

# Determination of the Arm Orientation for Brain-Machine Interface Prosthetics

Sam Clanton

*Robotics Institute / School of Medicine  
CMU / Univ. of Pittsburgh  
Pittsburgh, PA, USA, 15213  
sclanton@oeic.net*

Joseph Laws

*Electrical and Computer Engineering  
Carnegie Mellon University  
Pittsburgh, PA, USA, 15213  
jlaws@andrew.cmu.edu*

Yoky Matsuoka

*The Robotics Institute  
Carnegie Mellon University  
Pittsburgh, PA, USA, 15213  
yoky@cs.cmu.edu*

**Controlling prosthetics with brain-machine interface will soon become the most natural way to restore limb function to those who suffer from neurodegenerative disease or injury. Here, we first discuss the development of neural signal processing systems for brain-machine interfaces which provide control within the Cartesian (extrinsic) frames of motion. Then we justify the development of systems that provide control using the kinematic (intrinsic) frames of motion of the manipulator prosthetic device. An experiment to create a general model of natural arm motion is presented, along with its application to brain-machine interfaces.**

*Index Terms – neuroprosthetics, kinematics, brain-machine interface, biomechanics*

## I. INTRODUCTION

A significant cause of worldwide morbidity and mortality is disease or injury which causes loss of the ability to actuate limbs. Conditions which fall into this category include spinal cord injury, anterior lateral sclerosis (ALS, Lou Gehrig's disease), and cerebellomedullar disconnection (locked-in syndrome). These conditions cause varying degrees of dyskinesia, ranging from a retardation of normal movement, to quadriplegia, to the complete inability to exercise voluntary muscular control. In addition, conditions such as limb injury and myopathy can cause dysfunction of the extremities themselves. Severe diseases of both of these types can render a fully conscious patient unable to interact with his or her environment normally. In the case of the more severe neuromuscular disorders, patients often cannot live independently and rely on others for assistance with many basic daily activities. These diseases also lead to the death of patients, especially for those less able to afford satisfactory health care and assistance.

It is estimated that approximately 250,000 individuals in the United States alone have spinal cord injury [14]. This number is a fraction of those that have lost limb function worldwide as a result of disease or

injury. The substantial prevalence of these disorders, in combination with their severity, makes it imperative that satisfactory therapies for these conditions are developed. Current therapies for these patients include both various attempts at repair or reconnection of the dysfunctional neuromuscular systems, as well as the use of artificial devices to replace the function of the defunct extremities.

While some success has been made in regeneration of neuromuscular systems to restore the previous function of the body, our work focuses on the goal of replacing the deficient motor system with a prosthetic system which attempts to reproduce the capabilities of the original. Current prosthetic systems commonly rely on control signals generated from alternative signalling pathways from the motor system with the deficiency, e.g. the control of a prosthetic arm is based on muscular contractions at the shoulder. The development of more sophisticated prosthetic systems which can reproduce the movement and control fidelity of the human extremities must rely on more sophisticated control pathways that can incorporate the richness of signals inherent to the control systems of the human body.

## II. BRAIN-MACHINE INTERFACE WITH CARTESIAN (EXTRINSIC) COORDINATE FRAMES

One potential modality of more sophisticated neural control could employ a direct interface to the motor cortex to provide control signals for prosthetic devices. Some of the initial work in this area was pioneered by Georgopoulos et al, who discovered that population of neurons encode movement directions [20]. Since then, groups led by, for example, Schwartz, Donoghue, and Nicolelis, have continued progress in this area by developing more sophisticated recording techniques and signal processing algorithms. Common signal processing schemas for these control systems employ discrete classifiers, linear filters, and complex neural networks to develop reasonable estimates of the hand motion [3], [7], [8], [9]. Two-dimensional control of electronic interfaces with Cartesian coordinate frames has been commonly achieved with these methods.

Schwartz's group employs population vectors derived from Georgopoulos's original work [20]. Using this method, they demonstrated three-dimensional Cartesian coordinate frame and has interfaced it with a robotic manipulator. Recent progress has allowed primates to reach for orange slices placed in front of them with a brain controlled-robot arm [5].

