

NARAYANAN KRISHNAMURTHI

Center for Adaptive Neural Systems
Ira A. Fulton School of Engineering
Arizona State University
Phone: (480) 727-8396 ; Fax: (480) 727-8395
PO Box 874404, Tempe, Arizona 85287-4404
Email: Narayanan.Krishnamurthi@asu.edu

3730 South Mill Ave. Apt. C105
Tempe, AZ 85282
Phone: (480) 449-9712
Email: Narayanan.Krish@gmail.com

EDUCATION

- Ph.D., Indian Institute of Technology, Madras, India (1999)
Fields of specialty: Nonlinear dynamics and its applications to biomedical systems; Nonlinear signal processing
- M. Sc., Rama Krishna Mission Vivekananda College, Chennai, India (1992)
Field of specialty: Chemistry
- B. Sc., Rama Krishna Mission Vivekananda College, Chennai, India (1990)
Field of specialty: Chemistry

PROFESSIONAL INTERESTS

Keywords: Neuroplasticity, Neurorehabilitation, Bioengineering, Balance control, Cardiovascular function, Biomedical signal analysis, Nonlinear dynamics

- I have strong research interests to utilize neural plasticity in improving the quality of life in individuals with neurological disorders such as Parkinson's disease (PD) and spinal cord injury (SCI) through bioengineering, neuroscience, and rehabilitation. Currently, I am specifically working towards obtaining external funds to develop therapeutic techniques to improve cardiovascular and cardiorespiratory functioning after SCI, and to investigate the neuroprotective and clinical benefits of long-term exercise training in PD.
- My current main research work is the investigation of the effects of deep brain stimulation amplitude on cardinal symptoms of PD such as tremor, rigidity, bradykinesia, and posture and gait instability. The long-term goal of this study is to develop quantitative tools for the selection of optimum stimulation parameters of DBS system to obtain its maximum clinical benefits. I am also interested in the investigation of pathological changes in neuronal interactions among different brain regions in disorders such as PD and epilepsy. This may help to monitor the disease progression and possible prediction of seizure onset in epilepsy.
- I have extensive experience in characterizing physiological data using nonlinear dynamical techniques from the theory of chaos and fractals. These techniques are capable of providing better understanding of the underlying system when compared to that of linear signal processing techniques, and therefore I would like to utilize these wherever suitable.
- I am actively engaged in guiding graduate and undergraduate students from different disciplines such as Bioengineering, Electrical engineering, and Neuroscience.
- I have experience in teaching guest courses on biodynamics, signals and systems, and biomedical signal processing. From the above research experience, I have also acquired sufficient knowledge to teach introductory courses on computational biology, nonlinear dynamics and chaos theory, nonlinear signal processing, numerical methods, and human physiology.

ACADEMIC POSITIONS

Research Assistant Professor (02/07 – present); **Research Scientist** (10/01 – 02/07)

Brief description of selected projects

- **Effect of deep brain stimulation (DBS) amplitude settings on different impairments of PD:**

The goal of this study is to understand the effects of changing DBS stimulation amplitude setting on different motor impairments such as posture and locomotion control, tremor, and rigidity, and cognitive function (with respect to reaction time for conflicting task selection) in individuals with PD.

Preliminary analyses on posture control during dynamical posture shifts indicates that movement velocity while reaching for targets and movement fluctuations during target hold (measures of unsteadiness) are significantly reduced during altered and no stimulation conditions compared to that of clinically determined settings (CDS) conditions. The significant reductions in velocity and unsteadiness may be due to increased bradykinesia and rigidity, respectively, induced by reductions in DBS amplitude settings. With respect to gait control, stride-time variability (time from heel strike to the subsequent heel strike on the same side) is significantly increased during altered (reduced) or no stimulation conditions compared to that of CDS conditions. This change in stride-time variability may be of clinical importance since increased stride-time variability has been shown to be associated with falls.

The above quantitative measures with others (we are also currently developing indicators for tremor and rigidity) can potentially be efficiently obtained in the clinic and can be utilized for rapid assessment and iterative optimization of DBS settings.

- **Detection and estimation of direction of information flow:**

The detection of direction of information of flow between observed EEG traces (measured from different locations of the brain) was carried out using nonlinear and linear dynamical techniques. This information was used to identify the epileptic focus which can be further utilized for better epileptic seizure prediction. The analyses consisted of developing novel methods based on state-space approach and improving transfer entropy calculation. These methods can also be effectively used to identify and understand abnormal information exchange between different brain areas in individuals with PD.

