties of the neural population surrounding each recording site. As expected, micro-stimulations revealed spatially segregated clusters of arm and finger recording sites. A total of 600 well-isolated units were recorded from sites whose characteristic limb-part was either shoulder or elbow, and 200 units from sites whose characteristic limb-part was one or more fingers.

Here, we focus on properties of single units during preparation for movement. During this time, lasting more than one second during each trial, monkeys already knew in which direction they would have to reach and what type of grasp they will have to perform. However, no external stimuli were presented and the monkeys were not required to perform any action. Indeed, a study of 12 arm, wrist, and digit muscles did not reveal task-dependent activity.

Over 40% of the cells exhibited significant directional preference, and more than 20% displayed object preference. The probability of finding single unit activity in relation to reaching or grasping did not depend on recording site. Many well-isolated cells modulated their activity with respect to both reaching and grasping at the same time, and about 10% of the cells displayed non-linear interactions between the intended movement direction and the planned grasp type.

These results suggest that “grasping” neurons in reaching areas and “reaching” neurons in grasping areas act as agents that allow for the coordination of reaching and grasping during preparation for movement.

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Inference of arm movements from spiking activity and local field potentials in monkey motor cortex

Eilon Vaadia
Department of Physiology, Hebrew U

The ability to learn a person's intentions by 'reading' brain activity has always been a fascinating theme in the realm of science fiction. Recent advances in brain research indicate that this idea may not be so far-fetched after all, and the field of "brain machine interface" is rapidly growing.

We adopted three approaches in order to add to the understanding of movement related activity in the cortex and to improve our ability to reconstruct movements on the basis of this activity.

(1) We examined and compared the information content in two types of cortical signals; the spikes (Single Unit Activity- SUA) and the local field potentials (LFP, recorded simultaneously by the same electrode) and found that combining SUA and LFP improves inference of movement direction.

(2) We examined learning-dependent changes in the neural code. To do that we performed experiments in which we recorded neuronal activity in motor cortex while monkeys acquired new motor skills. We applied information measures to probe for learning-dependent changes in neuronal representation of movements and found that neuronal population conveyed more information about the direction of movement after learning, and that the specific improvement in encoding is correlated with an increase in the slope of the neurons' directional tuning. Further, the improved information enables a more accurate reconstruction of movement direction.

(3) We have constructed biologically-motivated algorithm to improve our ability to predict arm movement on the basis on neuronal activity. The algorithm (Dynamic discriminative tracker) is based on combining kernel that maps cortical activity into an abstract vector space ("spikernel") and a linear transition of the movement at time t-1 to predict the movement at time t. We demonstrate the merits of our modeling approach by comparing its performance to various standard kernels.

The implications for developing brain machine interface for clinical application will be discussed.

Rate-modulations of cortical neurons during arm movements and operation of a brain-machine interface

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Brain machine interfaces (BMIs) for movement control exploit the activity of brain cells that modulate their firing rates as a function of movement variables. The ultimate goal of such BMIs is to restore motor functions in severely paralyzed patients by extracting those signals from the neuronal modulations and using them to control prosthetic devices. Considerable progress has been made in recent years in characterizing the neuronal encoding of movement and in extracting specific movement variables, such as hand velocity and position. Even with respect to these variables, which are relevant in both normal movements and BMI operations, successful BMI experiments have revealed that a new neuronal representation emerged. Fundamentally, however, the main question is still whether *new* variables become significant in modulating the firing rates when the neurons start to operate a BMI. Here, we investigate this issue by comparing the extent of the overall modulations in the firing rate with the extent of the movement related modulations.

The extent of the overall modulations was estimated independent of the identity of the modulating signals by modeling the spike-trains as realizations of doubly stochastic Poisson processes. The extent of the movement related modulations was estimated using a spatio-temporal velocity tuning model.

Tuning characteristics of cortical neurons are usually defined with respect only to spatial features of the movement, most notably the direction of movement, during experiments involving stereotypical reaching movements. However, general arm movements, like the ones performed during the current BMI experiments, involve temporal patterns which cannot be captured only by spatial features. In particular, recent studies demonstrated that directional tuning characteristics also depend on the time-lag between the neuronal activity and movement. Here we developed a multi-lag velocity model which correlates the spike-count during the current 100msec bin with the spatio-temporal profile of the velocity in the surrounding 2sec window. The spatio-temporal patterns of velocity are described mathematically as consisting of different principal components corresponding to different frequencies and directions of velocity and acceleration. The correlations of the spike-counts with these principal components represent the spatio-temporal tuning of the neurons and determine the extent of the movement related rate modulations.

The analysis demonstrate that the extent of the overall modulations in the firing rated of cortical neurons increased sharply when primates started to operate a brain machine interface (BMI) and gradually decreased with subsequent training. Despite the overall increase in rate modulations, the fraction correlated with the spatio-temporal pattern of the movement remained approximately constant. These results suggest that novel factors become significant in operating the BMI, provide insight into motor learning and tool acquisition, and suggest that BMI can be improved.

Population-based corticospinal interactions during voluntary movements

Efrat Katz, Nofya Adamit, Yuval Yanai, Zvi Israel and Yifat Prut*
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Planning and executing voluntary movements requires cooperation between multiple motor centers. Of these, corticospinal (CS) interactions play a prominent role. Currently, little is known about the functional efficacy of these interactions and their spatiotemporal properties in behaving animals. This study was design to characterize ongoing CS interactions during voluntary movements.

Two monkeys were trained to perform an isoemtric flexion/extension wrist task. Cortical implant was situated above the motor cortex and a spinal chamber was implanted above the cervical enlargement. Local Field Potentials (LFPs) were recorded simultaneously from motor cortex and spinal cord during task performance.

Event-triggered averaging of both cortical LFP was expressed movement-related modulation more frequently (63%) then spinal LFP (%35).Passive wrist displacement was more efficient in evoking both cortical (99%) and spinal (65%) response. Cortical event-triggered LFP response was mostly manifested as a slow amplitude modulation while spinal response was often dominated by a brief period of increased frequency. This feature was seen in the time resolved spectrum computed for each signal, where spinal spectrogram often revealed a shift towards higher frequencies during sustained torque production.

Cortical-to-spinal correlation of LFPs appeared tri-phasic with average positive ($\rho= 0.12\pm0.11$) and negative ($\rho= -0.15\pm0.12$) peaks. The global maximum tended to occur at positive lags (24.0±88.1 ms) consistent spinal signal preceding the cortical signal. This may indicate that corticospinal correlations are greatly affected by ascending information. We found no indication of single–unit or multi-unit CS interactions. Coherence analysis further revealed that CS correlations are in addition to a low-frequency band (<10Hz) of enhanced interaction, a second band appeared at values of 20-30 Hz.

