Richard W. Nuckols - Research Statement

I am interested in the design and evaluation of technology for diagnosing, assisting, and rehabilitating functional human movement. In recent years, technology and state-of-the-art engineering techniques have driven the success of wearable robotic devices (exoskeletons/exosuits) in demonstrating the ability to augment or improve human movement. However, technology is only a part of the whole system. For wearable robotics to provide discernable value in 'real-world' environments, they must coordinate with the user. My research focuses on three related critical areas: 1) Development and implementation of new wearable sensing and assistive technologies, 2) fundamental and applied neuromechanics of human movement and human-robot interaction, and 3) implementation of wearable technologies and assistive devices in salient environments and tasks. My goal for this work is to translate technology into meaningful real-world use.

Development of effective human-robot systems requires a holistic approach involving a broad range of disciplines and areas of expertise. Therefore, it is valuable to describe my planned work first in terms of the individual research lab and later describe where this work will be incorporated within the larger community. My research will focus on the human-robot system where an understanding of the interaction between components is equally as important as understanding the individual parts. My unique background in mechanical engineering and robotics with expertise in neuromuscular physiology will enable my research lab to work in this space capturing both robotics and the human. My intended research program will use scientific and biomechanical principles and a human-in-the-loop cyclical engineering approach, "Understand-Build-Evaluate," as the foundation (Fig. 1). This process requires that we (1) *Understand*: Perform scientific studies and develop new tools to understand the mechanisms of human movement. I am uniquely positioned to bring new and innovative perspectives towards understanding and evaluating human response to wearable robotics as exemplified through my approach and experience with using new sensing tools such as ultrasound and tensiometry. (2) *Build*: Leverage our understanding to inform and build next-gen sensing, assistive, and rehabilitative technologies. I have developed new hardware and control designs for both healthy and clinical populations and will use these successes to guide the development of new systems. (3) *Evaluate:* Perform controlled and open-ended experiments with devices towards improving understanding of human mechanisms and human-robot interaction which leads to the next iteration of designs. While controlled lab experiments are important, I have and will continue to push for evaluation of technologies in salient environments such as clinical therapy and, in doing so, aim to solve real problems.

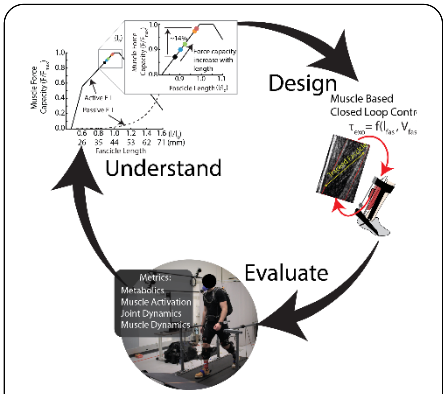

Figure 1: Scientific and engineering development cycle

My research will foster collaborations through which my lab will provide and draw from resources within the academic, medical, and industrial communities. Collaborations with research groups in engineering (new sensors, actuators, robotics, computer science), biomechanics (neuromuscular modeling, comparative physiology), and clinical disciplines (Physicians, Occupational and Physical Therapists) will be particularly important for my research activities. These collaborations will be aimed at increasing depth and diversity of the academic knowledge base and, importantly, the diversity of the people involved will help promote different perspectives, motivations, and ideas.

Previous and Current Research:

Exoskeleton Hardware and Control Development: I developed the hardware, high and low-level control [1] for impedance and neuromuscular based ankle exoskeletons used for heathy adults [2,3,4]. I also developed this for a speed adaptive proportional EMG control used in individuals' post-stroke [5]. I contributed to projects developing soft exosuit hardware and controls for targeting ankle, knee, and hip in healthy and clinical populations [6,7,8,9]. I am leading projects developing the hardware and controls for wearable robotics devices that can extend the capabilities outside the research lab and bridge the research gap between the lab, clinic, and community [8,10].

