RESEARCH STATEMENT – GREGORY S. SAWICKI

I am interested in the neuromechanics and energetics of locomotion systems that have interacting biological and artificial components (*e.g.*, skeletal muscles in parallel with electric motors). In recent years, rapid advances in state-of-the art engineering techniques have combined small, powerful actuators, embedded sensing and distributed feedback control -- giving rise to a new class of machines at the human-machine interface: *wearable robots.*

My research program focuses on a subset of wearable robots -- *lower-limb robotic exoskeletons*. These are machines that are worn on the legs in order to restore or augment human locomotion performance. To date, most lower-limb exoskeleton research has focused on the machine-side of the problem. Mechanical assistance from a lower-limb robotic exoskeleton could (1) aid patients recovering from neurological or musculoskeletal injury, (2) augment strength or (3) improve locomotor efficiency, but little is known about *how humans respond* to robotic assistance.

My research group places unique emphasis on understanding the *human-side* of the human machine interface. In the Physiology of Wearable Robotics Laboratory (PoWeR) (http://www.bme.ncsu.edu/labs/hpl) (**Fig. 1**) my trainees and I work at the intersection of the biological and engineering sciences to discover fundamental principles of locomotion physiology and then apply them back to the design of biologically-inspired exoskeletons that are capable of improving both healthy and impaired human locomotion (*e.g.*, for elite athletes, aging baby-boomers or post-stroke community ambulators). We use an integrative, multi-scale approach that combines concepts and techniques from many disciplines including: muscle physiology, mechatronic system design, controls engineering, movement science, neuroscience, biomedical imaging, mathematical modeling and simulation and rehabilitation medicine to characterize the physiological performance of the human user -- from whole-body down to individual muscles -- during locomotion with lower-limb robotic exoskeletons.

By focusing on the *human* side of the human-machine interface we have begun to create a roadmap for the design of lower-limb robotic exoskeletons that are truly symbiotic---that is, wearable devices that work seamlessly in concert with the underlying physiological systems to facilitate the emergence of augmented human locomotion performance.