Our results indicate that both spinal and cortical LFPs encode movement related parameters. However, cortical signal appears more sensitive to motor events, possibly due to the differences in neuronal organization between the two structures. In both cases, synchronous activation of afferents resulted in a robust response. LFP correlations were more frequent than single cell interactions a result which could indicate either that CS interactions are carried on a populated-based manner, or that the common synaptic volley reaching both areas is insufficient to drive single cells to fire synchronously. The coherence found in higher frequency band is similar to coherence found between cortical LFP and muscle activity and thus may indicate that during motor actions multiple co-active motor areas are coupled via synchronized interactions in this frequency band.

Posters

Different kinematic strategies in handwriting in writer's cramp

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Objectives: To describe the kinematic strategy applied by patients with writer's cramp (WC) during writing and drawing.

Background: WC is a task-specific idiopathic dystonia, which is characterized by inappropriate and prolonged activation in muscles of the forearm and hand during writing; EMG reveals excessive co-contraction of agonistic and antagonistic muscles during writing. In the current study we aimed to find out what is the kinematic strategy that is adopted by WC patients, influenced by the co-contractions during execution of graphomotor output.

Method: Two female WC patients (WC1 and WC2) and six healthy controls, 4 females and 2 males, were studied using digitizer tablet (WACOM, 12-12, sampling rate of 100HZ). The subjects completed two tasks, drawing and typical writing, consisting of 15 repetitions each: **task A.** drawing a 7-circle set (oooo ooo), **task B.** writing twice the first four letters in the Hebrew alphabet (אבגד אבגד). Computed variables included: means and standard deviations of tangential velocity, curvature, and consistency of character shape between repetitions. All variables were compared between each patient and the controls.

Results: Each WC patient adopted a different strategy in order to produce the required graphomotor output. In task A, WC1 wrote slower than normal, and showed low shape consistency and a wide spectrum of curvatures that included both sharp angles and long straight line segments atypical for circle drawing. In contrast, WC2 wrote faster than controls, and showed normal consistency and normal curvature. In task B, WC1 had a higher tendency to produce sharp angles and reduced velocity. WC2 kept the same handwriting profile of high velocity and low curvature, while in the controls the curvature was higher than in task A, and the velocities were reduced. Compared to controls, while WC1 showed an excessive variability between task A and task B, the writing variables of WC2 were nearly unaffected by the type of task.

Conclusions: WC patients are not a homogeneous group and adopt different handwriting strategies that may depend on the particular level and site of impairment. It is possible that each handwriting strategy reflects a different compensation mechanism related to the specific affected (a) group of muscles and/or (b) neuronal structure. Hence, further kinematic analysis of handwriting is a key to understanding the unclear pathophysiology of WC.

A Minimum Acceleration Criterion with Constraints Accounts for the Observed Trajectories in Reaching Movement as well as for a Three Phase Control Signal

Shay Ben-Itzhak[1] and Amir Karniel[2]

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Reaching movement is an elementary motor task considered a primitive for more complex motor tasks. Experimental studies have demonstrated that in typical conditions point to point reaching movements are performed in a straight line and a bell-shaped speed profile. We assume that the biological system evolved to find optimal solutions hence these profiles are the result of such optimization.

Many cost functions have been suggested in the literature. Some involve quantities depending on the dynamics of the system such as minimum energy, minimum torque or minimum torque-change, others involve quantities depending on the kinematics of the system, e.g. minimum acceleration, minimum jerk, and minimum crackle, and yet another recent approach suggests minimizing the errors caused by noise in the nervous system or environmental disturbances, which insert noise both to the control signal, and to the feedback sensors.

In this work we study the minimum acceleration criterion. A minimum acceleration criterion has been proposed in the past, but was rejected because its solution, based on calculus of variations, fails to predict rest of hand (i.e. zero acceleration) at the beginning and the end of the reaching movement. We used another approach to solve this problem, based on the minimum principle theorem, outlined by Pontryagin. In order to find a solution, we also assumed constraints on the maximum and minimum jerk values and therefore we call our criterion "A Minimum Acceleration Criterion with Constraints" (MACC). By using the minimum principle, we show that the analytical solution gives a bang-bang control on the jerk signal, where the quantity of jerk and switching times depend on the maximum and minimum available jerk value.

Comparing the analytical results of MACC to those of "Minimum Jerk Criterion" (MJC) shows almost no difference in the hand end point trajectory and velocity profiles. Noticeable differences appear in acceleration and jerk profiles. According to MJC acceleration and jerk profiles are polynomials of third and second order respectively. The MACC predict a piecewise linear acceleration profile, and a piecewise constant jerk profile.

In fitting the best parameter to experimental data we have found that the value of the maximum Jerk depends on the direction of movement in the workspace, e.g., when shoulder movements are required the maximum Jerk is smaller then in directions that require mostly movement of the elbow.

Altogether comparison with experimental results has not yet yielded clear evidence in favor of one of the two criteria. The MACC and the MJC can equally well explain the data we have examined so far.

Further studies are required to accurately measure acceleration and jerk in order to find out which criterion better describes human reaching movements.

Early vs. Late Resolution of Conflicts: Paying Attention to the Motor Cortex

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When different attributes of a visual stimulus demand different responses, the correct response to the relevant dimension is commonly slower when it is in conflict with the irrelevant dimension (e.g., the Stroop effect). A fundamental question is whether our brain has an innate ability to process numerical information independent of other features, such as line length, luminance or pitch. Moreover, it is still unclear at what levels of processing interference operates. Stimulus encoding, stimulus representation, response selection, and response execution have all been suggested as targets for such interference. We used fMRI with the size-congruity paradigm, in which numerical values and physical sizes varied independently. In line with earlier findings, incongruity was found to modulate activity in the intraparietal sulci. Earlier works suggested that this finding supports the idea that the conflict is resolved at a pre-response stage. However, by applying an innovative analy sis to the motor cortex activity we revealed aberrant activation of the ipsilateral (to the response hand) motor cortex in incongruent conditions. We could thus trace the neural signature of interference up to the motor cortex.
Furthermore, functional connectivity was highest between the motor cortex and intraparietal sulci and the frontal eye fields. This network analysis further indicated that interference also occurs during response stages.
These results contradict the common view that the processing of magnitude is subserved by a common mechanism. They suggest rather, that magnitude of number and size are processed in parallel by different neural substrates up to the level of the motor cortex.

Joint coordination during manipulative hand movements – characterization, segmentation and concise representation

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Manipulative hand-movements involve the coordination of a large number of joints and present a challenging problem in the theoretical field of motor control. This research focuses on characterizing the intrinsic joint-coordination during manipulative hand-movements, in order to facilitate their recognition for human computer-interfaces, and provide insight into the underlying human-motor control.

