BIOGRAPHICAL SKETCH

Provide the following information for the Senior/key personnel and other significant contributors.
Follow this format for each person. DO NOT EXCEED FIVE PAGES.

NAME: Lena H. Ting

eRA COMMONS USER NAME (credential, e.g., agency login): tingle

POSITION TITLE: Professor of Biomedical Engineering

EDUCATION/TRAINING *(Begin with baccalaureate or other initial professional education, such as nursing, include postdoctoral training and residency training if applicable. Add/delete rows as necessary.)*

INSTITUTION AND LOCATION	DEGREE *(if applicable)*	Completion Date MM/YYYY	FIELD OF STUDY
University of California, Berkeley	BS	1990	Mechanical Engineering
Stanford University	MSE	1993	Biomechanical Eng.
Stanford University	PhD	1998	Mechanical Engineering
Université de Paris V	Postdoc	1997-1998	Neurophysiology
Oregon Health and Science University	Postdoc	1999-2002	Neurophysiology

A. Personal Statement

I am a leader in *neuromechanics,* and successful director of a highly interdisciplinary research lab that has pioneered a new understanding of how movement intention translates to action through the complex interplay between the nervous system and the musculoskeletal system. My lab focuses on complex, whole body human movements such as walking and balance that have strong clinical relevance, as well highly skilled movements involved in dance and sport that can help us inform mechanisms of neurorehabilitation. We have discovered exciting new principles of movement that we are using to understand mechanisms of sensorimotor deficits and rehabilitation in stroke, spinal cord injury, Parkinson's disease, depression, and aging. Since 2014, my lab has been housed in the Emory Rehabilitation Hospital, facilitating collaborations with clinicians in Physical Therapy, Neurology, Geriatrics, Neurosurgery, and other clinical departments. We also have a number of collaborations to examine balance in flamingos, the role of biophysical properties of muscle in proprioception, and to develop principles to guide intuitive physical human-robot interactions based on human-human interactions. I co-direct the *Georgia Tech Neural Engineering* and I am on the executive committee of the *Emory Neuromodulation and Technology Innovation Center.* My research spans basic to clinical translation and is highlighted the follow in textbooks: *Principles of Neural Science*, *Motor Control: Translating Research into Practice*, *The Neurobiology of Motor Control: Fundamental Concepts and New Directions*, and in a popular science book entitled *Balance: a Dizzying Journey Through the Science of our Most Delicate Sense*.

1. *Sawers, A.,* **Ting, L.H.*** (2014) Perspectives on human-human sensorimotor interactions for the design of rehabilitation robots. *Journal of Neuroengineering and Rehabilitation* 11:142. doi: 10.1186/1743-0003-11-142. PMCID: PMC4197261.
2. **Ting, L.H**.,* Chiel, H.J., Trumbower, R.D., *Allen, J.L*., McKay, J.L., Hackney, M.E. Kesar, T.M. (2015) Neuromechanical principles underlying movement modularity and their implications for rehabilitation. *Neuron* 86(1):38-54*.* PMCID: PMC4392340.
3. **Ting, L.H**.,* Chiel, H.J. (2017) "Chapter 12: Muscle, biomechanics, and implications for neural control" In The Neurobiology of Motor Control: Fundamental Concepts and New Directions, Hooper, S. L., Büschges, A. (eds), Wiley, New York.
4. Chang, Y.H., **Ting, L.H.** (2017) Mechanical evidence that flamingos can support their body on one leg with little active muscular force. *Biology Letters* 13(5). pii: 20160948. doi: 10.1098/rsbl.2016.0948. PMCID: PMC5454233*.*

B. Positions and Honors

Positions and Employment

2002-2008 Assistant Professor, Biomedical Engineering, Emory University and Georgia Tech
2002-pres. Training Faculty, Neuroscience Program, Grad Div of Biological & Biomedical Sciences, Emory
2005-pres. Adjunct Faculty, Electrical and Computer Engineering, Georgia Institute of Technology
2006-pres. Adjunct Faculty, Applied Physiology, Georgia Institute of Technology
2008-2014 Associate Professor, Biomedical Engineering, Emory University and Georgia Tech
2014-pres. Professor, Department of Biomedical Engineering, Emory University and Georgia Tech
2014-pres. Professor, Department of Rehabilitation Medicine, Division of Physical Therapy, Emory