While control methods based on three-dimensional movement within Cartesian coordinate frames are novel and crucial for brain-machine interface, they suffer from inherent limitations when compared to the dexterous seven DOF arms in primates. These arms allow the primates to bring their hands to a particular location and *orientation* in space with the extra degree of freedom that allows multiple arm configurations for the same hand location/orientation. The control of particular configuration of the arm is not only important for keeping the arm out of the way when manipulating particular objects in space, but also is an important part of motion planning, where a different joint angle trajectory may be employed to reach the same target. For instance, a particular arm position at an instant can be more suited for striking an object than reaching for it, but simply knowing the Cartesian three coordinates and orientation of the hand cannot encode that information.

### III. BRAIN-MACHINE INTERFACE WITH KINEMATIC (INTRINSIC) COORDINATE FRAMES

Because of the limitations of the Cartesian-frame system described, it is desirable to establish a robotic neuroprosthetic control system that operates through the 7-DOF kinematic (intrinsic) frames. This kinematic coordinate frame approach is more likely to result in reconstructing the precise position and motion dynamics of each robotic link as in the original appendage than the Cartesian coordinate approach pursued.

Unfortunately, work in the brain-machine interface with kinematic coordinate frames has met with difficulty. So far, clear correlation between neural activity and joint angles have not been shown. Reina et al. [13] demonstrated some ability to directly predict joint angular velocities of a primate arm with data recorded from the motor cortex during reaching tasks using joint angular velocity population vectors. Predictions were significantly accurate for the joint velocities of elbow flexion as well as shoulder flexion/extension and rotation, while predictions of other joint velocities of the arm were not. When Cartesian hand velocity was predicted using the same neuronal data, the results were roughly as accurate as the three successfully predicted joint angular velocities. This led the authors to conclude that the predictive value of using joint velocities with population encoding may simply be

in the high correlation of those intrinsic reference frames to the extrinsic coordinate frames for reaching tasks.

In addition to the difficulty with using joint angular population vectors, this technique is further complicated by the fact that an artificial arm will (most likely) not match the kinematics of the original arm of the subject. Therefore, even if joint angles are accurately predicted from cortical signals, actuating the arm with similar parameters would not establish the hand configuration nor link orientation in space as was intended by the subject. Thus, a more sophisticated system than simple joint angle or angular velocity prediction will need to be developed for the control of an artificial 7-DOF prosthetic arm.

### IV. APPROACHES TO BRAIN-CONTROLLED PROSTHETICS

It has been shown that the activation levels of the neurons that are correlated with arm movement change when the transition is made from controlling a cursor with real arm movements to no arm movements [12]. This suggests that while a neuromotor model based on correlations between cortical activation and actual arm movement are useful for training, the control model of a neuroprosthetic may not need to be based on the predictive value of a model to the movement of an actual limb. In other words, the cortex may be able to control joint-angle parameters of a 7-DOF device by employing a model without necessary direct correlation to the 7 DOF control of an actual subject arm.

In addition, from the perspective of assisting the disabled who have little or no ability to move their arms, the closed-loop training phase with actual arm motion is impossible to perform. For this reason, the development of a brain-computer interface system which does not rely on motion data capture from the intended user of the prosthetic will be important for the practical application of these devices.

Our work is focused on a system which relies on experimentally-derived statistical models of seven arm joint angles to enable the control of a 7-DOF manipulator. Through the analysis of human subjects with different arm kinematics reaching for objects at known locations and orientations, we extrapolate probability distributions of joint angle configurations for reaching with manipulators of varied dimensions. These data are then used to inform a model that maps neural activation to 7-DOF reaching motions of a robotic arm.

### V. EXPERIMENTAL PROCEDURE

Experiments were conducted with human subjects to establish the model of arm joint angle configurations when subjects reached for specified target locations and orientations in space. During Experiments, subjects



Fig 1. Photograph of experiment in progress.

were seated in a chair and motion of their sternoclavicular joint was limited by a shoulder harness. To track the arm joint angles, a set of Vicon™ markers were attached to the right arm of the subject. A rigid frame was fixed in front of the subject with nine configurable target grips and one home target grip placed in locations relative to the center of the shoulder joint (Fig 1). Each grip was in a fixed place during each session, and translated and rotated between sessions. After all sessions, the grip locations and rotations covered a cube of 27 locations, each with 3 rotations (Fig 2). A small LED light was attached near each of the target grips to indicate the next reaching position and configuration.

There were nine sessions in the experiment, each containing 90 reaching movements (10 movements each to nine target grips). In each session, subjects were asked to reach for the grip target marked by the lit LED within one second from the time the LED lit up. The home grip lit up every other time to allow subjects to return to the home location before every reach-out movements. There was a two-second rest period between each trial.