Previous investigations demonstrated that during simultaneous hand-movements the different joints are tightly coordinated, and the resulting joint-space trajectory is approximately linear. Consequently, we explore the significance of the 1st eigen-vector of the joint-space trajectory in capturing the synergetic structure of the movement. Using the 1st eigen-vector as a feature-vector, we demonstrate the successful recognition of simultaneous hand-movements, for both user-dependent and user-independent systems.

We extend the investigation to sequential hand-movements that involve a sequence of coordinated motions. The quest to divide the complete movement into its basic motions and to define the nature of each motion is highly dependent on the segmentation technique. Here we present a new segmentation-technique based on the velocity of the initial eigen-functions of the joints' space.

The resulting segmentation of sequential hand-movements reveals that the different movement-segments trace either straight- or curved- joint-space trajectories. The straight joint-space trajectories are generated by task-related movement segments, and are similar to those generated during simultaneous hand-movements, while the curved trajectories involve repositioning movement-segments. We found that both movement-types obey the minimum-jerk criterion in the joint-space, and the difference in their shape is attributed to the presence of via points in the repositioning movements.

Features of Human Object Manipulation

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Although we grasp and manipulate objects nearly effortlessly, it is not clear how the central nervous system (CNS) selects a grasp for a particular object and task. The contact points with the object, the posture of the hand, the necessary fingertip forces and the impedance properties of the hand must all be determined in order to successfully grasp and manipulate an object. A method is proposed for analyzing some of these features during human grasping for object manipulation. The technique is based on examining the compatibility of of the selected grasp for various goals. The grasp Jacobian, which is a function of the posture of the hand, defines force and velocity ellipsoids, which represent the transmission ratio of the appropriate quantity from the joints to the object. Additionally, the stiffness ellipsoid of the grasp represents the resistance of the grasp to external perturbations. The features of these ellipsoids can provide an insight into why the CNS selects a particular grasp for a given task.

Four right handed subjects grasped and manipulated 5 objects with 9 different types of manipulation (lifting a cup from the side and the top, unscrewing and lifting the lid of a narrow jar, unscrewing and lifting the lid of a wide jar, lifting and stirring with a teaspoon and lifting a round puzzle piece). All the grasps involved only pad opposition. At the start of the manipulation, the joint angles of the hand were measured using the CyberGlove (Immersion) as well as the wrist position and orientation, using the Fastrak (Polhemus). From this data, the grasp Jacobian can be constructed. The grasp Jacobian is the relationship between the joint velocities of the hand and the velocity of the object being grasped. In separate recordings, the fingertip stiffness of each finger while statically grasping the object as if to manipulate it was estimated by repeatedly applying forces to the fingertips with the CyberGrasp (Immersion) and measuring the resultant displacement. The grasp stiffness was estimated from the finger stiffness matrices after assuming abduction stiffness values.

Invariant features of the ellipsoids were observed across subjects for some of the grasps, and these in turn could be related to salient task constraints. The features were related to the directions in which forces or velocities could be efficiently applied, and to the directions of stiffness. Greater variance was generally observed for parameters without an obvious connection to the task. For the same object, it was observed that different features were selected depending on the task being performed. Thus models of grasp planning must take into account not only the object geometry but also the desired manipulation.

Studying coritcospinal interactions in behaving primates using local field potential

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Planning and executing voluntary movements requires interaction among multiple motor centers. Of these, corticospinal (CS) interactions play a prominent role. Nevertheless, little is known about these interactions in the intact animals both in terms of efficacy, spatial extent and time scale. The aim of this study was to measure and characterize ongoing CS interactions during voluntary movements.

Two monkeys were trained to perform an isoemtric flexion/extension wrist task. Cortical implant was situated above the motor cortex and a spinal chamber was implanted above the cervical enlargement. Local Field Potential (LFP) was recorded simultaneously from motor cortex and spinal cord during task performance. This signal is considered to represent the local synaptic input.

Event-triggered averaging of cortical and spinal LFP revealed a clear movement-related waveform consistent with a synchronous incoming synaptic volley. The cortical-to-spinal correlation of LFP signals tended to be significant (CC = -0.130.04±-:) and the majority of these correlations had an off-zero peak that occurred in a time-lag consistent with spinal signal preceding the cortical signal. This may indicate that CS correlations are dominated by ascending information and not descending commands. As a control, CS correlations were computed for lower-thoracic spinal sites (instead of cervical sites). In these cases, only weak zero-phase correlation pattern were found, suggesting that specific anatomical connectivity pattern underlies CS correlation of LFP.

Our results indicate that correlating cortical and spinal LFPs uncover movement-related flow of information between motor cortex and spinal cord. The fact that often spinal LFP precede cortical LFP may suggest that information in the ascending pathway is more synchronously activated unlike descending command which is either organized in a patchy manner or transmitted in a less synchronous manner.

Bimanual Adaptation: Internal Representations of Bimanual Rhythmic Movements

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From tying your shoes and clipping your tie to the claps at the end of a fine seminar bimanual coordination plays a major role in our daily activities. A pillar phenomenon in bimanual coordination is the predisposition towards mirror symmetry in performance of bimanual rhythmic movements. Although learning and adaptation in bimanual coordination are phenomena which have been observed they have not been studied in the context of adaptive control and internal representations – approaches that were successfully employed in the arena of reaching movements and adaptation to force perturbations. In this paper we examine the dynamics of the learning mechanisms involved when subjects are trained to perform a bimanual non-harmonic polyrhythm in a bimanual index finger tapping task. Subjects are trained in this task implicitly, using altered visual feedback, while their performance is continuously monitored throughout the experiment. Our experimental results indicate the existence of significant ($p<<0.01$) learning curves (i.e. error plots with significantly negative slopes) during training and after effects with a wash out period after the visual feedback ceases to be altered. These results confirm the formation of internal representations in bimanual motor control. We present a simple, physiologically plausible, neural model which combines feedback and adaptation in the control process and which is able to reproduce key phenomena of bimanual coordination and adaptation.

INTERFACING: Modeling Motor Skill Acquisition as a Transition from Indirect to Direct Control of End Effector

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We propose two plausible models for motor control of an end effector: an indirect model in which CNS controls the end effector through control of hand, as opposed to a direct model in which CNS controls directly the end effector. We define these models formally, and analyze their characteristics. We then test some aspects of the models empirically: 7 Subjects were presented with a tracking task under 90 degree rotation.
Subjects' hand movements were measured using an Ascension 5mm MiniBird system. We distinguish between reversal trials in which target reversed its direction relative to its preceding trial, and perpendicular trials in which target direction is perpendicular to its previous direction. We show that reversals are significantly more successful than perpendicular trials (chi-square, $p<0.01$ for each and every subject), indicating that CNS performs the task based on computing hand to cursor relation, supporting the indirect control scheme.

