Building a realistic neuronal model that simulates multi-joint arm and hand movements in 3D space

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The question as to how the brain controls voluntary movements of the arm and hand still remains largely unsolved despite much research focused on behavioral studies, neurophysiological investigations, and neuronal modeling in computer science. This is because behavioral studies are usually performed without detailed knowledge of the underlying neuronal networks, neurophysiological studies often lack an understanding of the function, and neuronal models are frequently focused on a particular control problem with restricted knowledge of the underlying neuronal networks involved. Therefore, it seems appropriate to start by trying to integrate knowledge of neuronal networks with known function and computer based neuronal models to seek more realistic models that can better control robots or artificial limbs and hands. We propose to combine knowledge of a behavioral model for reaching with the hand toward an object, which is based on detailed knowledge of the underlying neuronal network, and a neuronal model that includes several functional levels, from the planning level via intermediate levels to the final level of control of motoneurons and muscles. [DOI: 10.2976/1.2803419]

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How does the brain control voluntary movements of the arm and hand when we want to reach and grasp an object? This question still remains largely unsolved despite much research focused on behavioral studies, neurophysiological investigations, and neuronal modeling in computer science. This is because behavioral studies are usually performed without detailed knowledge of the underlying neuronal networks, the reversed situation is usually the case for neurophysiological studies, and neuronal models are often focused on solving a particular control problem with restricted knowledge of the underlying neuronal networks involved. It seems that it is the appropriate time to start attempting to integrate knowledge of neuronal networks with known function and computer based neuronal models to seek more realistic models that can better

control robots or artificial limbs and hands. In this commentary, we propose a way to combine knowledge of a behavioral model for reaching with the hand toward an object that is based on detailed knowledge of the underlying neuronal network, with a neuronal model that includes several functional levels, from the planning level via intermediate levels to the final level of control of motoneurons and muscles.

Several computational models and control theories on arm and hand movements exist and a commonality between them is the goal of optimal control (for review see [Schaal, 2007](#)). Many of these neuronal models are capable of producing well controlled movement trajectories to move the hand from point A to point B. However, there is still no realistic neuronal model that can quickly simulate multijoint arm movements in 3D space with high speed and

Figure 1. (A) Network of the C3–C4 propriospinal system. Propriospinal interneurons (PNs) located in the C3–C4 spinal segments receive monosynaptic excitation from the cortico- (CST), rubro- (RuST), reticulo- (ReST) and tectospinal (TectST) tracts. The PNs project directly to motoneurons of virtually all types of forelimb muscles. In addition, the PNs give off ascending axon collaterals to the LRN, which is major mossy fiber input to the cerebellum. (B) Switching of ongoing target reaching. On the left side are movement trajectories of the wrist seen from above. The cat made a switching trial from the left to the right tube when the light illumination changed from the left to the right tube during the ongoing reaching movement. Single tube trials are shown in black and a switching trial in red. On the right side are the velocity profile of the forward component (dx/dt) and sideward component (dy/dt) for single tube trials (black) and for a switching trial (red). (C) Feedback inhibition of the C3–C4 PNs. Schematic diagram showing that primary afferents from forelimb muscles and skin evoke inhibition in the PNs via one inhibitory interneuron, which is excited from the corticospinal tract. (D) Hypermetria in target reaching after elimination of feedback inhibition. Feedback inhibition has been eliminated by a dorsal column transection in C5. The cat made a reaching movement toward the upper most tube, but missed the tube opening by several centimeters despite visual information.

accuracy while taking into account dynamic changes due to interacting forces and sudden changes in target position that require a fast modification of the ongoing movement.

There is a considerable amount of neurophysiological data concerned with properties of neuronal firing in relation to movement kinematics and dynamics (speed, direction, force, torques, distance, and accuracy) obtained by recordings from neurons in different regions of the motor cortex, cerebellum, and brain stem as well as from spinal interneurons and primary afferents. However, due to technical difficulties, this information has been obtained in separate ex-

periments. Therefore, there is virtually no knowledge of how the information is integrated and processed in neuronal networks to produce the motor command signals.

With respect to motor control of voluntary arm and hand movements, thus far there is only one example of a neuronal network with a proven function. It is a system consisting of motoneurons, spinal interneurons, brain stem systems, cerebellum, and various motor cortical regions. This system is denoted the C3–C4 propriospinal system [Fig. 1(a)] and has a primary function in the control of arm trajectories when grasping an object with the hand (Alstermark *et al.*, 1981b).