Other Professional Experience (selected)

2004 Veteran's Administration, *ad hoc* grant reviewer
2005-2010 Editorial Board, Journal of Applied Biomechanics
2006 NIH/NSF Collaborative Research in Computational Neuroscience, *ad hoc* reviewer
2006 NIH IFCN IRG Fellowship Study Section, *ad hoc* reviewer
2006 Biotechnology and Biological Sciences Research Council (UK), *ad hoc* grant reviewer
2007 NIH ZRG1 Musculoskeletal, Oral, Skin Sciences (MOSS-F), *ad hoc* grant reviewer
2007-2012 NIH Sensorimotor Integration (SMI) Study Section, *regular member*
2008 Natural Sciences & Engineering Research Council (NSERC) of Canada, *ad hoc* reviewer
2009-2012 National Science Foundation NSF, *Electronic Grant Review*
2011 Atlanta Clinical and Translational Science Institute (ACTSI), *Grant Reviewer*
2013-2020 Neural Control of Movement Society, *Board of Directors*.
2015 Training in Grantsmanship for Rehabilitation Research (TIGRR), *mentor.*
2014 NIH Musculoskeletal and Rehabilitation Sciences (MRS) Study Section, *ad hoc reviewer*
2017-2021 NIH Motor Function, Speech, and Rehabilitation (MFSR) Study Section, *regular member*

Selected Honors

1999-2002 Life Science Research Foundation Postdoctoral Fellowship
2004 Teaching Excellence Award, Biomedical Engineering Department, Georgia Tech and Emory
2006 Junior Faculty Teaching Award, Georgia Institute of Technology
2007 Arthur C. Guyton Award for Excellence in Integrative Physiology, American Physiological Soc.
2007 Above and Beyond Award, Biomedical Engineering Society, Georgia Tech Chapter
2008 Miller Visiting Professorship for Basic Research in Science, University of California, Berkeley
2016 Fellow, American Institute of Biological and Medical Engineers
2018 Visiting Scholar, Simons Institute Brain and Computation Program, UC Berkeley
2018 Visiting Scholar in Biomedical Engineering, Northwestern University
2018 Health Care Hero Award, Allied Health Professional Category, Atlanta Business Chronicle
2018 Mentoring Award, Emory University School of Medicine

C. Contribution to Science

1. Modular organization of motor control across motor skill, deficits, learning, and rehabilitation

My lab has played a major role in establishing key evidence for the modular organization of spatial muscle activity for movement. A unique contribution of my lab was demonstrating that motor modules, aka muscle synergies, produce the necessary biomechanical functions for movement. Further we showed that motor modules are specific to each individual, and robustly used across different motor tasks, such that they can be important markers of motor coordination that change with disease, rehabilitation, and other interventions. This work has provided the physical therapy and neurology research community with new tools for functional interpretation of previously unintelligible streams of electromyography data during movement. Our work on motor modules is highlighted in *Principles of Neural Science,* the definitive neuroscience text led by Eric Kandel, a leading physical therapy textbook *Motor Control: Translating Research into Practice*; and in a new textbook entitled *The Neurobiology of Motor Control: Fundamental Concepts and New Directions*.

a. **Ting L.H.***, Macpherson J.M. (2005) A limited set of muscle synergies for force control during a postural task. *Journal of Neurophysiology* 93:609-613.

b. Clark, D.J., **Ting, L.H.,** Neptune, R.R., Zajac, F.E., Kautz, S.A. (2010) Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. *Journal of Neurophysiology,* 103(2):844-57. PMCID: PMC2822696
c. **Ting, L.H**., Chiel, H.J., Trumbower, R.D., *Allen, J.L*., McKay, J.L., Hackney, M.E. Kesar, T.M. (2015) Neuromechanical principles underlying movement modularity and their implications for rehabilitation. *Neuron*, 86:38-54. PMCID: PMC4392340.
d. *Sawers, A., Allen, J. L.*,**Ting, L.H.*** (2015). Long-term training modifies the modular structure and organization of walking balance control. *Journal of Neurophysiology 114*(6), 3359-3373. doi:10.1152/jn.00758.2015. PMID: 26467521. PMCID: PMC4868379.