We describe two methods we are considering to dissociate between the two models: 1. Tracking tasks with nerve blocked patients, a condition in which the task must inevitably be performed through the direct model; 2 Designing tracking tasks in which cursor and hand do not maintain a fixed location mapping but the directional mapping is maintained, a condition in which the task requires use of the indirect model.

Finally we discuss implications of these models to skill acquisition.
Based on the characteristics of the models, we hypothesize that skill acquisition may involve a transition from an indirect to direct model.
We note that the transition to the direct model, which we term **interfacing**, is a computational correlate to the concept of embodiment that has been raised with respect to Brain Machine Interfaces (BMI), and to the concept of automaticity used in psychological research of motor tasks.

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MEC-1: A multi-electrode array on a chip

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We present MEC-1, a novel microelectrode array on a chip, and discuss technology development and testing. This device measures extracellularly at each microelectrode the local modification of the ion concentration due to neuronal activity, resulting in a potential difference between the microelectrode and the reference bath potential. MEC-1 is designed to replace present technology of glass-substrate MEAs and external signal acquisition.

Taking advantage of the high levels of integration possible with contemporary CMOS chip technology, the entire system on a chip would include electrodes, amplifiers, thermal regulators and data processing algorithms. The benefits of such systems are not only scalability and cost reduction. Offering larger number of closely spaced microelectrodes, it improves the special resolution of activity imaging.

We designed, fabricated and tested a prototype micro-electrode array chip. It comprises a variety of electrodes with preamplifiers and output buffers. The electrodes, when submerged in a salty solution with biological tissue, respond to potential differences caused by neuronal activity in the form of tiny fluctuations in electrode polarization potentials. Since those fluctuations range from 50uV to 1mV, low noise amplification is introduced. To ensure high sensitivity, the electrode impedance is made much higher than the amplifier input impedance. Moreover, since electrode impedance is proportional to the electrode area, smaller electrodes make the amplifier design more difficult. To meet this challenge, we designed a special low-noise, low-input-impedance differential amplifier. This high bandwidth amplifier provides 40db gain while adding only 5uV rms of input-referred noise. To define the operating point of the amplifier, small reset switches were added to the electrode-amplifier high impedance nodes. Those externally controlled switches are operated periodically to compensate for leakage currents causing voltage drift. To drive the amplified signal out of the chip, a unity gain buffer was added at the output of each amplifier.

The bio-electrical activity is highly dependant on the environment temperature. An accurate temperature control is essential for any in-vitro system. For this purpose a temperature sensor and a heater element were integrated into the prototype chip.

The chip was fabricated in 0.35um CMOS. It was first tested electrically. Following unsuccessful attempts to insulate the bonding wires with epoxy, we developed a new technique using a biocompatible silicon elastomer poly-dimethyl-siloxane (PDMS), a.k.a. Sylgard-184®. Finally, a glass O-ring was affixed to the chip with PDMS, forming a larger bath capable of containing a suitable amount of bio-medium.

The resulting bio-chip was used to characterize aluminum and coated electrodes, to verify sensor sensitivity and to culture rat hippocampal neurons for 6 weeks. The sensor recorded the neural activity several times during this period proving to be non-toxic.

Three-dimensional arm movements: from measurement to laws of motion

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There has been relatively little research on complex three-dimensional arm movements. We wished to study the relationship between path geometry and trajectory kinematics for such movements. One of the obstacles hindering progress in such research is the need for accurate smoothing and differentiation techniques, which will enable the extraction of high-order derivatives of time as well as local differential characterizations of the path from noisy experimentally-obtained position data. One such method, which we have developed and is especially suited for repetitive tracing of shapes, is demonstrated. Moreover, our progress in trying to determine the validity of the 1/3-power law for three-dimensional upper-limb motion, as well as the effect of path torsion on trajectory kinematics is presented. Last, we consider the consequences of the inherent noise for such power-laws.

Does the Brain use Smith predictor and/or Wave variables techniques to cope with delay?

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During our life course the brain received sensory information, issues motor commands and has to handle various kinds of delays. Some delays are internal (neural conduction time) and other external (from motor execution to the resultant sensory information, such as when driving, or manipulating a robot at a distant place via the internet). We know that a delay within a feedback control system can turn a stable system unstable, and therefore in considering any human machine interfaces, it is essential to understand how the motor control system deals with delay.

Control Engineers are aware of this problem for many years. Two salient engineering methods to handle systems with delay are the Smith Predictor (Smith, 1957) and the Wave-Variables theory (Niemeyer & Slotine, 2004).

The Smith predictor is a general control scheme for any processes with loop delays which is based on internal model of the delay. Generally, the prediction is dependent on knowing the plant model (forward or inverse) without the delay, as well as the estimated duration of the delay. The control is applied on the model without the delay, and then the difference between the actual feedback and the predicted feedback from the model with the delay is fed back to the system. This method is very sensitive to a mismatch at the model of the delay. It has been suggested that the cerebellum may function as such predictor by Miall et al. (1993).

The wave variables concept is taken from the field of teleoperation employing the theory of passivity. The standard power variables $(F,\dot{x})$ are encoded to new variables, and these are transmitted between the two sides of the system. There is a tuning parameter b that trades off speed and force, which is called the Wave Impedance and actually adds apparent damping to the master's side of the teleoperation system. Massaquoi & Slotine (1996) suggested that the cerebellum may function as a Wave Variable processor and contribute to motor control in this way.

In this project we try to develop an experiment based on operation in a virtual reality environment with haptics capabilities in order to explore the similarities and differences between the brain function and those two engineering methods.

Prior to planning the experiment a set of simulations were performed with Matlab and Simulink, which lead to the following conclusions:

- Employing the Wave variable technique we expect a sluggish responses with growing delay, since this technique tune the wave impedance to match the system properties. We also expect an after effect after learning certain set of system parameters, and then changing them, but not necessarily after changing the delay.
- For the Smith predictor we should expect learning the delay model. The system is sensitive to delay mismatches, and there should be an after effect after learning a certain delay, and then changing it.

The simulation results as well as pilot experimental results would be presented and discussed.