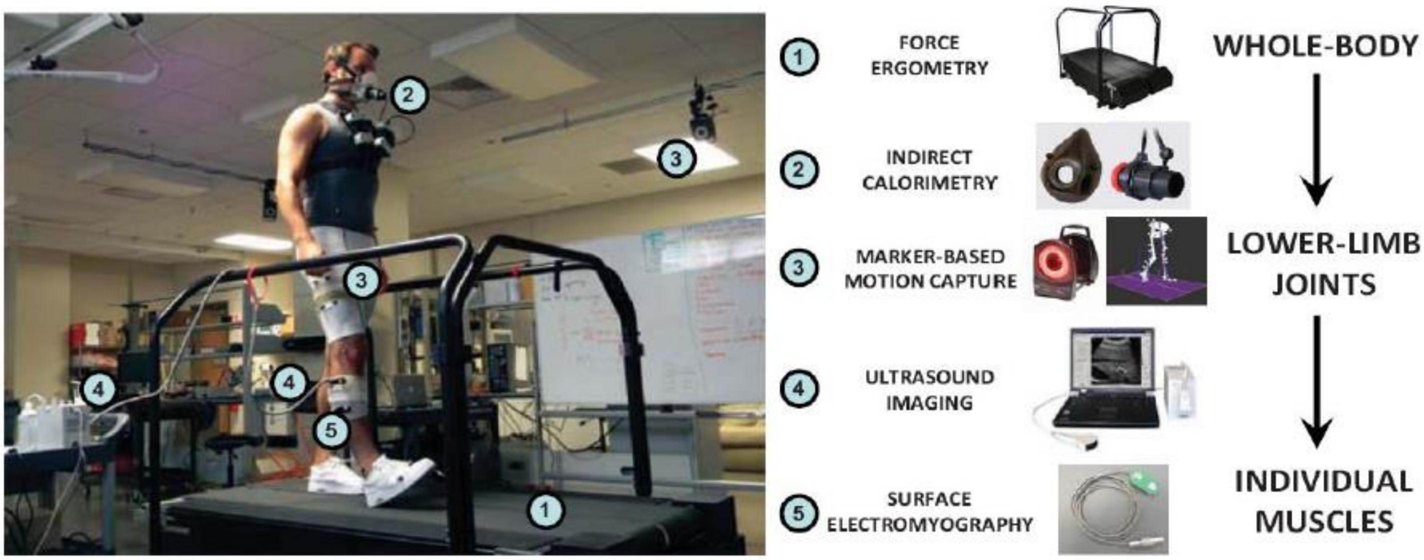


Figure 1. A multi-scale, integrative toolset to analyze human locomotion and establish a roadmap for biologically inspired lower-limb exoskeleton design. The Human Physiology of Wearable Robotics (PoWeR) Lab at NC State University is well-equipped to measure the biomechanics (force ergometry, marker-based motion capture, ultrasound imaging), metabolic energetics (indirect calorimetry) and neural control patterns (surface electromyography) from whole-body to individual muscles during locomotion. This battery of measurement techniques, primarily focused on the underpinnings of metabolic energy expenditure, forms the basis for determining optimal exoskeleton hardware and control for both healthy and impaired humans over a range of locomotion conditions (walk, run, uphill, downhill).

PREVIOUS RESEARCH CONTRIBUTIONS.

My early publications, based on my doctoral work at the University of Michigan focused on the development and testing of pneumatic lower-limb robotic exoskeletons to restore impaired (a) and augment healthy (b-d) human locomotion. I developed a family of lightweight, carbon-fiber lower-limb exoskeletons for the ankle, knee and hip (a-c). Initial studies focused on employing bilateral ankle exoskeletons controlled by therapist or user controlled push buttons to assist with body-weight supported treadmill training after spinal cord injury. I demonstrated that this was an effective way to restore walking without the labor intensive effort of a team of physical therapists (a).

The follow-up studies switched gears, and focused on using a novel controller based on the user's own muscle activity (*i.e.,* proportional myoelectric control) (b-d). Using this user-in-the-loop approach I embarked on a series of seminal studies to measure the neuromechanical and energetic response of humans to robotic ankle exoskeletons (b, d). These studies collectively demonstrated that humans have the potential to save up to 10% of the energy during walking using powered ankle exoskeletons and that the human ankle muscle-tendon complex is extremely efficient, making it a difficult site to apply mechanical assistance with large performance gains (d). My doctoral research kick started an active international effort to move exoskeletons out of science fiction and into reality and motivated me to pursue questions addressing the *muscle-level physiological response* of human users to lower-limb robotic assistance.

a. **Sawicki GS**, Domingo A, Ferris DP, "The effects of powered ankle-foot orthoses on joint kinematics and muscle activation during walking in individuals with incomplete spinal cord injury". *J Neuroengineering Rehabil.* 3:3 (2006).
b. **Sawicki GS**, Ferris DP, "Mechanics and energetics of level walking with powered ankle exoskeletons". *J Exp Biol.* 211:1402-1413 (2008).
c. **Sawicki GS**, Ferris DP, "A pneumatically powered knee-ankle-foot orthosis (KAFO) with myoelectric activation and inhibition". *J Neuroeng Rehabil*. 6(1):23 (2009).
d. **Sawicki GS**, Lewis CL, Ferris DP, "It pays to have a spring in your step". *Exerc Sport Sci Rev*. 37(3):130-8 (2009).