Muscle-tendon neuromechanics of human-robot interaction by using new sensing tools: This research focused on approaches for evaluating and understanding muscle-tendon mechanics during movement and application towards improving wearable robotic assistance. This understanding is crucial as the muscle is what uses energy and generates the force, yet directly measuring muscle dynamics is difficult. While previous work had provided insights into how exoskeletons affect whole body and individual joint biomechanics, my work specifically targeted gaining a better understanding of muscle dynamics [2,11,12]. No prior study had directly measured how exoskeletons affected muscle fascicle dynamics during exo-assisted walking. I used ultrasound imaging to visualize and measure the kinematics of the plantarflexor muscles of subjects walking with multiple levels of exoskeleton assistance (Fig. 2). I showed that assistance can alter muscle contraction dynamics, impact the muscle's ability to generate force, and thus ultimately affects the user's response. These findings are important as they help explain why and how individuals respond to exoskeleton assistance. This approach can be applied towards improving models of human-robot interaction, improving neuromuscular based controls, or aiding in understanding the deficits and changes occurring during intervention with clinical populations.

Muscle-tendon dynamics is an important biomechanical metric, yet the measurement continues to be challenging. To address this, I developed a computer-vision approach for estimating muscle dynamics at real-time rates from ultrasound images of the muscle. I showed that we can measure changes in muscle dynamics related to the individual and environmental demand which can inform assistive strategies (13,14).

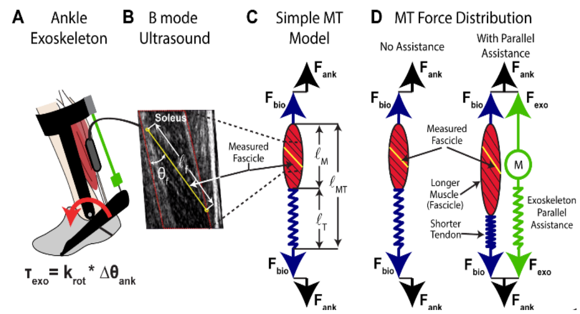

Figure 2: B-mode ultrasound imaging enable evaluation of the effect of exoskeleton assistance on muscle dynamics

I am at the forefront of developing and implementing new technologies to help answer previously unanswerable questions as exemplified by my work with ultrasound imaging to evaluate exo-assisted walking, development of image processing techniques, and use of ultrasound in developing assistive strategies. Another example of where I have looked for new tools is in the recent grant that I took the lead in writing: **NSF DARE #2019580:** "Quantifying Reductions in Musculoskeletal Loading due to Soft Exosuit Assistance using Shear Wave Tensiometry" (Conor Walsh, PI) in collaboration with Dr. Darryl Thelen (Wisconsin). The incorporation of muscle neuromechanics into research will be important for understanding healthy and clinical biomechanics and for the tailoring of assistance.

Individualized and adaptive wearable robotics for real-world application: I am interested in developing wearable devices that work in real-world environments and adapt with the user to their specific task. An effective starting point is an understanding of an individual's biomechanics in these variable tasks and environments. I conducted a biomechanics study to inform exoskeleton design requirements for incline walking and running [15]. I showed, for example, how during incline walking and running, joint power shifts between the ankle and hip. These analyses were organized into a framework for how wearable devices could interact with the person in changing environmental demands. I have also used this approach to provide perspective on state-of-the-art exoskeleton articles [16].

Surprisingly, few studies have investigated the efficacy of exo assistance across multiple walking tasks. I investigated how walking speed impacts the effectiveness of passive elastic ankle exoskeletons and showed that passive devices were effective at providing metabolic benefit at multiple speeds [3]. Furthermore, by investigating several walking speeds and assistance levels, we were able to demonstrate broader generality of biomechanical outcomes as predictors of effective exo use. While certain biomechanical metrics, such as delivered exo power, show good predictive strength at a single walking task, their predictive ability fails when generalized across speed. Rather, I showed that a general strategy of minimizing muscle activation of the assisted muscle, while limiting co-contraction of opposing muscles leads to the best whole-body energetic improvement across speeds [3].

Building off my prior work in muscle neuromechanics, I have more recently focused on leveraging muscle-tendon dynamics to design individualized and adaptive assistance profiles. I developed a muscle-based assistance (MBA) strategy wherein exosuit assistance was derived from direct measurements of individuals' muscle dynamics during specific walking tasks. Using this MBA approach, we were able to rapidly develop exosuit assistance profiles that were unique to the person and tasks and that produced field-leading metabolic benefit across these tasks. Furthermore, this work demonstrated the feasibility of online profile generation in a mobile exosuit for overground outdoor walking and highlights the potential for real-world use (14). Press Release

Improving clinical gait with wearable robotics: I am particularly interested in applications that make direct meaningful impact to users and society. Wearable technologies have the potential to enable better diagnostics, enhanced rehabilitation, and improved functional movement for individuals with gait deficits.

