Fundamentals of Neuromechanics

Instructor: Bradly Alicea, e-mail: freejumper@yahoo.com
Class Time, Location: TBA
Office Hours: TBA

The course content will be divided into three modules, each covering 1/3 of the term.

Part I: Introduction, Background, and Fundamentals (for those of you interested in the topic).

Part II: Academic Case Studies Synopses (for those of you with academic interests).

Part III: Application-oriented Case Studies (for those of you with applied interests).

Part I: Introduction	**Part II: Academic Case Studies Synopses***	**Part III: Application-oriented Case Studies**
Week 1: What is Neuromechanics?	Week 6: Randall Beer, Tad McGeer/Andy Ruina.	Week 11: Human Factors and Human-machine interaction.
Weeks 1, 2, and 3: fundamentals of movement: kinematics in animals and machines.	Week 7: Kiisa Nishikawa/Malcolm MacIver, Hilliel Chiel/Lawrence Rome.	Week 12: Augmented Cognition and Performance Augmentation.
Weeks 3 and 4: fundamentals of movement: kinetics and energetics in animals.	Week 9: Sandro Mussa-Ivaldi, John Jeka/Fay Horak.	Week 13: Neurorehabilitation.
Weeks 4 and 5: movement and the nervous system.	Week 10: Robert Full, James Marden/Hugh Herr.	Week 14: Mechano-interfaces (exoskeletons, piezoelectric devices, and harnessing power).
		Week 15: Haptics, haptic interfaces, and proprioception.

* a synopsis of each case study is presented at the end of the syllabus.

What is Neuromechanics?

Neuromechanics is an integrative science at the nexus of sensation and perception, neurobiology, biomechanics, and robotics. The science part is grounded in experimentation; therefore, we will cover a number of experimental case studies over the course of the term. The theoretical portion can be best understood by covering the basics, understanding the case studies, and reviewing major applications related to the field.

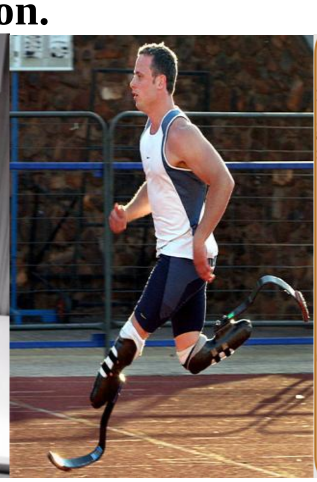
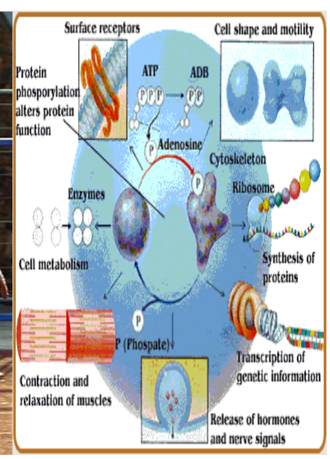
How's the grading?
There are two exams (one at the conclusion of Part I, and the other at the scheduled final exam time). There will also be two homework assignments (online), and one set of written reviews for Part II (online). One homework assignment will be given on topics covered during the measurement techniques section, while the other will involve a topic covered during the application section of the course. During Part II, each person in the class will choose ONE of the model systems and produce a short (2-4 pgs., double spaced) review. All second-hand information must be accompanied by a reasonable citation and cited in a bibliography, and there is to be no collaboration or plagiarism. Various .pdf tutorials will be made available throughout the course of the class on several topics. These tutorials should help you study, formulate a research idea, and generally be useful to you (please cite these tutorials as if they were a research paper).

Assignment	**Percent of grade**
Homework #1	16
Midterm	26
Model system report	16
Homework #2	16
Homework #3 *	10
Final	26
Total	**110**

NOTE: there is an optional Homework #3. It adds 10% to your grade, so that you can earn a maximum of 110% (you likely won't, but that isn't the point). Please take advantage of this opportunity. Homework #3 will most likely involve a quick research project proposing the application of neuromechanical principles to a particular problem. This could turn into a much more beneficial and large-scale research project down the road.

Part I: Description of Introduction.