Following 1.5 years of intensive training under an NIH F32 postdoctoral fellowship in muscle-tendon physiology within the Morphology Group of the Department of Ecology and Evolutionary Biology at Brown University, we opened the doors of the Human Physiology of Wearable Robotics (PoWeR) Laboratory which I established at NC State (c. 2010) (**Fig. 1**). Inspired by my new appreciation for muscle-tendon interaction dynamics and elastic mechanisms in biological systems, my trainees and I embarked on a number of initial basic science studies to begin to integrate the understanding of neuromechanics and energetics of human locomotion across multiple scales from whole-body to lower-limb joints to individual muscles. Our goal was to establish a *roadmap for biologically inspired design* of lower limb exoskeletons. We used high speed motion capture and force ergometery to demonstrate that humans distribute the majority of the lower-limb mechanical output to the ankle extensor muscles, perhaps in order to maximize use of efficient, elastic muscle-tendon structures during preferred speed walking. As walking speed increases, workload shifts to the hip, until at the transition from walk to run, workload shifts back to the ankle (e). Following up at the muscle level, we used novel B-mode ultrasound imaging techniques to show that indeed, humans utilize Achilles' tendon series elasticity to decouple joint movements from muscle length changes, and can actually use slower contraction velocities in the walk-run transition, enabling more economical force production (f). These studies highlighted the importance of the 'spring-in-your step' and firmly established the calf muscles as the predominant site for elastic energy storage and return in human gait. In fact, we showed that the human ankle can be conceptualized as a rotational spring with stiffness that varies with overground speed (g) - a useful concept that we successfully applied back to lower-limb exoskeleton design (h) (**Fig. 2**).

e. Farris D, **Sawicki GS**, "The mechanics and energetics of human walking and running: a joint-level perspective". *J R Soc Interface*. Jan 7; 9(66): 110-8. Epub 2011 May 25. (2012).

f. Farris D, **Sawicki GS** "Human medial gastrocnemius force-velocity behavior shifts with locomotion speed and gait". *Proc Natl Acad of Sci USA.* Jan 17; 109(3):977-82. Epub Jan 4. (2012).
g. Shamaei K, **Sawicki GS**, Dollar A, "Estimation of quasi-stiffness and propulsive work of the human ankle in the stance phase of walking". *PLoS One.* 8(3): e59935. Epub Mar 21. (2013).
h. Collins SH, Wiggin MB, **Sawicki GS**, "Reducing the energy cost of human walking using an unpowered exoskeleton". *Nature.* Jun 11; 522(7555): 212-5. Epub Apr 1. (2015).