It was first discovered by Anders Lundberg and colleagues in the mid 1970's when they found that disynaptic corticomotoneuronal excitation could be mediated via spinal interneurons located in the C3–C4 segments (for review see [Alstermark et al., 2007](#)). These interneurons were denoted as C3–C4 propriospinal neurones (PNs) ([Illert et al., 1977](#)). Interestingly, the major excitatory inputs to these interneurons were not from afferents but from various descending pathways. This was in clear contrast to all previously described interneuronal systems in the spinal cord, which in different ways were related to reflex control, posture, and locomotion (for review see [Baldiserra et al., 1981](#)).

A majority of the PNs received excitation not only from the corticospinal tract, but from the brain stem via the rubro-, reticulo-, and tectospinal tracts ([Illert et al., 1978](#)). This extensive convergence of descending pathways was the basis for Lundberg and colleagues to propose the updating hypothesis. The essence was that a motor command signal given from the motor cortex could be updated en route to the motoneurons by virtue of new signals given via the brain stem systems. This hypothesis was later tested and proven correct in behavioral experiments ([Alstermark et al., 1990](#); [Pettersson et al., 1997](#)). Cats were trained to make a fast visually guided reaching movement toward a small tube containing a morsel of food. A set of two or three such tubes were positioned in front of the animal at shoulder level. The correct tube for retrieving the food was indicated by light illuminating diodes. The light was randomly switched off in one tube after a variable delay and switched on in one of the other tubes. As shown in Fig. 1(b), the cat initiated a fast correction of the movement trajectory when switching from the left to the right tube. The shortest switching latencies observed are as short as 40–60 ms, which are too short for a visual processing at the cortical level or producing a new cortical command ([Alstermark et al., 1990](#); [Pettersson et al., 1997](#)). Together with results obtained after selective lesions of different brain stem pathways (rubro-, reticulo-, and tectospinal tracts), it is clear that the shortest switching latencies are due to an updating occurring in the C3–C4 PNs. These findings suggest that within a time span of less than 20 ms (subtracted delays for retinal processing and electro-mechanical delays in the muscles) information can be processed to estimate the amount of correction needed to reach the new target position and give new signals via the subcortical systems to the PNs.

Interestingly, the C3–C4 PNs have, in addition to their direct projection to forelimb motoneurons, ascending collaterals to neurons in the lateral reticular nucleus (LRN), which is a major mossy fiber input to the cerebellum ([Illert and Lundberg, 1978](#); [Alstermark et al., 1981a](#); [Alstermark and Ekerot, 1992](#)). Therefore, it seems reasonable to assume that the cerebellum is continuously informed about the ongoing activity in the C3–C4 PNs and if a change in the trajectory is needed, the cerebellum may quickly correct the activity in

the various brain stem systems to ensure a successful switching movement. At longer latencies the cerebellum may interact directly with the motor cortex and influence a new cortical command.

Another major problem for the brain is controlling the endpoint of reaching in terms of the onset of deceleration and timing the stop of the movement. This cannot be solved entirely by preprogramming for a multijoint movement like reaching with the arm. Information about the ongoing movement is also signaled from different receptors in the muscles, tendons, skin, and joints of the moving limb and such information may be used not only in reflex control, but also in the control of voluntary movements as was originally proposed by [Lundberg \(1999\)](#). The C3–C4 propriospinal system was used to test this question. In contrast to the weak or lacking excitation from forelimb afferents, all PNs receive strong disynaptic inhibition from low threshold muscle and cutaneous afferents (Fig. 1(c); [Alstermark et al., 1984](#)). This inhibition was denoted feedback inhibition and if it was blocked, the animals could not properly decelerate and terminate the reaching movement, but repeatedly were overshooting the tube opening as shown in Fig. 1(d) ([Alstermark et al., 1986](#)). The hypermetria was gradually compensated for by the use of vision, but remarkably this process took several days. Presumably, the sensory information from various receptor systems in the forelimb cannot be immediately compensated for by vision. It was proposed that feedback inhibition normally operates as an integral part of the descending motor command such that afferent information produced by the movement itself is used to calculate the onset of deceleration to produce an accurate termination ([Alstermark et al., 1986](#)).