## VI. MODELS

We used the experimental data to model how the individual arm kinematics depended on the joint angle configurations used to achieve the target grip locations. To create the model, the range of all possible joint angles for a particular hand location (corresponding to a target grip) is computed. The experimental data were then mapped onto the range computed.

The problem of finding all possible joint angle combinations to produce a particular hand location involves finding all allowable combinations of the 7-DOF inverse kinematics of a subject arm. To achieve this range, we employed the Jacobian transform inverse

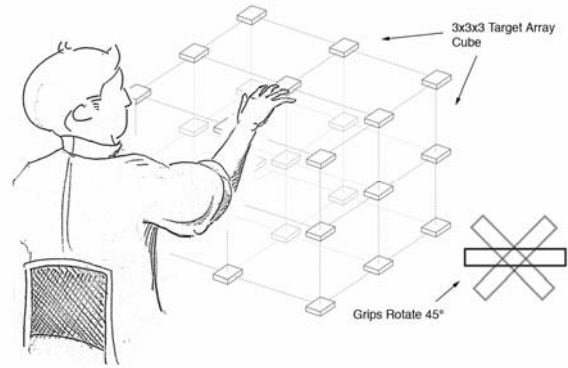


Fig 2. Schematic of locations of grip targets for experiment, with close-up of grip rotation.

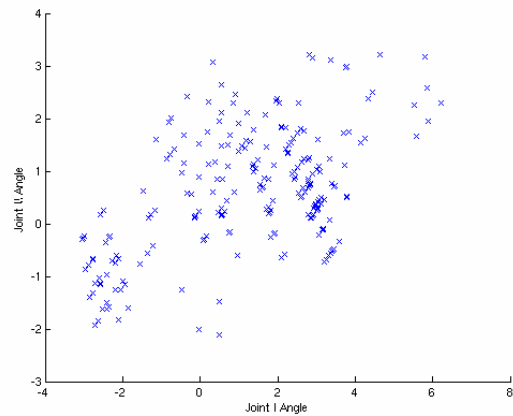


Fig 3. Plot defining approximate regions of allowable joint angles in two dimensions for a particular hand location and orientation.

kinematics method [22], converging on a target from an initial estimate of joint angles  $q$ :

$$q' = J^{-1}(q) \Delta (F(q) - T) \quad (1)$$

where  $T$  is the target position and orientation,  $F(q)$  is the forward kinematic position and orientation at joint configuration  $q$ ,  $\Delta$  is a 6-element vector of the difference in location and orientation of  $F(q)$  and  $T$ ,  $J^{-1}(q)$  is the inverse Jacobian transform at configuration  $q$ , and  $q'$  is a joint angular velocity, added to  $q$  as a closer estimate to inverse kinematic solution.

We ran this algorithm with initial joint estimates over the entire range of physiologic joint angle extents, creating approximate maps of joint angle constraints given a target grip location and subject arm geometry (Fig. 3).

To visualize the relationship between the possible joint angles allowable for a particular subject and the angles which are actually employed experimentally, we created a schematic of the relationship between two joints in Fig. 4. The actual complete model relationship exists as an extension of this in 7 dimensions.

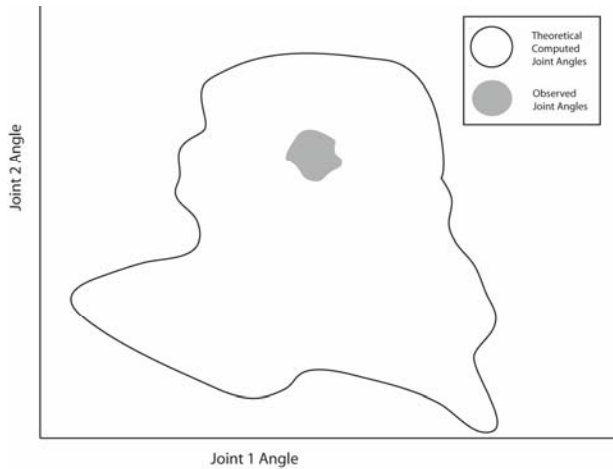


Fig 4. Schematic of relationship between theoretical and actual data.

Our current work focuses on how to best establish these relationships statistically to optimize their predictive value for the actual joint angles employed for manipulators of arbitrary segment lengths. For these manipulators, we can use their known kinematics to generate a region of allowable joint angles with our inverse kinematic search method. From the model we built, we then determine realistic joint angles that are employed by a human if the kinematic parameters of their arm were to match those specified.