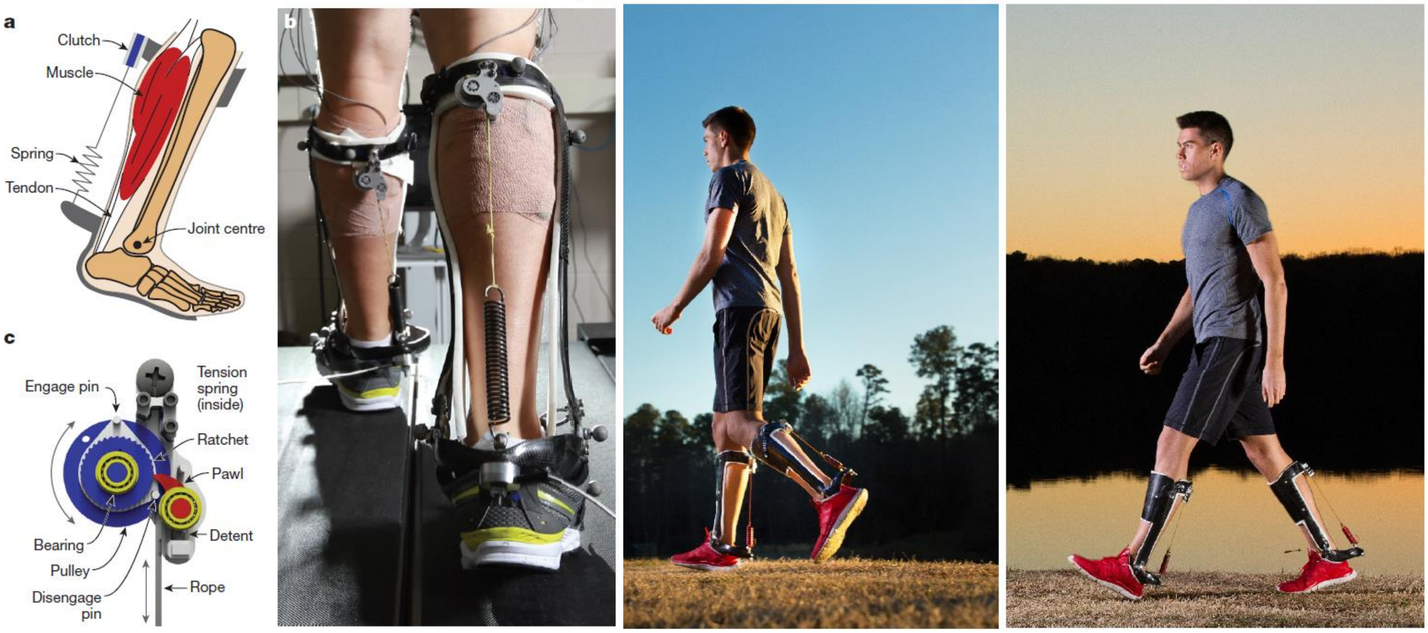


Figure 2. – Biologically-inspired passive-elastic wearable systems for augmenting locomotion performance. Inspired by our basic science experiments implicating elastic mechanisms within the human calf muscle as a primary source of locomotion efficiency we designed a device to provide 'a spring in your step' by storage and release of elastic energy in a parallel elastic element worn about the ankle (*i.e.*, an exo-tendon) enabled by a novel clutching mechanism. We recently demonstrated that this portable, unpowered elastic exoskeleton can reduce the metabolic cost of normal walking by ~7% below normal without adding any external energy from batteries or motors -- capitalizing on imperfections left over despite millions of years of evolution.

While building and testing our passive elastic exoskeleton prototypes (**Fig. 2**), we began to appreciate the importance of understanding how exoskeleton design impacts back on underlying neuromuscular function, and how parameters of assistive devices must be optimized in the context of the underlying physiological systems in order to fully maximize performance. To study this, we have used human hopping as a model system (i), and developed a class of novel musculoskeletal models of how ankle muscle-tendon dynamics are altered in the context of parallel mechanical assistance from an exoskeleton (k, l). These models can be compared with, and validated by, B-mode ultrasound images taken during robotically assisted locomotion with spring-loaded devices (j). We have shown that, while exoskeletons can reduce forces on underlying ankle muscles, they *do not* decrease mechanical work, and may actually *increase* injury risk (j-l). These somewhat counterintuitive findings highlight the importance of examining muscle dynamics during robotically assisted gait, and stress the importance of considering the dynamics of the combined human-machine system in wearable robot design.

i. Farris DJ, **Sawicki GS**, "Linking the mechanics and energetics of human hopping with passive-elastic ankle exoskeletons". *J Appl Physiol*. Dec 15; 113(12): 1862-72. Epub Oct 11. (2012).
j. Farris DJ, Robertson, BD, **Sawicki GS**, "Passive elastic exoskeletons reduce soleus muscle force but not work in human hopping". *J Appl Physiol*. Sep 1; 115(5): 579-85 Epub Jun 20. (2013).
k. Robertson BD, Farris DJ, **Sawicki GS**, "More is not always better: Modeling the effects of elastic exoskeleton compliance on underlying ankle muscle-tendon mechanics". *Bioinspir. Biomim*. Nov 24; 9(4): 046018. (2014).

l. Farris DJ, Hicks J, Delp S, **Sawicki GS**, “Musculoskeletal modelling deconstructs the paradoxical effects of elastic ankle exoskeletons on plantar-flexor mechanics and energetics during hopping”. *J Exp Biol*. Nov 15; 217(Pt 22) 4018-28. (2014).

In addition to the basic and applied scientific contributions described above, we have also extended our framework to address clinical problems, with a keen focus on understanding and improving gait impairments post-stroke. Our initial studies demonstrate that mechanical asymmetry in lower-limb mechanical power production is a key factor leading to increased energy cost and decreased mobility post-stroke (m-o). We are now in the midst of a NIH funded (R01 via National Robotics Initiative and R21) multi-year effort to understand impairments in individual muscle function during post-stroke walking, using B-mode ultrasound and then develop lower-limb ankle exoskeleton technology to apply optimal unilateral robotic assistance in order to improve post-stroke walking mechanics and energetics (p).