How then, can knowledge regarding the C3–C4 propriospinal system be used in neuronal modeling of reaching movements? A computational model has been proposed by Lan and colleagues that is based on a hierarchical organization of task planning, optimal controller, and spinal regulator [Fig. 2(a)] before signals are transmitted to three pairs of antagonistic muscles working across the shoulder and elbow joints as shown in Fig. 2(b) ([Lan 1997](#); [Lan et al., 2005b](#)). A major advantage of this model is that the problem of inverse computation between joint torques and movement trajectories is avoided. The movement trajectories are produced in a horizontal plane. The model uses a minimal effort criterion of muscular activity ([Hasan, 1986](#)) to control the excitability of motoneurons via segmental interneurons mediating reciprocal Ia inhibition between antagonistic muscles and recurrent inhibition. At the first hierarchical level, a central controller in the brain receives information from higher motor centers that provides specification of the target position in Cartesian coordinates. Next, the descending command is translated into a language that can be interpreted by spinal interneurons and motoneurons. In this way, a descending triphasic excitatory pulse to motoneurons [Fig. 2(c)(l)] produces a near straight hand movement trajectory together

Figure 2. (A) Hierarchical model of corticospinal sensorimotor system (modified from Lan *et al.*, 2005b). (B) A realistic virtual arm model with 15 muscles acting at the shoulder, elbow, and forearm. Some muscles have mechanical actions at two or more joints. For example, biceps flex both shoulder and elbow joints, and have strong action of forearm supination as well. In most simulations, simpler models of musculoskeletal system are used, such as that used in Lan (1997) with a pair of monoarticular muscles at the shoulder, a pair of monoarticular muscles at the elbow, and a pair of biarticular muscles across both the shoulder and elbow. (C) An example of optimal reaching movement generated by a simple hierarchical model controlling three pairs of antagonist muscles (Lan, 1997, with permission). The optimal control model was able to produce a near straight path of hand movement and bell shaped velocity, increased joint stiffness during the movement, triphasic antagonistic muscle activation pattern, as well as two descending commands—the triphasic excitation pulse to motoneuron pool and the “N” shaped virtual (equilibrium) trajectory, which together determine muscle inputs.

with triphasic electromyographic (EMG) activity between antagonistic muscles [Fig. 2(c)(i,j,k)]. Speed is determined by the pulse height and movement direction is controlled by a separate command for the final target position. The model allows for the control of fast and slow movements by using pulsed excitation and a constant excitation level, respectively, as originally proposed by Ghez and Vicario (1978) and Bizzi *et al.* (1982). The equilibrium-point model for motor control that implies a balanced contraction in opposing muscles was later modified to be compatible with dual control of speed and position (McIntyre and Bizzi, 1993).

In a further step to build a realistic model for movement simulation, a single joint model with one pair of antagonist muscles was constructed with a linear spindle sensor and spinal reflex circuits (stretch reflex, reciprocal inhibition, and recurrent inhibition) (Lan *et al.*, 2005a). This system's model was able to demonstrate separate control of final equilibrium (or target) position and movement trajectory via a γ static, descending command and a triphasic, α excitation command, consistent with the pulse-step hypothesis (Ghez, 1979) and the dual control strategy for posture and move-

ment inferred from deafferented human reaching movements (Gordon *et al.*, 1995). Thus, the model was referred to as “ α - γ model,” and was recently extended to control of posture and movement of a multijoint, multimuscle arm (Lan *et al.*, 2005b).

This model is attractive as a platform to start building a more realistic model of how the brain controls the arm and hand to reach and grasp for an object, but for that purpose more parameters have to be included. First, more degrees of freedom have to be added, since both the shoulder and elbow joints may rotate the arm. Also, more joints have to be included, like the wrist-, metacarpo-, proximal-, and distal-interphalangeal joints of the hand and digits since the model should control grasping. A realistic model must also be able to compute movement trajectories in 3D space. The effect of the arm movement on the center of gravity also has to be taken into account. When the arm is lifted and the hand starts to move outward from the body, the center of gravity is changing and the posture must be compensated for by controlling the muscles of the trunk and legs. Since the arm and hand movement is visually guided toward the target, it is nec-

essary to take into account shifts in gaze by considering associated eye and head movements. Thus, a future model must be able to cope with a more complicated situation in terms of a larger number of freedoms and muscles to be controlled. Of course, the C3–C4 propriospinal system alone is not sufficient to address this entire problem, but it has the advantage that the primary function is known and therefore the model can be tested with respect to arm and hand movements in 3D space. Obviously it is necessary to include neuronal circuitry controlling spinal reflexes like reciprocal Ia inhibition, crossed extensor reflexes as well as long propriospinal circuitries involved in the control of coordinating upper and lower limbs. Interestingly, subpopulations of the C3–C4 PNs are known to have projections to such spinal interneurons involved in reflex control (see [Alstermark et al., 2007](#)).