Human gait after stroke is heterogeneous, and we find that rehabilitation techniques and assistance strategies that are effective for one individual and situation are not necessarily effective in another. Basing our strategy on fundamental and clinical biomechanics, I contributed to developing a hip flexion exosuit for assisting gait in individuals post-stroke [6]. Using this system, I've investigated how assistance can be individualized such that it targets the needs of stroke survivors during overground gait in the lab [8].

While testing can be done in controlled lab environments, I am interested in getting systems outside of the lab and into the clinic and community as a way to better understand user needs and real-world device effectiveness. Using the mobile hip flexion system we developed, I am investigating how mobile hip flexion assistance can improve clinical therapy with outpatient and inpatient stroke survivors and their therapists at Shirley Ryan Ability Labs and Spaulding Rehab Hospital [10] (Fig 3).

Figure 3: Hip flexion "enhanced research" exosuit for evaluating how exosuit assistance can improve rehab.

Stroke recovery doesn't need to end when individuals complete clinical therapy. Wearable technologies provide the opportunity for continuation of therapy at home and the community. To investigate this, I am also leading a community study in which we provide an ankle exosuit to individuals post-stroke for a one-month independent home-use trial. While this study is still ongoing, it is providing a wealth of data on how individuals can independently use systems to improve gait mechanics and incorporate key elements of rehabilitation including dosage, intensity, and specificity.

Future Research

My lab will take a multi-tiered approach towards improving human function by addressing three parallel and interconnected research paths: 1) Development and implementation of new wearable sensing and assistive technologies, 2) fundamental and applied neuromechanics of human movement and human-robot interaction for healthy and clinical populations, 3) implementation of this technology in salient environments and tasks. I will build upon my unique past work with developing and applying innovative approaches with new sensing tools such as ultrasound and tensiometry for evaluating muscle neuromechanics and human-robot interaction. I have shown how these insights and tools can be used for developing effective assistance strategies and future work in my lab will continue these exciting directions. An initial effort will be towards further development of muscle-inspired assistive strategies for assisting and rehabilitating locomotion and evaluation of muscle-tendon dynamics in older adults and individuals' post-stroke.

Development and Implementation of New Sensing and Assistive Technologies: Our ability to understand human neuromechanics is heavily limited by our ability to collect robust and accurate measurements. Sensing technologies will therefore be an important arm of my lab's neuromuscular and wearable robotic research. This will provide multiple research paths for use as an evaluation and diagnostic tool and as a means controlling wearable devices.

My current and previous work has used new techniques such as ultrasound and tensiometry. There is much still to explore in this space in terms of application and development. An interesting extension of my previous work will be to use these technologies for assessing clinical gait. This may provide insight into how older adults or individuals post-stroke produce power with their plantarflexor muscles and how they progress through rehabilitation or with exo assistance. New sensing technologies will fall short without the ability to analyze and condense the data into a usable and interpretable form. In addition to building off some of my previous work with computer vision to enable measurement of muscle-tendon mechanics at real-time rates, we will incorporate the use of advanced analysis techniques including AI/ML.

This research aim will support collaborations. As exemplified by the NSF DARE grant, I will seek out collaborations for applying and developing sensing technologies that help us answer difficult questions. This aim may also enable unique datasets for musculoskeletal modeling research groups.

My lab's development of wearable technologies will be driven by both the need for tools that support parallel research efforts and toward the goal of products that make meaningful impact. In turn, guidance for the development of these technologies will come from the parallel research efforts investigating neuromechanics, human-robot interaction and real-world tasks. To allow early progress, we will also consider using the increasingly available commercial systems or through working with collaborators who have already developed prototype devices.