- **Mechanism of learning and adaptation in primates:**

The mechanism of learning and adaptation during task-reaching in primates was studied using information theoretic technique. The mutual information between multi-unit neural spike timings were calculated and the results showed the presence of increasing and decreasing trends of interactions (plasticity) across days between neurons in different cortical regions or within a cortical region. The analysis of shuffled spike-time data indicated towards spatial firing patterns of neurons as a possible mechanism for the plasticity observed.

Post Doctoral Fellow, Integrated Rehabilitation Engineering Program (02/00 – 09/01)

Boston University/Harvard Medical School

Major projects

- **Arterial pressure Vs Cerebral blood flow – Effect of aging:** Relationship between arterial pressure and cerebral blood flow and their possible changes due to healthy aging was studied through transfer function analysis. The results suggested that various regulatory responses to transient hypotension during standing blunt the transmission of arterial pressure changes onto cerebral blood flow. It was also observed that low-frequency cerebral autoregulation remained intact, but higher frequency regulatory mechanisms affecting cerebral blood flow velocity were altered in healthy elderly subjects.
- **Mechanism of posture control – Effect of age and pathology:** The differences in the posture control mechanism among different groups of people such as young, elderly, and fallers were investigated using a nonlinear statistical approach called detrended fluctuation analysis. The short-term and long-term correlations obtained from the center-of-pressure data indicated that the tendency to drift away from the equilibrium in short-term was higher for healthy elderly and fallers than that of the healthy young.

Project Assistant (10/99 – 01/00)

Department of Physics, Indian Institute of Technology, Madras, India

Interactive software modules were developed to explain the concepts of chaos theory using Visual Basic. This is being used in introductory courses on chaos theory and nonlinear dynamics.

Visiting Post Doctoral Fellow (03/99 - 07/99)

University of Potsdam, Potsdam, Germany

Electrocardiogram (ECG) data of healthy and pathological conditions were characterized using algorithmic entropy through symbolic encoding. The algorithmic entropy represents complexity of the dynamics involved in the different conditions of cardiac system.

Research Assistant (10/93 – 02/99)

Indian Institute of Technology, Madras, India

Title: Nonlinear time series analysis and its applications to human cardiac system and coupled chemical oscillators

A spectrum of nonlinear time series tools had been applied to human ECG. Specifically, the presence of deterministic chaos was demonstrated and unstable periodic orbits (UPOs) of human cardiac system were extracted. The number and the distribution of the extracted UPOs were shown to be capable of distinguishing normal and different pathological conditions of human cardiac system.

Grant Proposals

Title: **Electrical stimulation to improve orthostatic tolerance after spinal cord injury**

Role: Principal Investigator

Funded by Paralyzed Veterans of America

Title: **Exercise training in Parkinson's disease: Neural and functional benefits (NIH - R21)**

Role: Principal Investigator

Status: Pending

Title: **Improving cardiorespiratory function in persons with cervical spinal cord injury (will be submitted to NIH and other funding agencies)**

Role: Principal Investigator

Title: **Human blood pressure phenotypes: Systems analysis and physiological control (NIH – R33)**

Role: Co-Investigator

Status: Pending

INVITED REVIEWER

Journals:

- *IEEE Transactions on Biomedical Engineering*
- *IEEE Transactions on Neural Systems and Rehabilitation Engineering*
- *Journal of Neurology, Neurosurgery & Psychiatry*
- *Medical & Biological Engineering & Computing*

Research Proposals:

- *American Institute of Biological Sciences*

Conferences:

- *Program Committee Member - First International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC-2008)*

INVITED TALKS

1. **“Deep brain stimulation as a treatment for Parkinson’s disease”**, at Arizona School of Health Sciences, Mesa, AZ, 2nd November, 2006
2. **“Computational Analysis of Neurological Disorders”**, at State University of New York, Binghamton, 11th August, 2005
3. **“Parkinson’s disease: Effects of DBS settings on posture control”**, Brown Bag Seminar at Biodesign Institute representing the Center for Adaptive Neural Systems, 19th September, 2004.
4. **“Investigation of Motor and Sensory Cortical Interactions during Learning and Adaptation”**, at National Brain Research Institute, Gurgaon, India, June, 2003
5. **“Analysis of Neuronal Interactions during Adaptation and Learning in Motor Control of Primates: A Model Independent Approach using Information Theory”**, at the 2nd Joint EMBS/BMES Conference, Houston, TX, USA, Oct 23-26, 2002
6. **“Nonlinear and linear dynamical analyses of human ECG, EEG, and cerebral blood flow”** at the Department of Bioengineering, Arizona State University, 1st June, 2001