Since the model should control hand and digit movements, it is also essential to include the direct corticomotoneuronal system, which most likely is very important for independent digit control ([Porter and Lemon, 1993](#)). However, recent results in the Macaque monkey have shown that the direct corticomotoneuronal system is not solely responsible for the control of independent digit movements ([Sasaki et al., 2004](#); [Isa et al., 2007](#)). Independent digit movements of the index finger and thumb, as well as reaching with the forearm, could already be performed one week after a complete transection of the corticospinal tract in C4–C5 that spared the propriospinal system, but not (independent digit movements) or with clear deficiencies (reaching) after a corresponding transection of the corticospinal tract in C1–C2. Previously, it was demonstrated that C3–C4 propriospinal neurons in the Macaque monkey can mediate disynaptic corticomotoneuronal excitation to motoneurons innervating arm and hand muscles ([Alstermark et al., 1999](#); [Isa et al., 2006](#)). Therefore, the behavioral and neurophysiological findings suggest that a C3–C4 propriospinal system exists in the Macaque monkey and that it can provide the command signal for both accurate reaching and independent digit movements. In man, there is also strong neurophysiological evidence for the existence of a propriospinal system ([Pierrot-Deseilligny, 2002](#); [Pierrot-Deseilligny and Burke, 2005](#)).

Thus, it seems it is a good time to stimulate interdisciplinary research between computer based neuronal modeling and classical neurophysiological research obtained from animal and human experiments. Such interactions were started 40 years ago by Eccles, Ito, and Szentágothai in their classic book “The cerebellum as a neuronal machine” ([Eccles et al., 1967](#)) and was followed by Ito’s monograph “The cerebellum and neural control,” in which he proposed several models on how the cerebellum can act as a central calibrator for various reflexes and movements ([Ito, 1984](#)). A renaissance of this type of interdisciplinary interaction that includes identified systems in the cortex, brain stem, cerebellum, and spinal cord may be fruitful for neuroscience.

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REFERENCES

- Alstermark, B. and Ekerot, CF (1992). “Organization of the ascending projection from C3–C4 propriospinal neurones to cerebellum via the lateral reticular nucleus.” *Acta Physiol. Scand.* **146**, 151.
- Alstermark, B., Gorska, T., Johannisson, T., and Lundberg, A (1986). “Hypermetria in forelimb target-reaching after interruption of the inhibitory pathway from forelimb afferents to C3–C4 propriospinal neurons.” *Neurosci. Res. (N Y)* **5**, 457–461.
- Alstermark, B., Gorska, T., Lundberg, A., and Pettersson, LG (1990). “Integration in descending motor pathways controlling the forelimb in the cat. 16. Visually guided switching of target-reaching.” *Exp. Brain Res.* **80**, 1–11.
- Alstermark, B., Isa, T., Ohki, Y., and Saito, Y (1999). “Disynaptic pyramidal excitation in forelimb, motoneurons mediated via C3–C4 propriospinal neurons in the Macaca fuscata.” *J. Neurophysiol.* **82**, 3580–3595.
- Alstermark, B., Isa, T., Pettersson, LG, and Sasaki, S (2007). “The C3–C4 propriospinal system in the cat and monkey: a spinal pre-motoneuronal centre for voluntary motor control.” *Acta Physiol (Oxf)* **189**, 123–40.
- Alstermark, B., Lindström, S., Lundberg, A., and Sybirska, E (1981a). “Integration in descending motor pathways controlling the forelimb in the cat. 8. Ascending projection to the lateral reticular nucleus from C3–C4 propriospinal also projecting to forelimb motoneurons.” *Exp. Brain Res.* **42**, 282–298.
- Alstermark, B., Lundberg, A., NorrSELL, U., and Sybirska, E (1981b). “Integration in descending motor pathways controlling the forelimb in the cat. 9. Differential behavioural defects after spinal cord lesions interrupting defined pathways from higher centres to motoneurons.” *Exp. Brain Res.* **42**, 299–318.
- Alstermark, B., Lundberg, A., and Sasaki, S (1984). “Integration in descending motor pathways controlling the forelimb in the cat. 11. Inhibitory pathways from higher motor centres and forelimb afferents to C3–C4 propriospinal neurones.” *Exp. Brain Res.* **56**, 293–307.
- Baldissera, F., Hultborn, H., and Illert, M (1981). “Integration in spinal neuronal systems.” In *Handbook of Physiology: the Nervous System*, Brookhart, JM, Mountcastle, VB, Brooks, VB, and Geiger, SR (eds), pp 509–595, American Physiological Society, Bethesda, Md.
- Bizzi, E., Accornero, N., Chapple, W., and Hogan, N (1982). “Arm trajectory formation in monkeys.” *Exp. Brain Res.* **46**, 139–143.
- Eccles, JC, Ito, M., and Szentágothai, J (1967). *The cerebellum as a neuronal machine*, Springer-Verlag, Berlin Heidelberg, New York, Germany.
- Ghez, C (1979). “Contributions of central programs to rapid limb movement in the cat.” In *Integration in the Nervous System*, Asanuma, H., and Wilson, VJ (eds), p 305, IgakuShoin, Tokyo, Japan.
- Ghez, C., and Vicario, D (1978). “The control of rapid limb movement in the cat. II. Scaling of isometric force adjustments.” *Exp. Brain Res.* **33**, 191–202.
- Gordon, J., Ghilard, MF, and Ghez, C (1995). “Impairments of reaching movements in patients without proprioception. I. Spatial errors.” *J. Neurophysiol.* **73**, 347–360.
- Hasan, Z (1986). “Optimized movement trajectories and joint stiffness in unperturbed, inertially loaded movements.” *Biol. Cybern.* **53**, 373–382.
- Illert, M., and Lundberg, A (1978). “Collateral connections to the lateral reticular nucleus from cervical propriospinal neurones projecting to forelimb motoneurons in the cat.” *Neurosci. Lett.* **7**, 167–172.
- Illert, M., Lundberg, A., Padel, Y., and Tanaka, R (1978). “Integration in descending motor pathways controlling the forelimb in the cat. 5. Properties of and monosynaptic excitatory convergence on C3–C4 propriospinal neurons.” *Exp. Brain Res.* **33**, 101–130.