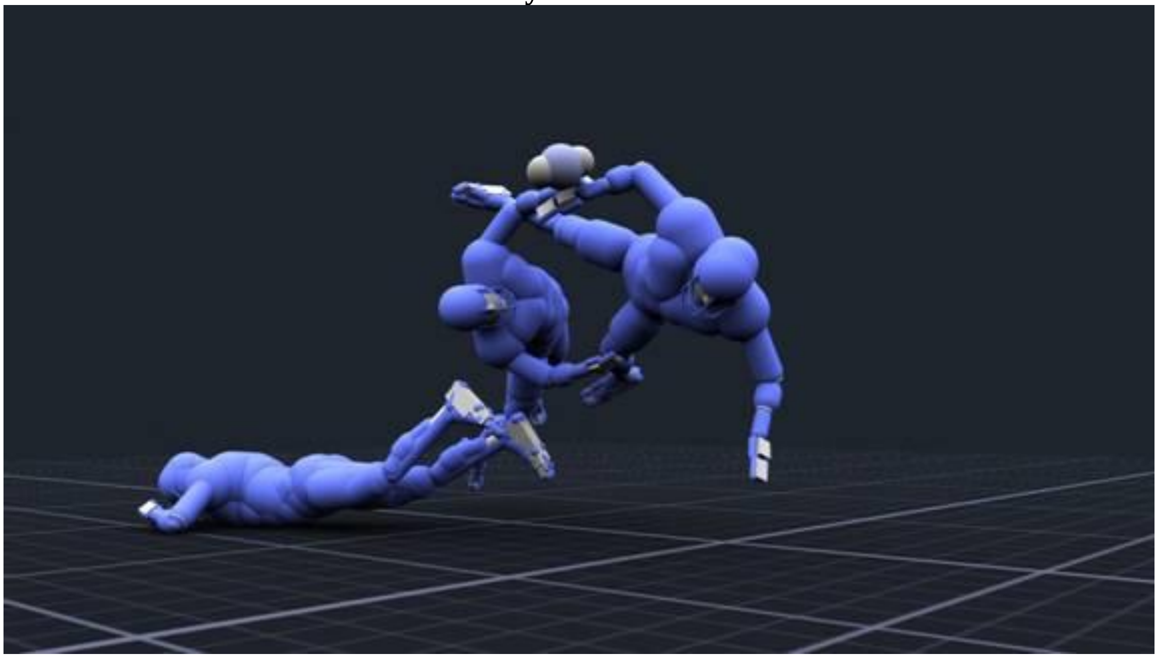
1. Fundamentals of Movement: kinematics in animals and machines

*** Central pattern generation (CPGs):**

This part of the lecture schedule will focus on central pattern generators (CPGs). The basic unit of movement production in the nervous system, CPGs can be defined as oscillatory primitives that serve as the basis for movement production in a wide variety of animal taxa, from insects to tetrapods. We will discuss how simple structures like CPGs have evolved into specialized types of movement such as flying, walking, and swimming.

***CPGs and simulation:**

Case study: NaturalMotion



Demos (Virtual and Physical):
Video: http://www.youtube.com/watch?v=ySRvKzZsDqw, http://www.youtube.com/watch?v=j1Uf8qpyDFM

Application Downloads: http://www.naturalmotion.com/endorphin.htm

Physical: indoor lab (TBA). CPGs and mechanisms such as emergent phenomena have also been incorporated into human motion generation simulations for video games and other interactive virtual environments. We will explore the work of Torsten Reil and his NaturalMotion method, with an exercise based on this simulation environment.

*** Movement disorders:**
This part of the lecture schedule will focus on balance disorders and their neuromechanical substrates. Featured disorders will include: ALS, muscular dystrophy, and balance disorders. We will also include a discussion of therapeutic techniques such as brain-machine interfaces, gene therapy, and sensory augmentation.

*** Measurement techniques:**
This part of the lecture schedule will focus on ways to measure movement, from motion capture (MoCap) and accelerometer systems to high-speed cameras, differential GPS, and stroboscopic methods. To segue into the kinetics section, EMG, imaging, and molecular methods will also be covered. There may be a homework assignment focusing on the computation of kinematic data.