2. Sensorimotor feedback for normal and impaired balance
We have an equally important line of research characterizing how muscles are recruited over time to generate functional movements. We showed that task-level goals, such as moving the body center of mass (CoM). specifies the temporal features of muscle activity for reactive balance in normal and impaired animals and humans. Using just 3 sensory channels, we can predict individual differences in muscle timing, as well as changes occurring in sensory neuropathy, and in Parkinson's disease. Our work has influenced research in normal and impaired human movement, as well as in the simulation of human movement, the control of robots, and theory regarding the role of delayed acceleration and force feedback in the controlling delayed systems.

a. *Lockhart, D.B.*, **Ting L.H.*** (2007) Optimal feedback transformations for balance. *Nature Neuroscience* 10(10):1329-1336*,* doi:10.1038/nn1986.
b. *Welch, T.D.J.*, **Ting, L.H.*** (2008) A feedback model predicts muscle activity during human postural responses to support surface translations. *Journal of Neurophysiology* 99:1032-1038.
c. *Safavynia, S.A.,* **Ting, L.H.*** (2013) Sensorimotor feedback based on task-relevant error robustly predicts temporal recruitment and multidirectional tuning of muscle synergies. *Journal of Neurophysiology,* 109: 31–45. PMCID: PMC3545166.
d. *Welch, T.D.J.*, **Ting, L.H.*** (2014) Mechanisms of motor adaptation in reactive balance control. *PLoS ONE* 9(5):e96440. doi: 10.1371/journal.pone.0096440*.* PMID: 24810991. PMCID: PMC4014487.

3. Neuromechanical modeling for understanding brain-body interactions for movement
Another unique strength in my lab is the use of musculoskeletal models to understand strategies for the neural control of movement. In contrast to most biomechanical simulations in which measured movements are recapitulated in simulation, our novel approach has been to use musculoskeletal models to explore the entire space of possible control strategies and motor outputs to understand the challenge that the nervous system faces in learning to move. Our work takes inspiration from neural simulations showing that vast redundancy leads to individual differences in controlling in how we move. Our work has challenged the notion that we move using optimal solutions, showing instead that we are likely "sloptimal" or just good enough. We have played an influential role in recent advances in musculoskeletal modeling showing that neural constraints such as motor modules are critical for producing faster and more realistic simulations of human movement that better predict how patients with orthopedic or neurological deficits walk.

a. *McKay, J.L.*, **Ting, L.H.*** (2008) Functional muscle synergies constrain force production during postural tasks. *Journal of Biomechanics* 41(2):299-306. PMCID: PMC4350792.
b. *Bingham, J.T., Choi, J.T***., Ting, L.H.*** (2011) Stability in a frontal plane model of balance requires coupled changes to postural configuration and neural feedback control, *Journal of Neurophysiology,* 106(1):437-48. PMCID: PMC3129728
c. **Ting, L.H.***, *Chvatal, S.A., Safavynia, S.A., McKay, J.L.* (2012) Neuromechanical considerations for predicting muscle activation patterns for movement. *International Journal of Numerical Methods in Biomedical Engineering,* Oct 28(10):1003-14*.* PMCID: PMC4121429.
d. *Simpson, C.S., Sohn, M.H., Allen, J.L*., **Ting, L.H.*** (2015) Feasible muscle activation ranges based on inverse dynamics analyses of human walking*. Journal of Biomechanics* 48(12):2990-7. doi: 10.1016/j.jbiomech.2015.07.037. PMID: 26300401. PMCID: PMC4592831.