- Illert, M, Lundberg, A, and Tanaka, R (1977). "Integration in descending motor pathways controlling the forelimb in the cat. 3. Convergence on propriospinal neurones transmitting disynaptic excitation from the corticospinal tract and other descending tracts." *Exp. Brain Res.* **29**, 323–346.
- Isa, T, Ohki, Y, Alstermark, B, Pettersson, LG, and Sasaki, S (2007). "Direct and indirect cortico-motoneuronal pathways and control of hand/arm movements." *Physiology (Bethesda)* **22**, 145–152.
- Isa, T, Ohki, Y, Seki, K, and Alstermark, B (2006). "Properties of propriospinal neurons in the C3–C4 segments mediating disynaptic pyramidal excitation to forelimb motoneurons in the Macaque monkey." *J. Neurophysiol.* **95**, 3674–3685.
- Ito, M (1984). *The cerebellum and neural control*, Raven Press, New York.
- Lan, N (1997). "Analysis of an optimal control model of multi-joint arm movements." *Biol. Cybern.* **76**, 107–117.
- Lan, N, Li, Y, Sun, Y, and Yang, FS (2005a). "Reflex regulation of antagonist muscles for control of joint equilibrium position." *IEEE Trans. Neural Syst. Rehabil. Eng.* **13**, 60–71.
- Lan, N, Song, D, Mileusnic, M, and Gordon, J (2005b). "Modeling spinal sensorimotor control for reach task." *Proc., IEEE-EMB Ann Conference, Shanghai, China.*
- Lundberg, A (1999). "Descending control of forelimb movements in the cat." *Brain Res. Bull.* **50**, 323–324.
- McIntyre, J, and Bizzi, E (1993). "Servo hypothesis for the biological control of movement." *J. Motor Behav.* **25**, 193–202.
- Pettersson, LG, Lundberg, A, Alstermark, B, Isa, T, and Tantisira, B (1997). "Effect of spinal cord lesions on forelimb target-reaching and on visually guided switching of target-reaching in the cat." *Neurosci. Res. (NY)* **3**, 241–256.
- Pierrot-Deseilligny, E (2002). "Propriospinal transmission of part of the corticospinal excitation in humans." *Muscle Nerve* **26**, 155–172.
- Pierrot-Deseilligny, E, and Burke, D (2005). *The circuitry of the human spinal cord*, Cambridge University Press, Cambridge, UK.
- Porter, R, and Lemon, R (1993). *Corticospinal function and voluntary movement*, Monographs of the Physiological Society, UK.
- Sasaki, S, Isa, T, Pettersson, L.-G, Alstermark, B, Naito, K, Yoshimura, K, Seki, K, and Ohki, Y (2004). "Dexterous finger movements in primate without monosynaptic corticomotoneuronal excitation." *J. Neurophysiol.* **92**, 3142–3147.
- Schaal, S (2007). "The new robotics-towards human-centered machines." *HFSP J.* **1**, 115–126.