2. Fundamentals of Movement: kinetics and energetics in animals

*** Basics of muscle, neural tissue, and plasticity:**

This part of the lecture schedule will focus on the basic functional units of movement and force production. A broad survey of muscle, connective tissues, sensory receptors, and brain tissues such as neurons, glia, and astrocytes will be featured. In addition, there will be a brief lecture section on the mechanical properties of biological tissues (e.g. Young's modulus). There may be a homework assignment on the mechanical properties of tissue.

*** Energetics and movement:**

This part of the lecture schedule will focus on the energetic demands of motility. Part of the focus will be on a series of papers by James Marden and colleagues, who have done work on linkages between force production, type of movement (e.g. swimming, flying, walking), the underlying mechanisms, and scaling between force production and movement. There may be a homework assignment involving this class module.

Focus on: Statics

In living systems, statics is an accounting of mechanical and functional processes at a single point in time. This stands in contrast to dynamics, which characterize the system function over time. We use free-body (also called Maxwell-Cremona) diagrams to describe the kinetics (forces) at each degree of freedom (joint) in the system. From these models, we can predict the consequences for a range of interactions between an organisms' morphology and its environment.

In each free-body diagram, there are two series of forces (measured in newtons/meter - N m^2) which act in three dimensions. The first of these are called internal forces, and are generated by the neuromuscular system. Internal forces can be generated laterally and horizontally (producing lateral force) and rotationally (producing torque). The second of these are external forces, and are generated through interaction with the environment. One example is surface reaction forces, which are inertial forces which result from a collision between an object and a non-compliant (e.g. rigid) surface. External forces also act laterally, horizontally, and rotationally.

The idea of a statics model is that the entire system is in equilibrium so that

$$\mathbf{I - E + G = 0,\ \Delta I - \Delta E + \Delta G = 0}$$

where I = internal forces and E = external forces and G = gravity (constant of 9.8 m/sec). The internal and external forces cancel each other out at every joint in the system, and balance across the entire system.

*** Molecular aspects of brain and muscle function**:

This part of the lecture schedule will focus on the molecular bases of motor learning and memory and muscle plasticity. Recent findings have clarified the major pathways, genes, transcripts, and proteins involved in neuromuscular adaptation. This will be a very basic introduction.

Focus on: Molecular Biology

It's in your genes……this is a phrase that gets thrown around a lot in the press and in everyday conversation, but is never sufficiently explained. In this tutorial, you will be introduced to terminology and basic theories of heredity, gene action, association studies, and gene expression. We will also touch on basic molecular signaling pathways important to both muscle physiology (PPAR, IGF-1), and learning and memory (ERK, MAPK). Finally, we will briefly touch on what happens when genomic systems are perturbed experimentally via knockout experiments and pharmacological blockers. The idea is to acquire a sufficient vocabulary in order to understand academic articles in the field.

3. Movement and the Nervous System

*** Embodied systems:**

This part of the lecture schedule will focus on embodied systems, which are important in the design of human-machine systems and human augmentation. The lecture structure will focus on considering the body by itself, the brain by itself, and finally the brain and body together.

*** Surface Reaction Forces, Gravity, and Adaptation:**

Case study: How would Jesus Run? Just like the Basilisk.

Readings:
Hsieh, S.T. and Lauder, G.V. (2004). Running on water: three-dimensional force generation by basilisk lizards. PNAS USA, 101, 48, 16784–16788.

(1996). A walk on the wild side - hydrodynamic model explains how *Basiliscus* lizard skips across water. http://findarticles.com/p/articles/mi_m1200/is_n1_v149/ai_17811969

Demos (Virtual and Physical):
Video: http://www.youtube.com/watch?v=Qhsxo7vY8ac

Physical: outdoor lab (TBA)

*** The neural correlates of force production and movement:**

This part of the lecture schedule will focus on the neural correlates of force production and movement. The approach will be to review neuroimaging and animal model studies to understand what parts of the brain are involved in imagined movement, changes in the recruitment of motor units during the course of training, and basic sensation and perception.

*** Aging and disorders of the CNS and movement:**

This part of the lecture schedule will focus on aging processes in human and other animal species. Of particular interest will be the effects of aging on bone, muscle, and neural systems. Case studies will be included that focus upon myelination, Alzheimer’s disease, and neurorehabilitation strategies.