m. Wutzke C, **Sawicki GS**, Lewek M, “The influence of a unilateral fixed ankle on metabolic and mechanical demands during walking in unimpaired young adults”. *J Biomech.* Sept 21; 45(14): 2405-10. Epub Jul 26. (2012).
n. Mahon C, Farris DJ, **Sawicki GS**, Lewek M, “Individual limb mechanical analysis of gait following stroke”. *J Biomech*. Apr 12; 48(6): 984-9. (2015).
o. Farris DJ, Hampton AS, Lewek MD, **Sawicki GS**, "Revisiting the mechanics and energetics of walking in individuals with chronic hemiparesis following stroke: From individual limbs to lower-limb joints". *J Neuroeng Rehabil.* Feb 27; 12(1): 24 (2015).
p. Takahashi KZ, Lewek MD, **Sawicki GS**, "A neuromechanics-based powered ankle exoskeleton to assist walking post-stroke: A feasibility study". *J Neuroeng Rehabil*. Feb 25;12:23 (2015).

CURRENT RESEARCH FOCI AND ANTICIPATED FUTURE DIRECTIONS:

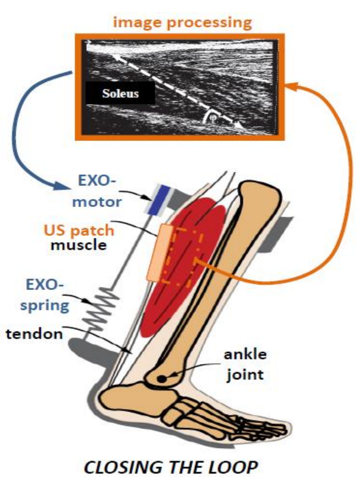
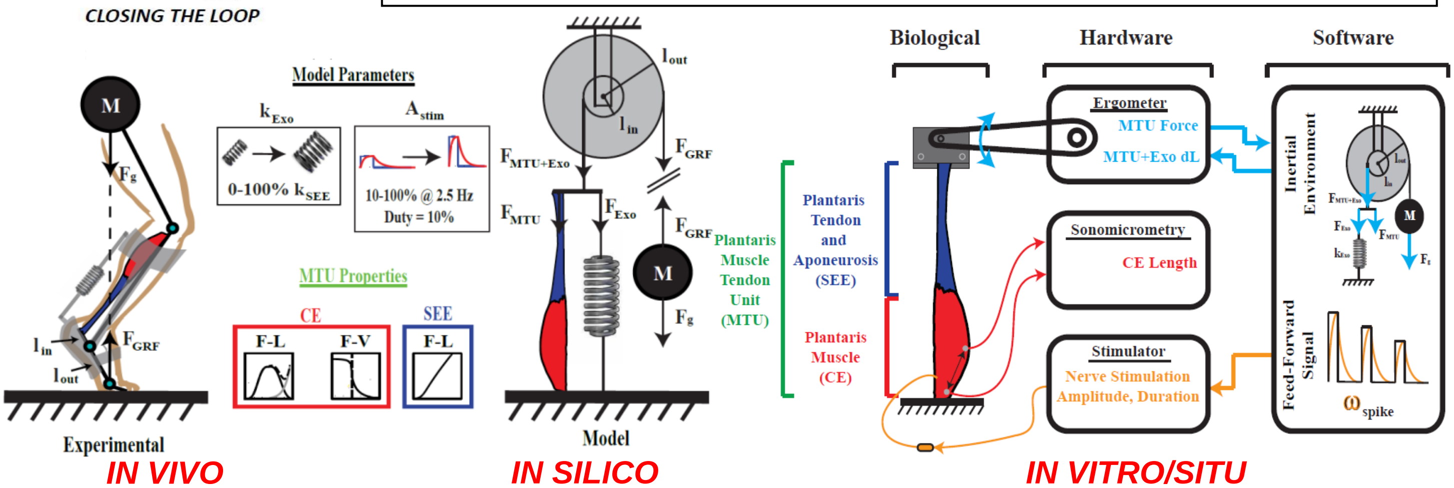