Although these statistical relationships are not yet well characterized, we make inferences based on geometric analysis of the problem. For example, assume that illustration Figs. 5a and 5b below corresponds to data from our subjects. Also, assume that for each subject the exact locations and areas of the data may be different, but the general shape for each was roughly the same.

Given a computed possible angle set, the area of experimentally observed angles (the filled-in area in Fig 5) cluster in a particular place within the area of theoretical angles (the outer, unshaded region). This technique allows the area of experimental data to correspond to a probability distribution derived with the same relationship of peak and shape to the distribution of theoretical joint angle combinations.

For our illustrated data in Fig. 5, the cluster of experimental data is wider within the left joint graph than that in the right joint graph area. For these data, the distribution of derived data is correspondingly wider for the left pair than for the right. Thus, we infer joint angles are more highly concentrated within a central region for the left joint pair and our model a higher priority on constraining the first joint angle more than the second.

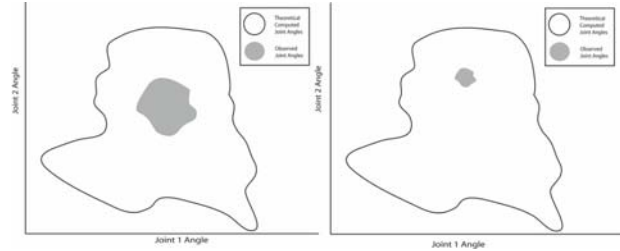


Fig 5. Two types of relationships implying lesser (a) or greater (b) constraint on the model joint angles.

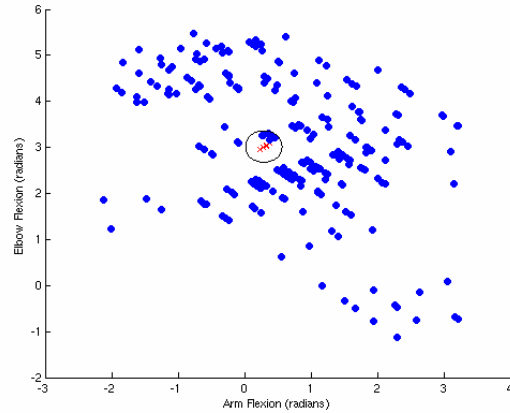


Fig. 6. Possible (circles) vs. actual (crosses) arm/elbow flexion angles for particular hand location. Note that these points are analogous to a region like the wider region shown in Fig. 4. If the search algorithm were to be performed at more initial joint angle search points, the theoretical plot would approach a continuous region.

## VII. PRELIMINARY RESULTS AND DISCUSSION

Using the Vicon™ tracking data, primary component analysis was conducted to isolate individual joint axis motion from overall rotation matrices of each joint. To produce joint angle combination graphs analogous to Figs. 4 and 5, the inverse kinematic search algorithm was performed on the location of one of the experimental grips. Fig. 6 shows computed allowable joint angle configurations for this location for arm and elbow flexion angles. Some of the computed joint angles in Fig. 6 are outside of the physiological range of the joints: although the kinematic search algorithm is seeded with physiologic boundaries on joint angle extents, the solutions it produces are sometimes outside of those extents.

Fig. 6 also plots experimental data (as the small region of ‘x’ points). These data were derived by evaluation of the data points at which the subject reached the grip targets. As shown, these points occupy a particular region within the plot of “working” joint angle combinations.

With data from full set of subjects, a complete model will allow us to recreate the inner zone of “real” joint angle combinations, given a graph of allowable combinations for multiple joints of mechanical arms.

From this, control models can be pursued for neural interface systems to provide control to prosthetics that do not correspond kinematically to physiological arms, but where full control over the degrees of freedom of the device are desired.