Focus on: neural coding:
How do we represent abstract concepts in our brains? In the section on CPG's, we covered how the brain encodes simple commands. Indeed, biological movement is often quite complex, and is related to phenomena ranging from spatial navigation to touch and self-awareness. This tutorial will cover the topic of neural coding, an emerging area in the computational neuroscience literature. Of particular interest will be how the brain encodes information related to movement, such as the movement vector, the cerebellar internal model, and somatotopic maps. For those of you who are more adventurous, the tutorial also includes a section on molecular and cellular cognition.

Selected Readings/Reference Books and Articles:

Basic Resources (all will be on hold at library or otherwise made available):

Enoka, R. (2001). Neuromechanics of Human Movement. Human Kinetics, Champaign, IL.

Shadmehr, R. and Wise, S.P. (2005). Computational Neurobiology of Reaching and Pointing. MIT Press, Cambridge, MA.

Wolfe, J.M., Kluender, K.R., Levi, D.M., Bartoshuk, L.M., Herz, R.S., Klatzky, R.L., and Lederman, S.J. (2006). Sensation and Perception. Sinauer Associates, Sunderland, MA.

Useful Reviews Articles:

Barry, B.K. and Enoka, R.M. (2007). The Neurobiology of muscle fatigue: 15 years later. Integrative and Comparative Biology, 47(4), 465-473.

Bejan, A. and Marden, J.H. (2006). Unifying constructal theory for scale effects in running, swimming, and flying. Journal of Experimental Biology, 209, 238-248.

Chong, L., Culotta, E., Sugden, A. (2000). On the move: molecular to robotic. Science, 288, 79-106.

Delcomyn, F. (1980). Neural basis of rhythmic behavior in animals. Science, 210, 492-498.

Enoka, R.M. and Duchateau, J. (2008). Muscle Fatigue: what, why, and how it influences muscle function. Journal of Physiology, 586.1, 11-23.

Enoka, R.M. and Fuglevand, A.J. (2001). Motor unit physiology: some unresolved issues. Muscle and Nerve, 24, 4-17.

Enoka, R.M. and Stuart, D.G. (1992). The neurobiology of muscle fatigue. Journal of Applied Physiology, 72(5), 1631-1648.

Marden, J.H. and Allen, L.R. (2002). Molecules, muscles, and machines: universal performance characteristics of motors. PNAS USA, 99(7), 4161-4166.

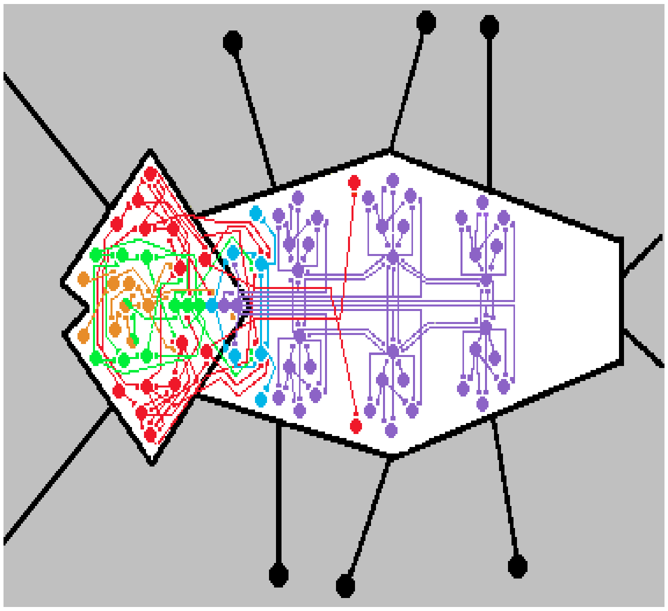
Montooth, K.L., Marden, J.H., and Clark, A.G. (2003). Mapping determinants of variation in energy metabolism, respiration, and flight in *Drosophila*. Genetics 165(2): 623-635.

Morasso, P., Bottaro, A., Casadio, M., and Sanguinetti, V. (2005). Preflexes and internal models in biomimetic robot systems. Cognitive Processing, 6(1), 25-36.

Terrier, P. (2000). High-precision satellite positioning system as a new tool to study the biomechanics of human locomotion. Journal of Biomechanics, 33(12), 1717-1722.

Part II: Academic Case Studies Synopses.