Figure 3. - Fundamental neuromechanics and energetics of human-machine interaction. We are interested in moving toward lower-limb exoskeletons that are truly symbiotic---that is, wearable devices that work seamlessly in concert with the underlying physiological systems to facilitate the emergence of augmented locomotion performance. To do this we will continue employing a parallel structure in our approach that involves (1) *in vivo* measurements of muscle dynamics during locomotion with exoskeletal devices to understand how artificial device parameters interact with the underlying physiological structures to create novel combined system dynamics (left, top and bottom) (2) *in silico* models that can be used to simulate, optimize and predict human-machine system performance offline (middle, bottom) and (3) *in vitro* and *in situ* animal preparations that allow for direct observation of muscle contraction and reflex signaling during dynamic interaction with virtual loads and devices programmed into a ‘smart ergometer’ interface (right, bottom). A longer term goal is to realize devices that can close the loop between biological and artificial by communicating across the human-machine interface both mechanically (left, top) and electrically.



Current projects in the lab fall into *three* parallel and interconnected research lines.

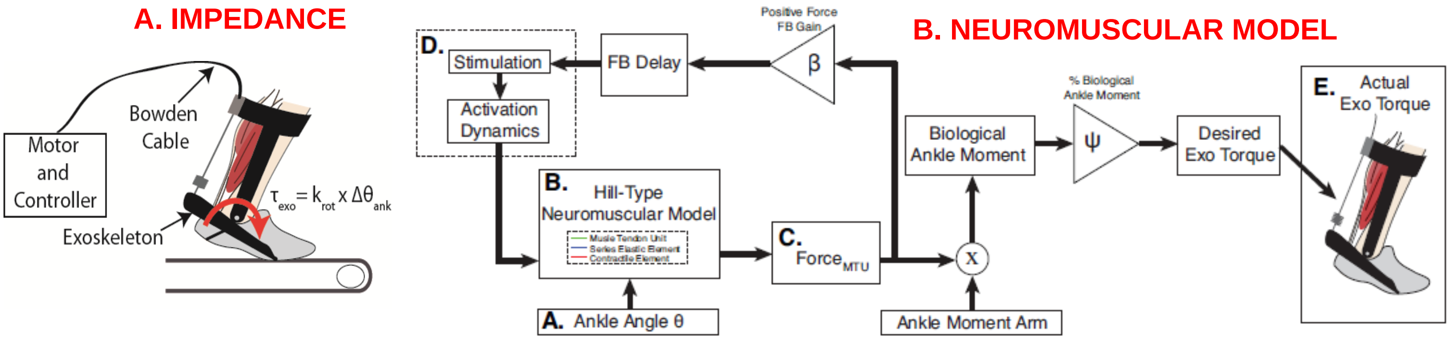
I. Fundamental Neuromechanics and Energetics of Human-Machine Interaction. It is becoming more and more apparent that the success of lower-limb wearable robotics (*e.g.,* exoskeletons and prostheses alike) will depend on a more formal understanding of the interaction between biological and artificial components to generate efficient and robust locomotion. This entails establishing a novel framework that can address the neuromechanical exchange of energy and information across the human-machine interface and be used to generate a set of fundamental principles that outline the performance of these hybrid systems. We are actively working to build and employ a comprehensive toolset that includes *in vivo, in silico* and *in vitro/in situ* approaches that all aim to develop a 'bottom-up' approach to generating successful symbiotic wearable robots (**Fig. 3**). Recently, in collaboration with neurophysiologist Tim Cope in Applied Physiology at Georgia Tech, we have extended our recent *in vitro* work using frog muscle-tendon to 'build locomotion up' on the benchtop (q, r) to an *in situ* preparation in the rat that enables simultaneous recordings from afferent nerves -- opening the door to examining how biological reflex pathways can be integrated with wearable robot hardware and software.

q. Sawicki GS, Robertson BD, Azizi E, Roberts TJ, "Timing matters: Tuning the mechanics of a muscle-tendon unit by adjusting stimulation phase during cyclic contractions". *J Exp Biol*. Oct; 218(Pt 19): 3150-9. Epub Jul 31. (2015).
r. Robertson BD, Sawicki GS, "Unconstrained muscle-tendon workloops indicate resonance tuning as a mechanism for elastic limb behavior during terrestrial locomotion". *Proc Natl Acad Sci USA.* Oct 27; 112(43): E5891-8. (2015).