WORKSHOPS

- Attended workshop on **Proposal Budgets**, April 12, 2007, Arizona State University, Tempe, AZ, USA
- Attended workshop on **Locating Funding**, March 14, 2007, Arizona State University, Tempe, AZ, USA
- Attended workshop on **The Fundamentals of Research Administration for the Investigator**, January 2007, Arizona State University, Tempe, AZ, USA
- Attended workshop on **Successful Grant writing and Collaborative Projects**, February 24, 2005, Arizona State University, Tempe, AZ, USA
- Attended International IEEE EMBS Summer School on **Biocomplexity, Bioscaling and Biosignal Interpretation**, June 24 – July 1, 2001, Dartmouth College, Hanover, NH, USA
- Attended the Montreal 2000 Summer school on **Nonlinear Dynamics in Biology and Medicine**, May 22 – June 2, 2000, Montreal, Quebec, Canada

AWARDS AND SCHOLARSHIPS

2006: First World Parkinson Congress – Junior Scholarship Award

2001: Neural Control and Autonomic Regulation (NCAR) Young Investigator Award Finalist

2000: Integrated Rehabilitation and Engineering Program Fellowship from Center for Applied Bio Dynamics, Boston University

1999: Max-Planck Institute Visiting Post Doctoral Fellowship, Germany

1996: Awarded 'Excellent' performance in Honours Diploma in software Technology and systems Management from NIIT, Madras, India

1995: Senior Research Fellowship from the University Grants commission, India

1993: Qualified in the Graduate Aptitude Test in Engineering

1993: Junior Research Fellowship from the University Grants commission, India

PROFESSIONAL SKILLS

Personal Attributes:

- Highly motivated and inspired to succeed
- Trained with excellent leadership qualities
- Excellent analytical abilities, decision-making and presentation skills
- Possess commendable skills in oral and written communication
- Ability to understand principles underlying the methods

Computer Skills:

- Programming packages : MATLAB, SPSS and Maple
- Programming languages : C, C++, Visual Basic and Fortran
- Operating systems : Unix (AIX, IRIX, LINUX), Windows XP
- Platforms : IBM RISC 6000, Silicon Graphics, Digital Workstations
- Graphic packages : Origin, Grapher and Harvard Graphics
- Word processors : MS Office and Latex

PUBLICATIONS (My first name 'Narayanan' has been used in all of my publications)**Peer-Reviewed Journal Publications:**

1. **Narayanan, K.**, M. Stefani, P. Mahant, J. Samanta and J.J. Abbas, "Deep brain stimulation settings alter posture shift velocity and unsteadiness in Parkinson's disease" (submitted to *Parkinsonism and Related Disorders*)
2. L.D. Iasemidis, P.M. Pardalos, D-S Shiau, W.Chaovalitwongse, **Narayanan, K.**, A. Prasad, K. Tsakalis P. Carney and J.C. Sackellares, "Long-term prospective on-line real-time seizure prediction", *Clin Neurophysiol.*, 116, 532-544 (2005)
3. B. Veeramani, **Narayanan, K.**, A. Prasad, L.D. Iasemidis, A. Spanias and K. Tsakalis, "Measuring the direction and the strength of coupling in nonlinear systems - A modeling approach in the state space", *IEEE Signal Processing Letters*, 11 (7), 617-620 (2004)
4. S. Sabesan, **Narayanan, K.**, A. Prasad, A. Spanias, J.C. Sackellares, and L.D. Iasemidis, "Predictability of Epileptic Seizures: A comparative study using Lyapunov exponent and entropy based measures", *Biomed Sci Instrum.*, 39, 129-35 (2003)
5. B. Veeramani, A. Prasad, **Narayanan, K.**, A. Spanias, and L.D. Iasemidis, "Measuring information flow in nonlinear systems - A modeling approach in the state space", *Biomed Sci Instrum.*, 39, 65-70 (2003)
6. R. Venugopal, **Narayanan, K.**, A. Prasad, A. Spanias, J.C. Sackellares, and L.D. Iasemidis, "A new approach towards predictability of Epileptic Seizures: KLT Dimension", *Biomed Sci Instrum.*, 39, 123-128 (2003)
7. L.D. Iasemidis, P.M. Pardalos, D-S. Shiau, W. Chaovalitwongse, **Narayanan, K.**, Shiv Kumar, P.R. Carney and J.C. Sackellares, "Prediction of Human Epileptic Seizures based on Optimization and Phase changes of brain electrical activity", *J. Optimization Methods and Software*, 18 (1), 81-104 (2003)
8. **Narayanan, K.**, J.J. Collins, J. Hamner, S. Mukai, and L.A. Lipsitz, "Predicting Cerebral Blood Flow Response to Orthostatic Stress from Resting Dynamics: Effects of healthy aging", *The American Journal of Physiology*, 281: R716-R722 (2001)
9. **Narayanan, K.**, R.B. Govindan and M.S. Gopinathan (2000) "Evidence for low dimension chaos in electrically coupled chemical oscillator in batch condition", *Indian J. Chem. A* 39: (1-3) 345-355
10. **Narayanan, K.**, R.B. Govindan and M.S. Gopinathan, "Unstable Periodic orbits in Human Cardiac Rhythms", *Phys. Rev E* 57, 4594-4603 (1998)
11. Govindan, R.B., **Narayanan, K.**, and M.S. Gopinathan, "On the evidence of Deterministic Chaos in ECG: Surrogate and Predictability Analysis", *Chaos* 8, 495-502 (1998)