4. Human-human interaction for understanding human-robot interaction
This work emerged from an Emerging Frontiers in Research Innovation grant from the NSF in the area of Mind, Machine, Motor Control (M3C). Our vision and research in this project played a central role in the

establishment of a new program under the NSF CMMI division called Mind, Machine, Motor Nexus (M3X), and we were awarded the first research grant from this program. I am also Co-PI of an NSF NRT training grant in the area of human-centered robotics that fits well within this theme. The key idea is that understanding physical human-human interactions, such as between patients and physical therapists, is critical to the design and development of effective assistive and/or rehabilitative robots that can be used intuitively by people. When we began, there were fewer than a twenty papers in the area of human-human physical interactions, which is now a burgeoning area of research. Specifically, we use physical interactions in partnered rehabilitative dance as a basis for understanding therapeutic and intuitive physical interactions for motor assistance and rehabilitation.

a. *Sawers, A.,* **Ting, L.H.*** (2014) Perspectives on human-human sensorimotor interactions for the design of rehabilitation robots. *Journal of Neuroengineering and Rehabilitation* 11:142. doi: 10.1186/1743-0003-11-142. PMCID: PMC4197261.
b. Chen, T.L., Bhattacharjee, T*., McKay, J.L.,* Borinski, J.E., Hackney, M.E., **Ting, L.H.,*** Kemp, C.C. (2015) Evaluation by Expert Dancers of a Robot That Performs Partnered Stepping via Haptic Interaction*. PLoS ONE* 10(5):e0125179. doi: 10.1371/journal.pone.0125179. PMCID: PMC4438977.
c. *Sawers, A.,* Bhattacharjee, T*., McKay, J.L.,* Hackney, M.E., Kemp, C.C., **Ting, L.H.*** (2017) Small forces that differ with prior motor experience can communicate movement goals during human-human physical interaction. *Journal of Neural Engineering and Rehabilitation* 14(1):8. doi: 10.1186/s12984-017-0217-2. PMCID: PMC5282658.
d. *Song, Y.S.*, Ha, S., Hsu, H., **Ting, L.H.,** Liu, C.K. (2017) Stair negotiation made easier using novel interactive energy-recycling assistive stairs. *PLoS ONE* 12(7):e0179637. doi: 10.1371/journal.pone.0179637. PMID: 28700719. PMCID: PMC5507489.

4. Multiscale modeling of muscle spindle proprioceptive function for understanding sensorimotor control
A new direction in my lab, motivated by our human balance research, concerns the development of a multiscale model muscle spindle sensory afferents, which provide essential signals for balance, reflexes, and proprioception. Our work shows that muscle spindle uniquely follow muscle fiber force and its time derivative (dF/dt, or yank), resolving many paradoxes and nonlinearities seen classically when muscle spindles are considered length and velocity encoders. We have developed a model incorporating molecular dynamics of muscle cross-bridge interactions, biophysical dynamics of neurons, and biomechanical properties of the muscle to allow for predictive simulations of movement in health and disease. Our work is directed at providing a framework for understanding how concurrent changes in muscle properties, neural dynamics, and neural circuits cause motor dysfunction and can potentially treated through multiple avenues.

Recent abstracts include:

- Horslen B.C., Campbell K.S. , Blum K.P., Cope T.C., Nardelli P., **Ting L.H.** Movement shapes sensory feedback: movement-history-dependent changes in muscle spindle encoding and muscle fiber stiffness. Neural Control of Movement Annual Conference, Santa Fe NM, May 1-4, 2018. Poster # 2-B-10.
- Blum, K.P., Nardelli, P., Cope, T.C., **Ting, L.H.**, 2017. Estimated muscle fiber forces predict history-dependent muscle spindle spike rates. Neural Control of Movement Society Annual Meeting. Dublin, Ireland, May 1-5, 2017.