Randall Beer: insect neuroethology and brain-body-environment interaction



Selected Readings:

Beer, R.D. (2006). Beyond Control: The Dynamics of Brain-Body-Environment Interaction in Motor Systems. In D. Sternad ed. Progress in Motor Control V: a multidisciplinary perspective. Springer, Berlin.

Phattanasri, P., Chiel, H.J. and Beer, R.D. (2007). The dynamics of associative learning in evolved model circuits. Adaptive Behavior 15(4), 377-396.

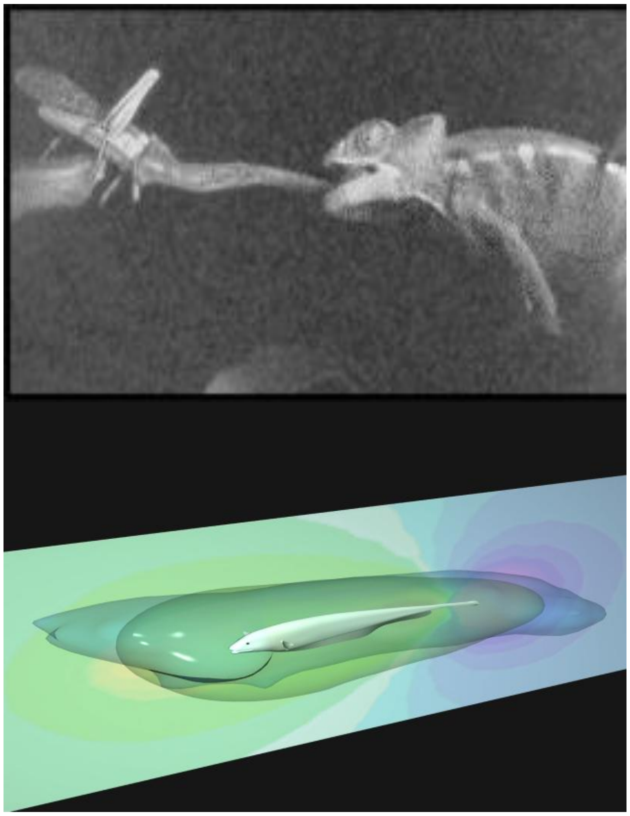
Tad McGeer and Andy Ruina: dynamic walking

Selected Readings:

McGeer, T. (1990) Passive dynamic walking, International Journal of Robotics Research, Vol. 9, No., 2, pp. 62-82.

Collins, S.H., Ruina, A.L., Tedrake, R., Wisse, M. (2005) Efficient bipedal robots based on passive-dynamic walkers, Science, 307: 1082-1085.

Kiisa Nishikawa and Malcolm MacIver: prey capture in lizards and fish



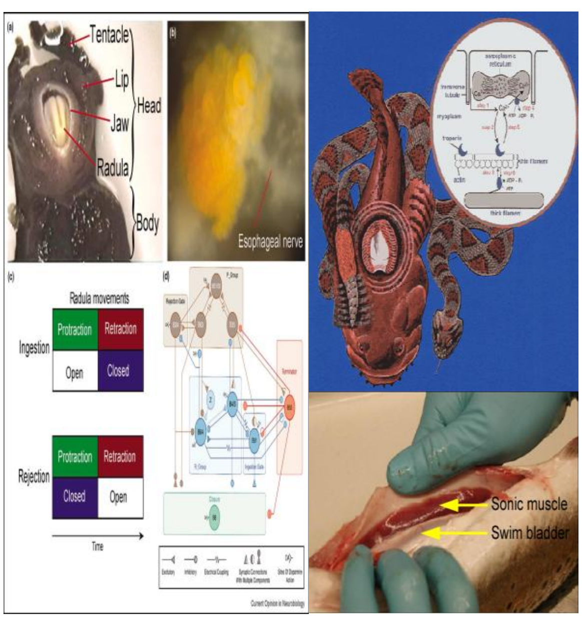
Selected Readings:

Corbacho, F.J., Nishikawa, K.C., Weerasuriya, A., Liaw, J-S., and Arbib, M.A. (2005). Schema-based learning of adaptable and flexible prey-catching in anurans I. The basic architecture. Biological Cybernetics, 93(6), 391-409.

Herrel, A., Meyers, J.J. Aerts, P. and Nishikawa, K.C. (2001). Functional implications of supercontracting muscle in the chameleon tongue retractors. Journal of Experimental Biology, 204, 3621-3627.