An Integrated System for Multichannel Neuronal Recording with Spike / LFP Separation and Digital Output

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Recent advances in fabrication of MEMS microelectrode arrays, together with the ability of coupling the arrays directly to VLSI chips, allow simultaneous monitoring of hundreds of neurons. Communicating raw neuronal signals from a large number of units results in prohibitively large data rates. When sampled with 20Ksps, eight bit precision, even a hundred of electrodes would generate 16Mbps, too large for common methods of low-power wireless communications. Evidently, some form of data reduction must be applied prior to communication. It is possible to detect the presence of neuronal spikes and communicate only active portions of recorded signals, which may at best lead to an order of magnitude reduction in the required datarate. Another order of magnitude reduction can be achieved if the neuronal spikes are sorted on the chip and only mere notifications of spike events are transmitted to the host.

This work focuses on an integrated neuronal recording front-end with on-chip A/D conversion, designed for further integration with spike sorting. Prior to performing the A/D conversion, the front-end splits the neuronal firing activity band (SPK) and the local field potential band (LFP) in the analog domain, immediately after the first amplification stage. The two signal bands are processed by separate analog chains and are both made available to the host in digital form. The required data acquisition dynamic range (i.e. ADC precision) is consequently reduced from 10 to 7 bits.

A front-end neuronal recording IC has been designed, fabricated on a 0.35μm CMOS process, and tested. The chip contains twelve true-differential input channels, SPK/LFP band separation, on-chip A/D conversion and high-speed serial data communication. The on-chip controller is capable of detecting spikes by means of threshold crossing; it can transmit only the portions of signal containing spike activity. Analog SPK and LFP outputs of every channel are also provided.

Modeling and compositionality of monkey drawing movements

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In this study we have analyzed the kinematic properties of monkey scribbling movements recorded over several consecutive days. The constrained minimum-jerk model was used to model the movements. A necessary mathematical condition that must be obeyed by movement paths for trajectories that satisfy both this model and the 2/3 power law was formulated. Parabolic segments constitute a particular solution and the only one that is invariant under equi-affine transformations. Minimum-jerk trajectories passing through one via point obey the local isochrony property. The analysis of such trajectories showed that they follow parabolic paths. We further examined what geometrical characteristics uniquely define such segments and the relation they obey between equi-affine distance and movement duration.
Further analysis of well-practiced monkey drawing movements has indicated that their decomposition yielded 3-4 different clusters of parabolic segments. Thus, parabolic segments might constitute the underlying motion primitives from which the scribbling movements are constructed.

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Keywords: models, learning, segmentation, motion primitives

Putative role of leak currents in regulation of rhythmic activity in the pyloric network of *Homarus americanus*

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The pyloric network in the lobster *Homarus americanus* is a central pattern generator (CPG) that is involved in feeding. Its rhythmic activity is generated by a group of three electrically coupled pacemaker neurons. The rhythm depends on intact neuromodulation delivered to the CPG via the stomatogastric nerve (*stn*). When the *stn* nerve was cut, oscillations were abolished or dramatically slowed down. Using the dynamic clamp technique, we were able to restore the oscillations by artificially reducing potassium leak conductances in the pacemaker neurons. Similarly, when the *stn* nerve was intact, we were able to completely abolish the pyloric oscillations by artificially increasing potassium leak conductance. This manipulation, however, was accompanied by an unrealistic decrease in the input resistance of the cells. Previous studies suggested that leak currents in pyloric neurons are a mixture of potassium and sodium currents. We therefore repeated the dynamic clamp manipulation, modeling the leak conductance as a combination of potassium and sodium conductances. With this configuration, a modest increase and decrease in the potassium and sodium components of the leak conductance, respectively, was sufficient to completely abolish the oscillations, with no significant change in input resistance. These results raise the possibility that neuromodulatory inputs control the pattern of the pyloric rhythm by modifying the properties of leak currents in pyloric pacemaker neurons.

Low cost haptic telerehabilitation system

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The goal of this project is to develop a low-cost, user-friendly, portable telerehabilitation system for physical therapy with accompanying software for use at home, using the Internet to connect to rehabilitation specialists in the clinic. The system uses commercially available force-feedback joysticks together with specially written software. The position of the joystick and the forces exerted on it at each point in time are recorded in a text file. We have developed a prototype exercise where the task is to use the joystick to reach targets on the screen. The exercise can be done in 2 different modes. In the stand-alone mode, the joystick has been programmed to assist the patient in this task by providing gentle forces in the correct direction. In the telerehabilitation mode, the joystick is guided by a remote user who is connected to the patient by a standard broad-band internet connection. We have tested this system on the internet and have found the delay to be minimal.

Decoding planned trajectories in the Posterior Parietal Cortex E. B.

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There are current conflicting results concerning the involvement of the Posterior Parietal Cortex (PPC) in the computation of the movement dynamics. On the one hand, activity of cells in this area is invariant to dynamics-related manipulations1. On the other hand, stimulation of the PPC interferes with arm trajectory adjustments during the learning of new dynamics2. What is the role of this area in the computation of the dynamics for movement execution? A recent sensory-to-motor transformation theory3 proposes a new role for the PPC. It views this area as an intermediate stage between perception and action where goal-oriented motions are resolved geometrically, i.e. through action simulation prior to movement. The geometric stage solves the transformation from abstract goals to simulated actions and yields a length-minimizing (geodesic) path efficient with respect to the perceptual space, and the action-simulation space geometries. At this stage time is not treated as a free parameter arbitrarily pre-defined. It is rather another dimension that is initially dependent upon the problem's geometry. This time-independent action-simulation path serves as input to the execution system. It is a "free-fall" path; the shortest that reaches the goals in one step along the geodesic direction pointing down the straight line with respect to the space-time metric. It is the ideal path for the kinetic energy and provides a reference to the execution system for error correction. Thus, when disrupted it impairs dynamic-related learning. The geometric solution minimizes the energy integral but it is given by a time-independent partial-differential equation that enables building the solution incrementally. This facilitates on-line error correction in the presence of perturbations. We present evidence from the PPC in favor of this space-time decoupling solution. Before movement execution, during the planning period, trajectories were decoded using 34 cells for leftward and 30 cells for rightward targets from the areas 5 and PRR of the PPC of one monkey. A new experimental paradigm that required temporal visuomotor adaptation was used. The experiment interleaved a delayed center-out reaching task that was "second nature" to the monkey with a new task that required avoiding a physical obstacle interposed on the way to visual targets. The new task was simple enough that did not require training, yet complex enough that it elicited a change in geometry (highly curved and long paths) that called for a change in temporal strategy. Electromagnetic sensors were attached to the arm to measure the behavior concurrently with the neural activity. Learning was monitored across time. The delay activity before movement in the PPC cells was highly different between tasks. Thus a simple leave-one-out Linear Fisher Discriminant decoding algorithm on the neural data was used to predict not only the target direction of motion across experimental conditions, but also the trajectories. The first transition from simple to obstacle-avoidance reaches predicted during the memory period the spatial path and its length, i.e. the spatial route in straight vs. curved trajectories, and the exact path length. The second transition within the obstacle block, (where the paths had been resolved prior to movement and conserved across trials, but the adequate speed profiles were pending), enabled prediction of speed-related features before the movement. Specifically it was possible to predict broken-slow vs. smooth-fast speed profiles. In support of the action simulation theory, the data shows that delay period activity prior to movement execution in the PPC reflects separable spatial and temporal aspects of reach trajectories.