a. *Blum, K.P.,* Lamotte D'Incamps, B.L., Zytnicki, D., **Ting, L.H.***(2017) Force encoding in muscle spindlesduring stretch of passive muscle.. *PLoS Computational Biology* 13(9):e1005767. doi: 10.1371/journal.pcbi.1005767. PMCID: PMC5634630.
b. De Groote, F., *Blum, K.P.*, *Horslen, B.C.,* **Ting, L.H.** Interaction between muscle tone, short-range stiffness and increased sensory feedback gains explains key kinematic features of the pendulum test in spastic cerebral palsy: A simulation study. *In review.*

Complete List of Published Work in MyBibliography:
http://www.ncbi.nlm.nih.gov/sites/myncbi/lena.ting.1/bibliography/40561351/public/?sort=date&direction=ascending

D. Research Support

Ongoing Research Support

NSF DGE 1545287 Howard (PI) 9/15 – 8/20
Accessibility, Rehabilitation and Movement Science (ARMS): An Interdisciplinary Traineeship Program in Human-Centered Robotics
To train robotic students in human-robot collaborations for motor assistance and rehabilitation.
Role: Co-PI, 5% to provide educational experiences in clinical research

NIH R01 NR016151 Shen (Lead PI) 9/15-8/18
NRI: Collaborative Research: Quadrupedal Human-Assistive Robotic Platform (Q-HARP)
Our role is to measure interaction forces between caregivers frail older adults during assisted walking in order to provide design target for an assistive robot.
Role: Collaborating PI, 5% (0.6 month)

NIH R01 HD90642 Ting (PI) 9/16/16-5/31/21
Collaborative Research: Multi-scale models of muscle spindles for understanding sensorimotor control
To develop a model based on muscle cross-bridge, musculotendon, and neuron biophysics to accounts for behaviorally-relevant history-dependent sensory encoding of muscle spindle proprioceptive afferents.

Udall Pilot Grant 1P50NS098685 Ting (PI) 5/1/2017-9/30/2018
Common neurophysiological markers underlying cognitive and balance deficits in Parkinson's disease
To test whether cortical evoked potentials during cognitive and balance tasks are reduced in individuals with PD who have balance deficits.

NIH R01 HD46922-6 Ting (PI) 4/01/04-5/31/16
Neuromechanical Modeling of Postural Responses: Mechanisms of balance impairment in Parkinson's disease
To use a combination of experiments and neuromechanical modeling to identify the role of rigidity on balance impairments in individual with Parkinson's disease.

NSF CMMI 1762211 Ting/Essa (MPI) 6/1/18-5/31/21
Collaborative Research: Enhanced gait dynamics via physical human-human and human-robot interactions at the hands To model human gait dynamics during partnered stepping using unsupervised machine learning methods, and to apply the gait model to control a robotic handle that will alter the user's gait dynamics.

<u>Completed Research Support</u>
NIH R01 HD46922-6 Ting (PI) 4/01/04-5/31/16
Neuromechanical Modeling of Postural Responses
To develop computational models and analyses of musculoskeletal coordination for balance in normal and neurologically impaired animals.

NIH R21 HD075612 Ting (PI) 8/1/13-5/31/15 (NCE to 5/31/17)
Mechanisms of improvement in neurorehabilitation of Parkinson's Disease
To investigate whether improvements in balance following adapted tango rehabilitation are mediated by basal ganglia versus cerebellar plasticity.

NSF/EFRI 1137229 Ting (PI) 9/1/11-8/31/15 (NCE to 8/31/17)
Partnered Rehabilitative Movement: Cooperative human-robot interactions for motor assistance, learning, and communication. To develop novel models and sensory-motor theory to forge new paths toward robots with physical intelligence to enhance, assist, and improve motor skills in humans with varying motor capabilities.

NCSRR Pilot Project Fregly (PI) 1/1/2017-12/31/2017
Computational Design of FastFES Rehabilitation to Improve Post-Stroke Gait
Role: Co-I for collection and analysis of data

GT/GSU Center for Advanced Brain Imaging Ting (PI) 7/1/2016-6/31/2017
Neuroimaging to predict gait rehabilitation outcomes post-stroke
To identify whether brain structure and resting state connectivity predict responders and nonresponders to gait rehabilitation.