Nelson, M. E., M. A. MacIver, and S. S. Coombs (2002). Modeling electrosensory and mechanosensory images during the predatory behavior of weakly electric fish. Brain, Behavior, and Evolution 59(4):199-210.

Hillel Chiel and Lawrence Rome: swallowing and other specialized neuromuscular behaviors.



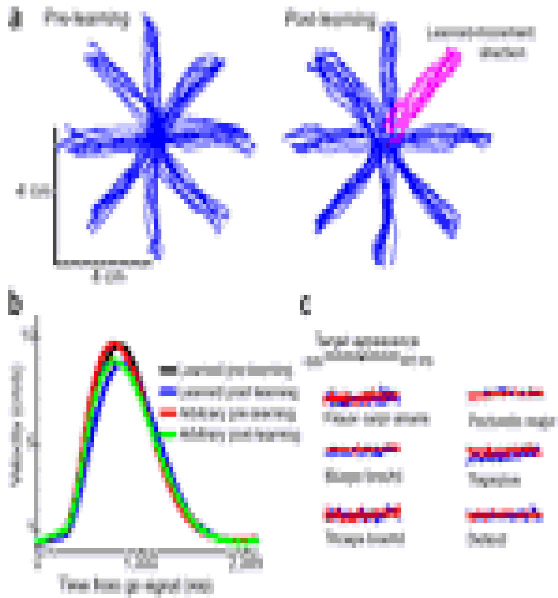
Selected Readings:

Neustadter, D.M., Drushel, R.F., Crago, P.E., Adams, B.W., and Chiel, H.J. (2002). A kinematic model of swallowing in *Aplysia californica* based on radula/odontophore kinematics and in vivo MRI. Journal of Experimental Biology, 205, 3177-3206.

Sutton, G.P., Mangan, E.V., Neustadter, D.M., Beer, R.D., Crago, P.E., and Chiel, H.J. (2004). Neural control exploits changing mechanical advantage and context dependence to generate different feeding responses in *Aplysia*. Biological Cybernetics, 91, 333-345.

Young, I.S. and Rome, L.C. (2001). Mutually exclusive muscle designs: the power output of the locomotory and sonic muscles of the oyster toadfish (*Opsanus tau*). Proceedings of the Royal Society of London B, 268, 1965-1970.

Sandro Mussa-Ivaldi and Reza Shadmehr: motor learning and memory



Selected Readings:

Mussa-Ivaldi, F.A. (1995). Geometrical Principles in Motor Control. In: M.A. Arbib (Ed.) Handbook of Brain Theory. MIT Press, Cambridge, MA.

Mussa-Ivaldi, F.A., Giszter, F.A. and Bizzi, E. (1994). Linear combination of primitives in vertebrate motor control. PNAS USA, 91, 7534-7538.

John Jeka and Fay Horak: balance and virtual environments

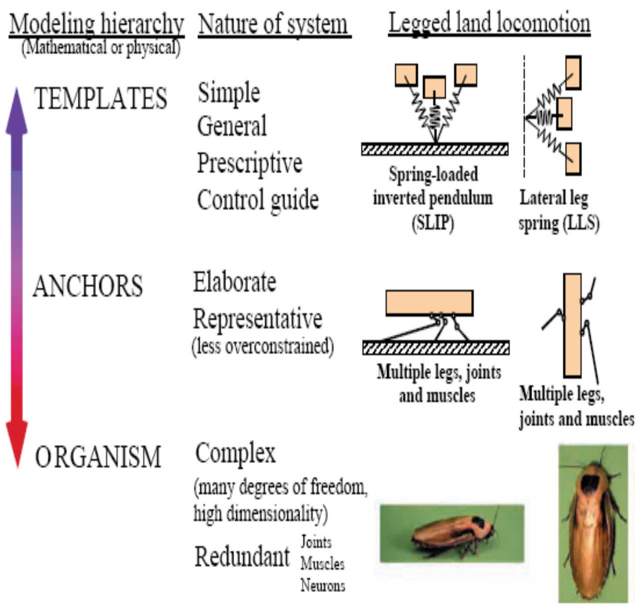
Researchers have developed a portable "Ipod-like" device that can be used to help correct balance disorders in patients with Parkinson's. Photo courtesy of OHSU.