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iMEA: An integrated multi-electrode array for neuronal recording and digital electronic spike detection and sorting

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For many years, the common technique for probing a neuron was to attach a thin electrode to the neuron and measure its electrical activity. As the number of neurons under investigation increased so did the number of electrodes, but even though the electrodes were getting smaller, the number of electrodes one can manually place in a small region is limited. The processing of all these electrodes is also complex and expensive thus requiring a new approach for neural research. First, in order to deal with multi-neural sensing, the separate electrode is replaced by an array of micro-electrodes array (MEA). Second, small scale IC's are designed in order to allow easier and less expensive analog analysis of the neural signals, more suitable for dealing with neural signals properties, and placed nearer the neurons themselves. Third, since by the use of MEA one is not able to place each electrode where one desires, attached directly to a single neuron, algorithms are designed to allow Spike Detection (SD) and Spike Sorting (SS) in a noisy environment with more than one neuron that is sensed by an electrode. Algorithms are also designed in order to reduce the data rate required for processing the large amount of data generated by a large number of neurons.

The integrated MEA (iMEA) is designed as a complete and independent system that creates an interconnection between multiple living neurons and a computer where their activity can be investigated. It is designed in order to minimize the hardware which is currently used for monitoring the activity of neural tissues in both size and price, and in order to allow execution of real-time on-line spike detection and sorting algorithms, which are currently implemented off line in software.

The first two versions, iMEA-1 and iMEA-2, were based on the first version of the NeuroProcessor chip (NP1). It had eight analog input channels, each connected to one electrode of an MEA, and eight analog output channels which produced the amplified neuronal signals. The analog signals were then acquired and digitized with a data acquisition board and passed to the computer

.

iMEA-3 is based on NP3, a third generation NeuroProcessor chip which has 12 analog input channels, and which digitizes the recordings and produces a high speed digital serial bus at the output, for easy communication to a computer over the least number of wires. iMEA-3 uses multiple copies of the NP3 chip and records all 60 MEA channels simultaneously. It also employs a programmable digital logic chip (a FPGA), which performs on-line real-time spike detection and sorting algorithms. iMEA-3 is connected to the PC through high speed Ethernet local area network.

Evidence for problem solving at the cortical level during adaptation of the motor system to changing loads

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Movement-related potentials (MRPs) recorded from the scalp are the electrical signals generated by the brain related to the generation of voluntary movement. These potentials have been shown to vary due to the force exerted by subjects as well as their familiarity with the task. It has recently been shown that when a subject adapts to a new motor task, the power of MRPs does not change monotonically, but instead there appears a large increase in its power after several repetitions of the task. This increase is most evident in MRPs recorded from locations over the prefrontal cortex.

In this study we investigate how this peak of activity is related to task parameters. Six subjects were asked to perform a motor task which required adaptation. A modified version of the matching pursuit algorithm was used in order to remove a significant portion of the electroencephalographic (EEG) noise overlapping the MRPs recorded in the experiment. Small groups of MRPs were then averaged according to experimental parameters.

By changing the number of alternative force levels that appeared in the experiment and their type, we were able to show that both the number of task executions before the appearance of the peak of activity as well as its power are related to the number of forces the subjects knew were possible. This suggests that the peak of activity is the manifestation of the comprehension of the task. We argue that this is a demonstration of the philosophical principle known as creative cumulation: the sudden understanding of the task parameters when enough information is collected.

Low–Power Architectures for Spike Sorting

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Separation and sorting of action potential waveforms ("spikes") originating from different neurons (spike sorting) requires high bandwidth communications between the electrodes and the sorting computer, as well as high-performance processing. When a large number of signals are to be handled, typical transmission resources are insufficient.

We investigate *Neuroprocessors*, which are front-end integrated circuits for processing neuronal recordings, with spike sorting capabilities. In this work we focus on spike sorting algorithms and architectures that trade off some classification accuracy in return for significant savings in power. Two reduced-complexity spike sorting algorithms are introduced: the *Integral Transform* (IT) and the *Segmented PC*. The classification accuracy of the proposed algorithms is verified by an algorithm based on principal components analysis (*PCA*).

The IT algorithm achieves 98% classification accuracy for about 2.5% of the computational effort of PCA spike sorting. The Segmented PC algorithm, which combines features of both IT and PCA, is more accurate than the IT algorithm by a fraction of one percent, but incurs twice or three times the complexity.

Low–Power Algorithm and Architecture for Spike Detection and Alignment

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Typical settings of neuronal recording experiments in test animals and human subjects require high bandwidth communications from the recording electrodes to the processing computer, where spikes are detected and sorted. When a large number of recording electrodes is needed, typical transmission resources are insufficient and power-hungry. In addition, the large number of wires results in heavy cables that severely constrain the subject. Consequently, it is desirable to pre-process and reduce the volume of the recorded data so that it can be transmitted wirelessly.

We investigate implantable integrated circuits for power-efficient front-end processing of spikes, in order to minimize the communication bandwidth from the recording electrodes to the back-end computer. In this work we focus on power-efficient *detection and alignment* (D&A) of spikes as a pre-requisite to successful on-chip spike sorting. For instance, given a sampling rate of 24Ksps and 12 bit sampling precision, the raw data rate is 288Kbits/second. Spike D&A enables transmission of only active spike data and filtering out the inter-spike noise. Assuming a high rate of 100 spikes/sec/electrode and 2msec/spike, D&A reduces the data rate to 60Kbits/sec. Spike sorting converts each spike to a short datagram (~20 bits), reducing the required data rate down to 2Kbits/sec per electrode, less than 1% of the original rate. Power requirements of typical D&A algorithms could be prohibitively high for simultaneous recording form a large number of electrodes. We consider D&A algorithms and architectures that trade off some subsequent classification accuracy in return for significant savings in power.

We introduce the *Maximum Integral Transform Alignment* (MITA) algorithm for spike D&A, and compare it with an algorithm based on principal components analysis (MPA). The MITA algorithm achieves 99% classification accuracy for about 0.05% of the computational efforts of PCA spike D&A.