II. Biologically-inspired Passive Elastic-Mechanisms – Exploiting Structure to Improve Function. The recent success of our unpowered elastic ankle exoskeleton (**Fig. 2**) has motivated us to challenge the notion that net energy transfer from a device to a person is necessary for restoring or augmenting locomotion performance. For example, based on the concepts of power amplification (s, t) and power attenuation via energy transfers through series elastic tissues in biological muscle-tendon systems, we have begun to work on passive devices that can improve performance of unsteady locomotion during tasks like jumping, accelerating, decelerating and rejecting perturbations. In addition, we are pursuing ideas for improving locomotion performance by altering the structural properties of the human foot-ground contact using optimized foot-shoe interfaces to change the time course of energy exchange between muscles and the environment (u). More generally, we are interested in exploring ways to alter the mechanics of the local environment via optimally designed, unpowered wearable structures in order to improve skeletal muscle performance.

s. Sawicki GS, Sheppard P, Roberts TJ, "Power amplification in an isolated muscle-tendon unit is load dependent". *J Exp Biol*. Nov; 218(Pt22):3700-9. (2015).
t. Rosario MV, Sutton GP, Patek SN, Sawicki GS**,** (In Review) "Muscle-spring dynamics in time-limited, elastic movements". *Proceedings of the Royal Society B: Biological Sciences.* (2016).
u. Takahashi KZ, Gross M, van Werkhoven H, Piazza S, Sawicki GS**,** (In Review) "Adding stiffness to the foot modulates soleus force-velocity behaviour during human walking ". *Nature Scientific Reports.* (2016).

III. Physiologically-based Exoskeleton Control Systems. While passive, unpowered lower-limb exoskeleton solutions may be more elegant, cost effective and energy efficient; they are not adaptable – potentially limiting their performance in the context of a changing user, task or environment. Thus, we envision devices that have the capability to superimpose controlled actuation on top of an optimized unpowered, passive structure at the core. We have developed an exoskeleton simulator with colleagues at Carnegie Mellon University that is versatile enough to apply torque to any of the lower limb joints with any specified pattern (**Fig. 4**). This powerful laboratory-based diagnostic tool facilities a systematic approach to exploring exoskeleton control. Historically, control of exoskeletons has involved high gain position control of joint kinematics – a playback method to match normal human motions. We are beginning to examine other control approaches, designed to