Peer-Reviewed Book Chapters:

1. S. Sabesan, **Narayanan, K.**, A. Prasad, L.D. Iasemidis, A. Spanias and K. Tsakalis, "Information flow in coupled nonlinear systems: Application to the epileptic human brain", In: *Data Mining in Biomedicine*, Eds: P. Pardalos, V. Boginski, A. Vazacopoulos, Springer Optimization and its Applications Series, Springer, pp. 483-504 (2007).
2. R.B. Govindan, **Narayanan, K.**, M.S. Gopinathan and N. Pradhan, "Unstable periodic orbit spectra of theoretical and experimental dynamical Systems", In: *Nonlinear Phenomena In Physical And Biological Sciences* edited by S. K. Malik, M. K. Chandrashekharan and N. Pradhan (2000)
3. R.B. Govindan, **Narayanan, K.**, and M.S. Gopinathan, N. Pradhan, R. Sreenivasan, and P. Dwivedi , "The Spectrum of Unstable Periodic Orbits Of The Human Brain", In: *Nonlinear Dynamics and Brain Functioning* edited by R. Sreenivasan, N. Pradhan and Paul E. Rapp, Nova Science Publishers, Inc, 1999

Peer-Reviewed Conference Proceedings and Abstracts:

1. **Narayanan, K.**, A. Sitek, P. Mahant, J. Samanta and J.J. Abbas, "Effects of Deep Brain Stimulation Amplitude on Gait in Parkinson's Disease", 37th Annual Meeting of Society for Neuroscience, November, November 3-7, 2007, San Diego, CA.