EEG Gamma-Band Power and Time-Domain Features as Separate Single-Trial Brain Computer Interface Inputs

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Gamma-band activity (28-40Hz) is known to be associated with attention and voluntary motor tasks. In the present study gamma-band power and time-domain predictive features serve as two separate dimensions of input into a Brain Computer Interface (BCI) device. Time-domain features predict intent to initiate movement and gamma-band power features determine laterality of desired movement.

Subjects were presented with two types of auditory selective-attention tasks: one containing a target stimulus, appearing unilaterally; and the other containing two target stimuli, presented interchangeably to either ear. Target stimuli required motor response in the form of a button press with the ipsilateral index finger.

EEG was recorded using a 20 channel system with a chin reference (International 10-20 system). Data was sampled at 256Hz with cutoff frequencies at 0.1 and 100Hz. Off-line data was low-pass filtered at 48Hz.

Frequency-domain data analysis was based on spectral power of signals and estimated with the multitaper method. Average multitaper-estimated spectra of the data showed a significant difference in power in the gamma-band, between left and right movement tasks. No subject training was required in order to achieve this power spectra difference.

Time-domain analysis, based on averaged signal amplitude, showed a difference between movement and non-movement sections in 360ms prior to motor response. Thus information contained in the time course preceding actual motor response can be used as a predictive tool in a BCI device.

Single-trial classification, using Support Vector Machines, was performed in two separate dimensions. Classification between left and right movements was conducted using frequency-domain features; classification between movement and non-movement segments was done using time-domain features.
Features were chosen according to electrodes with the most significant difference ($p<0.001$) and concentrated at frontal and central electrodes. Single-trial classification using frequency-domain features resulted in 75.7% accuracy, averaged across four subjects. Classification using time-domain features resulted in 72.3% accuracy, averaged across four subjects.

Comparing the two types of auditory selective-attention tasks showed that gamma-band activity was maximized when subjects attended to a single target, as opposed to multi-target attention. In the multi-targeted movement task, difference between left and right averaged spectra was insignificant, resulting in single-trial left/right movement classification accuracy of only 50% across subjects. Hence, gamma-band activity is state-dependent (attended side) rather than response-dependent (movement side).

Subliminal feed-forward learning of hand trajectory with computer mouse during cursor perturbation

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Reaching movements are usually well characterized by invariant characteristics of the hand trajectory (roughly a straight line path and a bell shaped speed profile). In order to preserve these invariant characteristics under force perturbations or when the visual feedback is altered, the brain adapts and demonstrates learning and after-effect of learning. While holding a computer mouse the reaching movement may have similar characteristics, especially if the trajectory is wide enough.

The adaptation and after effects indicate the existence of internal representation, possibly an inverse model located in the cerebellum, that is built by experience from trial to trial. Such feedforward controller can act faster than the feedback path which may last more than 200m seconds.

In this study we try to reveal the possible relation between subliminal motor adaptation to altered visual feedback and the activity of the autonomous system as measured by heart rate (HR) and photoplethysmography (PPG). We attend to verify the ‘three phases learning’ theory, which claims that learning proceeds through three stages. First, the subject experiences increased emotion towards the appearing problem. Second, the specific learning (e.g. motor learning) process occurs. Third, the emotions recede after acquiring adaptive level of motor learning.

Three subjects performed the experiment based on an interactive computer game. The subjects perform repeated hand movements holding a computer mouse, while the screen cursor is affected by a small visual angle perturbation that creates a small increasing gap between the cursor trajectory and the original hand trajectory. For each movement, the geometrical location of the hand 200ms after perturbation starts was measured and analyzed.

We report our preliminary results which indicate clear motor learning of hand movements from trial to trial: subjects learned to alter the hand movement direction angle to compensate for the visual perturbation. Moreover, autonomic indices demonstrate major autonomic response upon the introduction of visual perturbations. Autonomic activity returns to baseline level after same motor adaptation is achieved. At least in one subject one can see good similarity between the sympathetic system signal (as measured by the PPG signal) and the differential values of hand movements direction related to the ideal expected hand direction.

Further study is required in order to explore the ‘three phases learning’ theory in the context of adaptation to perturbed reaching movement.

Non-uniform representation of hand movements along the human visuomotor pathway

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During daily life, we grasp different objects located in various locations. Are the representations of movements to different visual fields (VFs) uniformly distributed in the human somato-motor brain areas? In order to address this question, we constructed two experiments in the fMRI environment. In the first experiment, subjects where asked to use their right or left hand to grasp 3D plastic tools located either to the right or to the left of a central fixation point. The results from 8 subjects show significantly stronger activation for right-hand movements to the right VF, compared with right-hand movements to the left VF. This pattern is along all the visuomotor pathway, from high visual areas to frontal motor areas, in both hemispheres. The opposite pattern was not significant. However, the results for left-hand movements were inconsistent across subjects. The disparity in the right-hand results could be due to a motor, a visual, or a visuomotor factor. In order to distinguish between these possibilities, a second experiment was constructed, in which subjects were asked to move their right-hand to one of two optional positions, while fixating once to the right and once to the left of each movement's end-point. Future results from this experiment may deepen our understanding of visuomotor processing in the human brain.

The role of Haptics in the sense of Presence

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'Presence' is the domain that relates to the feel of 'being there' in a mediated environment. A considerable part of presence research is devoted to generating a visual kinesthetic field that generates that feel of - as if-presence in a mediated world. Our view of presence is beyond 'being there'. We view presence as a state that allows embodied action, hence presence becomes 'being and doing there'. However, 'doing' means to manipulate objects that do not exists, to through and catch a virtual ball in a mediated environment. Without the force feedback associated with such acts, without the feel of heaviness and texture, the sense of presence is broken.

The poster described here, will present a series of experiments related to active, bodily, haptic presence, and will explore the role of haptics in generating presence. We will discriminate between 'immersion' which is the degree of similarity of the mediated environment and the physical environment, and between presence, which includes perception and top-down exploration of the environment. Several experiments and their results will be presented:

1. Presence and brain activities: Interaction between touch and visuals: an fMRI study that shows cortical activations in the visual cortex
2. Auditory cues generate haptic illusions
3. Memory of haptic patterns
4. Breaks in Presence – behavioral and EEG based neural correlates
5. Learning of haptic patterns
6. Haptic Stroop effect

Bimanual Coordination with Altered Sensory Feedback (A preliminary study)

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Our everyday life requires motor coordination in most of our activities: driving a car, playing a piano and even spreading butter on a toast.
Bimanual coordination are characterized by fixed relative phase between hand movements (Cohen 1971; Schoner and Kelso 1988; Mechsner et al. 2001; Swinnen 2002 and many others).

This tendency towards symmetry was originally referred to homologous muscles but recently it was suggested that the perceptual level may also influence the symmetry opening the possibility to employ altered feedback in order to facilitate the execution of otherwise difficult tasks.