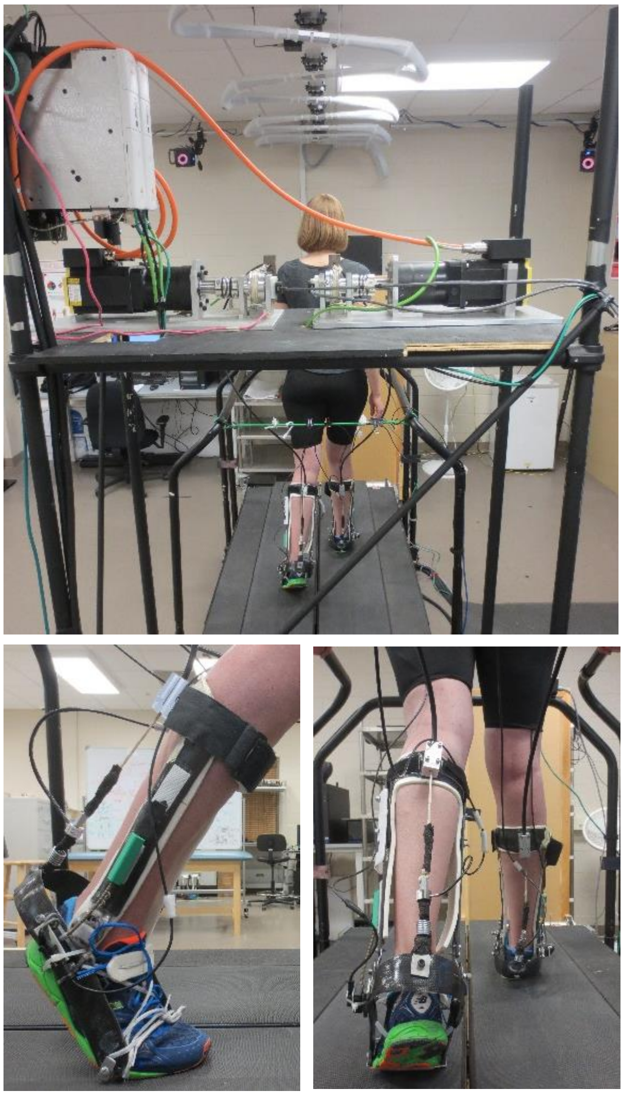
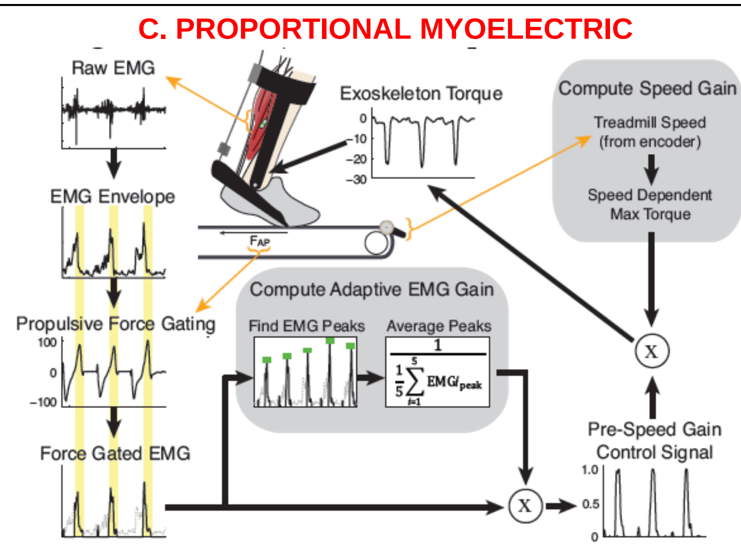


Figure 4. – Systematic design and evaluation of physiologically-based lower-limb wearable robot controllers. To streamline the design and evaluation of lower-limb wearable robot control schemes, we built a laboratory based, bilateral ankle exoskeleton simulator system that is lightweight and can produce high torque and power with high bandwidth closed-loop control (bottom, left). Actuation and control are sourced off-board using a pair motors tethered via Bowden cable transmission to a pair of lightweight (~1.5 kg) carbon fiber end-effectors worn about the user's ankle. We are studying A. impedance (*i.e.*, enforced stiffness/damping), B. neuromuscular model (*i.e.*, predicting user's muscle force/torque output) and C. proportional myoelectric (*i.e.*, mapping user's muscle activity) based controllers. This lab-based system is integrated with instrumented treadmill and motion capture systems so we can measure center of mass and joint mechanics, joint kinematics, muscle activity (EMG) and length changes (B-mode ultrasound) and whole-body oxygen consumption during walking and running across speeds and surface gradients.



capture salient features of physiological control systems observed during normal human gait. We are currently evaluating and comparing performance of three promising control schemes on both healthy and impaired (*i.e.*, post-stroke) humans: (A) impedance, (B) neuromuscular model and (C) proportional myoelectric control (**Fig. 4**). Future projects will use the simulator to address the whole-limb (*i.e.*, ankle, hip, knee, foot) during a myriad of locomotion tasks (*i.e.*, walking/running/hopping; up/downhill; with load; rough/viscous terrain).

Recently, in collaboration with Christian Hubicki and Aaron Ames in Mechanical Engineering at Georgia Tech, we have begun to formulate 'off-line' an optimal control approach designed to find novel combinations of exoskeleton actuation and human movement strategies to maximize performance of the combined human-machine system. Along these lines, we anticipate future research projects that will move our optimal control approach 'on-line' and combine it with visual or tactile biofeedfack (*e.g.*, via Occulus Rift) to direct the user's movements toward patterns that benefit maximally from designed exoskeleton torque patterns.