2. A. Downing, **Narayanan, K.**, and J.J. Abbas, "Postural control of self-initiated weight shifts in able-bodied children and adults", Annual Conference of American Society for Biomechanics, 2007 (submitted)
3. **Narayanan, K.**, S. Mulligan, P. Mahant, J. Samanta and J.J. Abbas, "Deep brain stimulation alters postural control in Parkinson's Disease", abstract presented at 36th Annual Meeting of Society for Neuroscience, October, October 14-18, 2006, Atlanta, GA
4. **Narayanan, K.**, S. Mulligan, P. Mahant, J. Samanta and J.J. Abbas, "Deep Brain Stimulation Effects on Posture Control in Parkinson's Disease", World Parkinson Congress, February 22-26, 2006, Washington D.C (published in Movement Disorders, Vol. 21, Supp. 13, P209, page S115, 2006)
5. S. Mulligan, **Narayanan, K.**, P. Mahant, J. Samanta and J.J. Abbas, "Effect of deep brain stimulation on posture control in Parkinson's disease", 9th International Congress of Parkinson's disease and Movement Disorders, March 5-8, 2005, New Orleans, LA (published in Movement Disorders, Vol. 20, Supp. 10, P478, page S141, 2005)
6. E.T. Hsiao-Wecksler, **Narayanan, K.**, B.S. Lee, C.A. Laughton, and L.A. Lipsitz, "Does Tai Chi affect postural sway & muscle activity in older adults?" 27th Annual Meeting of the American Society of Biomechanics, Toledo, OH, September 25-27, 2003
7. S. Sabesan, **Narayanan, K.**, A. Prasad, and L.D. Iasemidis, "Improved Measure of Information Flow in Coupled Non-Linear Systems", The Proceedings of IASTED International Conference on Modeling and Simulation, Palm Springs, USA, 2003, pp. 329-333
8. B. Veeramani, **Narayanan, K.**, A. Prasad, and L.D. Iasemidis, "On the use of Directed Transfer Function for Nonlinear systems", The Proceedings of IASTED International Conference on Modeling and Simulation, Palm Springs, USA, 2003, pp. 270-274
9. R. Venugopal, A. Prasad, **Narayanan, K.**, and L.D. Iasemidis, "Nonlinear Noise Reduction and Predictability of Epileptic Seizures", The Proceedings of IASTED International Conference on Modeling and Simulation, Palm Springs, USA, 2003, pp. 240-245
10. L.D. Iasemidis, A. Prasad, **Narayanan, K.**, J.C. Sackellares, P.M. Pardalos, D.S. Shiao and W. Chaovalitwongse, "Prediction of epileptic seizures by linear and nonlinear methods", International Nonlinear Sciences Conference on Research and applications in the Life Sciences, Vienna, Austria, February 7-9, 2003
11. A. Prasad, **Narayanan, K.**, K. Tsakalis and L.D. Iasemidis, "Hysteresis in coupled chaotic oscillators and application to epileptic seizures", International Nonlinear Sciences Conference on Research and applications in the Life Sciences, Vienna, Austria, February 7-9, 2003
12. **Narayanan, K.**, D.J. Weber, J. He, A. Prasad, and L.D. Iasemidis, "Analysis of Neuronal Interactions during Adaptation and Learning in Motor Control of Primates: A Model Independent Approach using Information Theory", Proceedings of the Second Joint EMBS/BMES Conference, Houston, TX, USA, Oct. 23- 26, 2002, pp 2552-2553
13. **Narayanan, K.**, and L.A. Lipsitz, "Do resting Cerebral Pressure - Flow dynamics predict Cerebral blood flow responses to Orthostatic Stress? Effects of healthy Aging", presented in Experimental Biology 2001, 31 March - 4 April, 2001, Orlando, FL, USA
14. **Narayanan, K.**, R.B. Govindan, M. Ramasubba Reddy and M.S. Gopinathan, "Dynamics of cardiac system through unstable periodic orbits", Proceedings of 19th International Conference - IEEE/EMBS Oct.30 - Nov. 2 1997, pp 2019-2021

REFERENCES

James Abbas, Ph.D., Co-Director, Center for ANS in Ira A. Fulton School of Engineering, Associate Professor, Harrington Department of Bioengineering, Ira A. Fulton School of Engineering, at Arizona State University, Tempe, AZ 85287-9709, P.O. Box 879709, Phone: (480) 965-9521, Fax: (480) 727-7624, Email: james.abbas@asu.edu

Leon Iasemidis, Ph.D., Associate Professor/Associate Editor IEEE-TBME, Epilepsia, Harrington Department of Bioengineering, ECG Building, Fulton School of Engineering, Arizona State University, Tempe, AZ 85287-9709, P.O. Box 879709, Phone: (480) 965-9134, Fax: (480) 965-0037, Email: Leon.iasemidis@asu.edu

Alfonso M. Albano, Ph.D., Professor, Department of Physics, Bryn Mawr College, 101 N. Merion Ave., Bryn Mawr, PA 19010, Phone: (610) 526-5359, Fax: (610) 526-7469
E-mail: aalbano@brynmawr.edu

M.S. Gopinathan, Ph.D., Professor, Department of Chemistry, Indian Institute of Technology, Madras, Chennai – 600 036, Tamil Nadu, India, Phone: 91-44-257 8246, Fax: 91-44-235 0509
Email: gopi@iitm.ac.in

Elizabeth T. Hsiao-Weckslar, Ph.D., Assistant Professor, Departments of Mechanical & Industrial Engineering and Bioengineering, 124 Mechanical Engineering Building, MC-244, 1206 West Green St., University of Illinois at Urbana-Champaign, Urbana, IL 61801, Phone: (217) 333-3415, Fax: (217) 244-6534; E-mail: ethw@uiuc.edu