Selected Readings:

Jeka, J.J. (2006). Light touch contact: not just for surfers. The Neuromorphic Engineer, 3(1), 5-6.

Jeka, J.J., Kiemel, T., Creath, R., Horak, F.B., and Peterka, R. (2004). Controlling human upright stance: Velocity information is more accurate than position or acceleration. Journal of Neurophysiology, 92, 2368-237.

Robert Full: anchors, templates, and legged locomotion

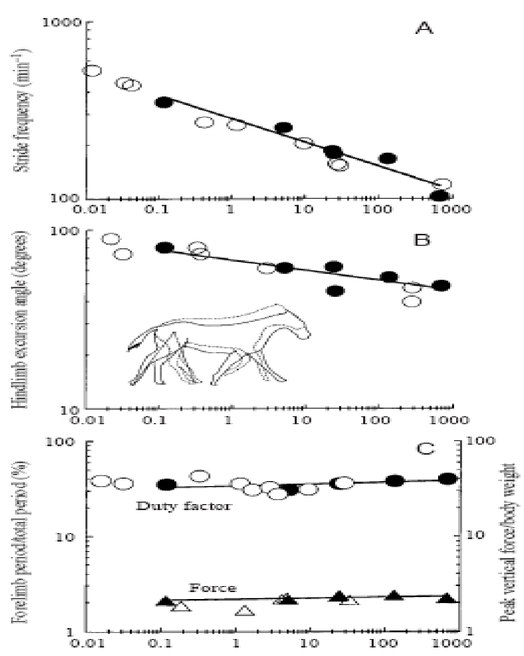


Selected Readings:

Full, R.J. and Koditschek, D.E. (1999). Templates and Anchors: neuromechanical hypotheses of legged locomotion on land. Journal of Experimental Biology, 202, 3325–3332.

Holmes, P., Full, R.J., Koditschek, D., and Guckenheimer, J. (2006). Dynamics of legged locomotion: Models, analysis, and challenges. SIAM Review, 48(2), 207-304.

James Marden and Hugh Herr: functional scaling and biomechatronics



Selected Readings:

Herr, H. and Dennis, R.G. (2004). A swimming robot actuated by living muscle tissue. Journal of Neuroengineering Rehabilitation, 1, 6.

Herr, H.M., Huang, G.T. and McMahon, T.A. (2002). A model of scale effects in mammalian quadrupedal running. Journal of Experimental Biology, 205, 959-967.

Bejan, A. and Marden, J.H. (2006). Unifying constructal theory for scale effects in running, swimming and flying. Journal of Experimental Biology, 209, 238-24

Part III: Applications.

1. Human Factors and Ergonomics (human-machine interaction):
This part of the lecture schedule will focus upon human factors issues in applying neuromechanical principles to systems design. The focus will be on wearable computing.

2. Augmented Cognition and Performance Augmentation:
This part of the lecture schedule will introduce the concepts of augmented cognition and performance augmentation at an introductory level. There will also be an introduction to the basic tools of the field, such as the application of mitigation strategies and creating performance state gauges.

3. Neurorehabilitation:
This part of the lecture schedule will provide a recap of prior studies and technologies covered in class along with additional examples. The additional examples will focus on recovery of function after stroke using robotic systems and the use of virtual environments and other digital media to retrain postural stability in the elderly.

4. Mechano-interfaces (exoskeletons, piezoelectric devices, and harnessing power):
This part of the lecture schedule will provide a glimpse into the future of neuromechanical applications, bringing together all of the topics in this class module. We will explore the world of wearable devices that produce electricity, the making of artificial muscles, and wearable devices that increase your strength and endurance!

Human-powered devices:

With all the recent hype over renewable energies and the proliferation of mobile devices, one emerging area of research is in harnessing the output of human neuromuscular systems for purposes of small-scale electrical generation. There will be a tutorial based on harnessing energy from human movement and wearable devices.

Links:
Quick Wikipedia Reference: http://en.wikipedia.com/wiki/Human-powered _transport

5. Haptics, Haptic Interfaces, and Proprioception:
This part of the lecture schedule will provide a quick introduction to the senses of touch and somatosensation. We will explore some of the neural pathways and coding strategies involved. There will also be discussion of applying scientific findings about this sensory modality to interface and prosthetic technology design.