In this study we developed an experimental setup to measure and perturb movements of the two index fingers in a virtual reality environment that can generate altered visual feedback such as exchanging between symmetric and anti-symmetric movements.

The symmetrical and parallel movements were presented to the subject, which was later instructed to perform the movement he/she feels easier. The subject was connected to a 3D virtual reality system, which has the ability to record fingers position and saw two balls representing his/her fingers. In one condition the balls followed the movement of the fingers while in the second condition, one of the balls moved in mirror to the hand it was supposed to represent, so that symmetrical movements appeared like parallel and parallel movements seemed symmetrical.

In both parts subjects clearly preferred the symmetric movements. Whenever an attempt to move the hands in parallel was observed, a corrected movement followed and the subject returned to the symmetric movement after a very short time. These results do not support the assumption that visual perceptual space is the main factor which makes the movements easier or harder, nevertheless it is possible that the perceptual level does not relay solely on vision and that proprioceptive information is also important.

We discuss the required future experiments and the technical options provided by our system to generate force perturbations as well as more realistic images of the fingers instead of moving balls that represented the fingers in our pilot experiment.

Spatial memory: Influence of combined visual and haptic information (preliminary study)

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People use combined sensory information to build a representation of the world surrounding them. Vision typically provides most of the information; however, most models assume that additional accurate information from other modality should only improve our internal representation of the world.

Virtual reality systems allow us to build an immersive environment, in which one can perform various tasks such as observing and manipulating 3D objects.
Force Feedback could be added to the virtual reality system in order to provide haptic information correlated with the visual information.

Hypothesis :
Combination of visual and haptic sensory information significantly improves spatial representation, thus improving navigation skills.

Methods :
A virtual topographic surface containing several objects with different visual and haptic information was used to examine the hypothesis. The virtual scene was created using the VRML and Python programming languages on a Reachin system.
One group of subjects experienced vision only (vision group) and the other both vision and haptics (haptic&vision group).

Results and discussion:
The vision group had better performance (smaller latency) in finding the target than the haptic&vision group.
This result contradicts our hypothesis since additional sensory information (haptic) impaired navigation skills.
We suggest that in our experiments haptic information demanded more motor skills and bimanual coordination (using both the spacemouse and force feedback device). Perhaps a longer adaptation period is required in order to overcome this effect.

Real time motion prediction

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Geometric algebra, based on the algebras of Grassmann and Clliford, is an isomorphic approach to screw theory for representing rotations using screws called rotors. It offers computational advantages with respect to quaternions and rotation vectors. In this work we use geometric algebra for the prediction of human arm movements.

In most telerobotic systems the configuration and dynamics of the robot differ considerably from those of the human operator. Typically human motion is physically restricted with devices varying from single joint restrainers to master robotics arms shaped precisely as the slave telerobot. Researchers have been working on relieving the human operator from the burden of adapting himself to the robot for better exploiting human prehension skills. Anticipating human motion can give the system additional time to plan the robot's motion keeping the system synchronized with the human operator.

There are various models of human arm motion control. These models are used for testing hypotheses regarding human motion generation and for producing human like motion in anthropomorphic robots and computer animation. We chose to use a model based on the work of Liebermann et al. This model assumes that the upper arm follows Listing's law throughout the motion. This assumption constrains the upper arm segment to move about a single rotation axis. The minimum jerk model is used for describing the temporal evolution of the upper arm trajectory. The model additionally assumes a linear relation between the elbow flexion-extension angle and the angle about the rotation axis of the upper arm. The elbow pronation - supination angle is currently not included in the model since it is irrelevant for determining the movement end point. Evidence has been presented for a correlation between this angle and the shoulder rotation angle. We intend to incorporate this into the model later on.

Using geometric algebra the motion can be represented using rotors. The rotation axis can be easily extracted from the rotor. Applying the assumption of a constant rotation axis of the upper arm motion its rotation axis is found using a Kalman filter. The final angle of rotation about the rotation axis and the ratio between this angle and the elbow flexion-extension angle are estimated using linear regression.

All the calculations are linear and can be implemented in real time. Motion initiation is identified using a threshold value on the velocity. After motion initiation is identified the end point posture prediction process is launched and concurrently motion termination is sough using a threshold value. In case motion terminates before the prediction process has concluded the prediction process is terminated. The prediction algorithm will be tested using an existing database of pointing movements recorded from four subjects with the Optotrak motion capturing system (Northern digital).

Prediction of M1 Neural-Code via Neural-Biomechanical Model

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The primary motor cortex (M1) plays a major role in voluntary movement. Projections from M1 influence muscles through direct synapses on motor-neurons and indirecly through inter-neurons. Each M1 neuron affects several muscles, while each muscle is affected by many M1 neurons.
Single cell recordings in M1 of behaving monkeys display changes in neural activity that begin approximately 100 ms prior to movement onset and correlate with EMG, force, velocity and position.
M1 neurons display preferred direction with cosine tuning with respect to end point movement or external force. A controversial interpretation of the observations is that M1 arm neurons employ population direction coding. An opposing view claims that cosine tuning is an artifact of hand geometry (Mussa-Ivaldy 1988).
A basic question relates to the mechanism by which M1 neurons contribute to movement.
Do cells in M1 control high level movement features such as direction of hand movement,
or do they directly control specific spatio-temporal patterns of muscle activation or both (depending on the class of neuron involved)?
In order to address this question we develop a neural-biomechanical model and compare its predictions with experimental data.
Our physiological model describes the causal relation from M1, through the spinal cord, muscles, musculoskelatal geometry and up to arm dynamics and kinematics.
Given a motor task (e.g. point-to-point reaching in real space) we strive to determine the control command (M1 signal) while respecting the biological constraints.

This problem is highly ill-posed, suffering from a high degree of redundancy (a difficulty often referred to as the Bernstein problem) since a given task can usually be accomplished by M1 in many different ways/ The task thus bears strong affinities to classical Optimal Control Theory problems.

The redundancy of the system is resolved by adding biologically plausible optimization criteria. Each trajectory in the space of neural inputs to the muscles is associated with a cost value. The selected trajectory is the one for which the cost is minimal.

We compared the predictions of our model to the experimental results of Sergio and Kalaska (1998), and reproduced the observed activity in M1 during reaching movements as well as during isometric tasks. Previous attempts (Todorov 2000) considered neither the antagonistic muscles nor the mutli-joint arm dynamics which significantly influence the predictions of the model.

Understanding the musculoskeletal system and its interaction with the environment is essential for understanding the neural code of the motor areas in the brain. In spite of the complexity of our model, it is still far from reflecting exactly all the complexities of the real biological system. We are currently working on more a realistic model.

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