#### REFERENCES

- [1] J.P. Donoghue, A.V. Nurmikko, G. Friehs, M.J. Black. "Development of a Neuromotor Prosthesis for Humans," *Journal of Clinical Neurophysiology* (in press), 2004.
- [2] Serruya, M.D., Hatsopoulos, N.G., Paninski, L., Fellows, M.R., and Donoghue, J.P. "Instant neural control of a movement signal," (2002) *Nature* 416:141-2.
- [3] Serruya, M., Hatsopoulos, N. Fellows, M. Paninski, L., and Donoghue, J. "Robustness of neuroprosthetic decoding algorithms," *Biological Cybernetics* 88 (3): 219-228 March 2003.
- [4] Schwartz, A.B.: "Cortical neural prostheses," *Ann. Rev. Neurosci.* 27:487-507, 2004.
- [5] Schwartz, A.B., Moran, D.W. and Reina, G.A.: "Differential representation of perception and action in the frontal cortex," *Science*, 303:380-383, 2004.
- [6] Taylor, D.M., Helms Tillery, S.I. and Schwartz, A.B.: "Information conveyed through brain-control: Cursor versus robot," *IEEE Trans. Neural Syst. Rehab. Eng.*, 11: 195-199, 2003.
- [7] Johan Wessberg and Miguel A. L. Nicolelis: "Optimizing a Linear Algorithm for Real-Time Robotic Control using Chronic Cortical Ensemble Recordings in Monkeys," *Journal of Cognitive Neuroscience* 16:6, pp. 1022-1035
- [8] Deon Garrett, David A. Peterson, Charles W. Anderson, and Michael H. Thaut: "Comparison of Linear, Nonlinear, and Feature Selection Methods for EEG Signal Classification," *IEEE Transactions on neural systems and rehabilitation engineering*, vol. 11, no. 2, June 2003
- [9] U. T. Eden, W. Truccolo, M. R. Fellows, J. P. Donoghue, E. N. Brown: "Reconstruction of Hand Movement Trajectories from a Dynamic Ensemble of Spiking Motor Cortical Neurons," *Proceedings of the 26th Annual International Conference of the IEEE*. September 1-5, 2004
- [10] Wei Wu, Michael J. Black, David Mumford, Yun Gao, Elie Bienenstock, and John P. Donoghue. "Modeling and Decoding Motor Cortical Activity Using a Switching Kalman Filter," *IEEE transactions on biomedical engineering*, vol. 51, no. 6, JUNE 2004 933
- [11] Helms Tillery, S.I., Taylor, D.M., Schwartz, A.B.: "The general utility of a neuroprosthetic device under direct cortical control," *Proceedings of the Engineering in Medicine and Biology Society 25th International Conference*, 2043-2046, 2003.
- [12] Miguel A. L. Nicolelis, Dragan Dimitrov, Jose M. Carmena, Roy Crist, Gary Lehew, Jerald D. Kralik, and Steven P. Wise. "Chronic, multisite, multielectrode recordings in macaque monkeys," *PNAS* September 16, 2003 vol. 100 no. 19 11041-11046 NEUROSCIENCE
- [13] Reina GA, Moran DW, Schwartz AB. "On the Relationship Between Joint Angular Velocity and Motor Cortical Discharge During Reaching," *J Neurophysiol.* 2001 Jun;85(6):2576-89
- [14] Christopher Reeve Paralysis Foundation, <http://www.christopherreeve.org/>
- [15] Serruya, M.D., Hatsopoulos, N.G., Paninski, L., Fellows, M.R. & Donoghue, J.P. "Instant neural control of a movement signal," *Nature* 416, 141-142 (2002).
- [16] Taylor, D.M., Tillery, S.I. & Schwartz, A.B. "Direct cortical control of 3D neuroprosthetic devices," *Science* 296, 1829-1832 (2002).
- [17] Wessberg, J. et al. "Real-time prediction of hand trajectory by ensembles of cortical neurons in primates," *Nature* 408, 361-365 (2000).
- [18] Vaughan, T.M.; "Guest editorial brain-computer interface technology: a review of the second international meeting," *Neural Systems and Rehabilitation Engineering*, *IEEE Transactions on* Volume 11, Issue 2, June 2003 Page(s):94 - 109
- [19] Chapin, J. K., Moxon, K. A., Markowitz, R. S. & Nicolelis, M. A. L. "Real-time control of a robot arm using simultaneously recorded neurons in the motor cortex," *Nature Neurosci.* 2, 664-670 (1999).
- [20] Georgopoulos AP, Schwartz AB, and Kettner RE. "Neuronal Population Coding of Movement Direction," *Science*. 233:1416-1419 (1986).
- [21] Muller, K.-R.; Anderson, C.W.; Birch, G.E.; "Linear and nonlinear methods for brain-computer interfaces," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Volume 11, Issue 2, June 2003 Page(s):165 - 169
- [22] Corke, P.I. "A Robotics Toolbox for MATLAB," *IEEE Robotics and Automation Magazine*, Volume 3, Issue 1, 24-43