Neuromechanics and Energetics of Human Movement and Human-Robot Interaction: The foundation of much of my lab's work will be towards improving our understanding of how humans generate effective movement and respond to environmental and task demands. This work will scale from whole-body mechanics to the low-level muscle neuromechanics. By studying how individuals interact with wearable robotic systems in dynamic environments, my lab will develop a more complete and generalizable understanding of human movement and human-robot interaction. This will help with identification of new application areas for wearable technologies and lead to more effective assistance strategies that respond with the user and task. My lab will also investigate the limitations and deficits in human movement so that we can design around limitations or compensate for deficits. While I and others have performed work towards this understanding in healthy individuals, there is still much to explore to better understand individual needs and variability among heterogeneous clinical populations. We will also combine new sensing technologies with more common tools (IMU, EMG) for a more complete monitoring of biomechanical state within the lab, the clinic and community. For example, initial neuromechanics focused work will target the evaluation and exploitation of MT dynamics for post-stroke rehabilitation.

Finally, my lab will work towards bridging gaps between research areas in wearable robotics and assistive technologies. For example, instead of thinking about locomotion as a lower-limb only focus, we can expand into approaches that address the needs of upper extremity coordination during gait and provide more holistic strategies.

Implementation of technology and studying its impact in salient environments: This research aim will focus on investigation of wearable tech in salient environments for better movement evaluation, augmentation, assistance, and rehabilitation. The details of how wearable assistive devices should be used in real-world environments is still largely unknown. Development of strategies for these environments will draw heavily from my work in neuromechanics and how humans adapt to changing environmental demands. Healthy populations will be recruited to investigate the possibilities of augmenting performance and as a benchmark for evaluations of testing in community and recreational settings. For development of systems for assistance and rehabilitation, testing early with specific populations such as older adults and individuals' post-stroke will be important. Potential environments for evaluation include outdoor recreation, community and in-home assistance and rehab, and in-clinic rehabilitation.

This is a challenging topic and these developments take a significant amount of up-front work to develop protocols, relationships, and collaborations. In my current role, I initiated and am leading a collaboration with Spaulding Rehabilitation Hospital (Dr. Randie Black-Schaffer) and Shirley Ryan Ability Labs (Dr. Arun Jayaraman) to begin testing assistive devices in outpatient and inpatient environments. Furthermore, I have worked with industry collaborators, and the community-based device for the project I am leading has recently gained FDA breakthrough status. This experience in developing and evaluating an exosuit in a community setting will serve as background for developing future studies, collaborations, and grants. Finally, this effort will also provide opportunities for new data analysis approaches and associated collaborations. How best to evaluate and interpret sparse data from unsupervised tasks in diverse environments is not well understood but is a promising research direction.

Funding Strategy: As a postdoc, I have taken the lead in writing two collaborative grants that were awarded.

- **NIH R21AR076686:** "Real-time quantification of muscle-tendon dynamics for individualized and adaptive robot-assisted locomotion" (Robert Howe (PI) and Conor Walsh (Co-I).
- **NSF DARE #2019580:** "Quantifying Reductions in Musculoskeletal Loading due to Soft Exosuit Assistance using Shear Wave Tensiometry" (Conor Walsh, PI) in collaboration with Dr. Darryl Thelen (Wisconsin).

I will build off this experience with NIH and NSF grant processes and am ready to submit competitive proposals to fund my independent research. My research is highly collaborative and I will seek out collaborative funding opportunities with research groups in engineering (sensing, actuators, robotics, computer science), biomechanics (neuromuscular modeling, comparative physiology), and clinical disciplines (Physicians, OT and PT).

Initial study directions, such as the evaluation and exploitation of MT dynamics for post-stroke rehabilitation, will feed into larger R01-level proposals. One of my large scope research interests will be aimed at understanding the needs of individuals post-stroke undergoing early stage in-clinic rehabilitation and developing effective assistive devices that can be used by therapists to improve early-stage post-stroke rehabilitation.

Broader Impacts: These research aims will contribute to our understanding of functional human movement and lead to development of technologies for rehabilitating and assisting clinical populations. Effective locomotion is an important indicator of well-being, and thus, we want to enable individuals to move about the world successfully. An important consideration with development of technologies, especially for healthcare, is equity and access. Therefore, as we develop these technologies, we will be focusing on developing systems that can be affordable, accessible, and desirable to a wide variety of users.

Participation in Engineering and Biomechanics: I believe that promoting the study of movement biomechanics is an effective way to generate interest in science and engineering. This topic is extremely relatable and linked to many activities that people enjoy, such as exercise and/or recreation. Therefore, the lab will be intentional about outreach, making science interesting, and expanding recruitment of under-represented populations that otherwise may not know about these opportunities or fields of study.

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