NSF GRFP Graduate Research Plan

Research Title: Adaptive Neck-Shoulder Exoskeleton for Reducing Surgeon Fatigue

Overview: In operating rooms across the United States, many surgeons routinely endure over six hours of sustained arm abduction and head flexion during procedures[1,2]. Maintaining this posture continuously loads the trapezius and deltoid muscles and causes upwards of 75-85% of surgeons to experience musculoskeletal pain, with nearly 50% reporting that this pain directly interferes with their work performance[2,3]. Furthermore, fatigue in these muscles increases the risk of surgical error and burnout, factors that substantially contribute to the approximately 250,000 annual deaths caused by medical error in the United States alone[4,5]. Wearable exoskeletons have been shown to reduce muscle activation by up to 50% during repetitive industrial tasks[6], yet limited research has explored their application to more precise surgical tasks. Whereas industrial exoskeletons simply support their users during load-bearing activities, surgical tasks impose a more challenging set of design requirements and require minimal interference with the surgeon's fine-motor abilities and cognitive focus. My proposed research addresses two critical knowledge gaps: First, I will quantitatively model how neck and shoulder fatigue degrade surgical precision during prolonged fine-motor tasks. Second, I will develop a novel exoskeleton that reduces surgeon fatigue without sacrificing dexterity or mental focus. This research will establish foundational design principles for wearable robotics used to assist physicians, expanding the role of robots in surgery from systems that directly operate on patients to those that support the surgeons providing care.

Aim 1: To model how prolonged loading in the neck and shoulders affects fine-motor control and cognitive fatigue during surgical tasks. <u>I hypothesize that prolonged arm abduction and head flexion decrease task precision while increasing cognitive workload.</u> While the literature has established that long surgical procedures cause progressive fatigue and pain, no biomechanical model exists that explains *how* muscle performance and tremor change over time as a surgeon operates. To develop this model, participants will perform standardized micro suturing tasks in simulated surgical postures while I collect surface EMG (trapezius, deltoid), IMU data (posture, tremor), performance metrics (completion time, errors), and cognitive assessments (NASA-TLX, SAGAT). This work will bridge the gap between qualitative surveys on surgeon fatigue and the biomechanical implications of procedures lasting many hours. Furthermore, these data will establish critical fatigue thresholds that enable the exoskeleton described in **Aims 2 and 3** to provide assistance *before* fatigue degrades performance to the point where surgical errors occur. If in-person experiments are not feasible, I will use OpenSim to simulate upper-limb muscle fatigue under static surgical postures and computational human performance models (e.g., NASA's HPM toolkit) to estimate cognitive workload during prolonged surgical tasks.

Aim 2: To evaluate whether an adaptive exoskeleton can reduce surgeon fatigue without decreasing dexterity or increasing cognitive workload. <u>I hypothesize that adaptive assistance can substantially reduce neck-shoulder muscle activity while preserving the user's ability to perform fine-motor tasks with precision and cognitive clarity.</u> Unlike existing surgical exoskeleton systems such as the HAPO exoskeleton, which provide passive mechanical support, my proposed exoskeleton will deliver dynamic assistance tailored to the user's physiological state (**Fig. 1**). Because the neck and shoulders are biomechanically coupled, passive systems that target only one region can unintentionally transfer load to the other. In contrast, my proposed active exoskeleton would sense and adapt across both joints simultaneously, coordinating assistance to maintain stable head and arm posture. I will first design and fabricate a soft exoskeleton with actuators that provide support at the shoulders and a neck brace that supports head flexion. I will then validate this device using a within-subject crossover experiment, comparing trials with no exoskeleton (baseline), constant assistance, and adaptive closed-loop assistance. My control strategy will modulate assistance by comparing real-time EMG and IMU data to the thresholds established in **Aim 1**, scaling support as the user grows increasingly fatigued. I will evaluate the device's

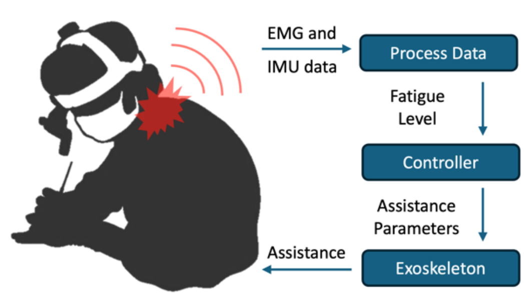

Figure 1. Exoskeleton feedback loop

success through muscle activation, tremor, task performance, and cognitive load across all conditions. If I am unable to build a standalone exoskeleton device within the project timeline, I will use a tethered exoskeleton emulator with off-board motors for **Aims 2 and 3**.

Aim 3: To characterize trade-offs between assistance and task interference across various exoskeleton transparency levels and identify optimal parameters for surgical performance. <u>I hypothesize that when assistance levels exceed user expectations, cognitive workload will increase as users become distracted from the task at hand.</u> Although **Aims 1 and 2** may yield an exoskeleton that reduces fatigue during surgical tasks, this alone does not guarantee clinical feasibility. For surgeons to adopt and effectively use the device, it must provide assistance while remaining essentially imperceptible during procedures. If this assistance is noticeable or unpredictable, it risks distracting the surgeon, potentially negating any fatigue benefits by introducing new cognitive burdens. **Aim 3** will therefore define the maximum assistance an exoskeleton can feasibly provide in a high-precision context before it begins to interfere with the user's task performance. By systematically varying assistance gain and applying multi-objective optimization to maximize task precision while minimizing cognitive interference, I will reveal the thresholds at which assistance begins to restrict the surgeon's abilities rather than augmenting them.

Research Environment: I will pursue these aims under the joint mentorship of Prof. Steve Collins and Prof. Scott Delp, whose expertise in exoskeletons and biomechanics provides the ideal environment for my research. I will use the Neuromuscular Biomechanics Lab's resources in musculoskeletal modeling to develop a biomechanical baseline for this work in **Aim 1**; I will then use the Biomechatronics Lab's human-in-the-loop optimization platforms to develop the adaptive exoskeleton described in **Aims 2 and 3.**

Intellectual Merit

<u>This work represents the first attempt to expand dynamic exoskeleton assistance from gross-motor applications into precise, cognitively demanding use cases.</u> **Aim 1** will establish the first quantitative model linking neck and shoulder fatigue to declines in fine-motor precision and increases in cognitive workload during prolonged surgical tasks. **Aim 2** will develop and validate a closed-loop exoskeleton that adapts assistance based on the user's physiological state, introducing new methods for multimodal sensing, real-time inference, and coordinated neck-shoulder support. **Aim 3** will define transparency and assistance-gain limits for high-precision tasks, providing generalizable design principles for wearable robots used in medicine. These contributions will advance biomechanics, human-robot interaction, and adaptive control, driving the development of the next generation of surgeon-assistive technologies. My prior experience designing and prototyping wearable robotic systems, as well as evaluating them in human-in-the-loop experiments, equips me to carry out **Aims 1, 2, and 3** from concept through experimental validation. Ultimately, this work positions wearable robots not just as tools for preventing injury, but as platforms for augmenting human capability in the most physically demanding forms of patient care.

Broader Impacts

<u>This work will lay the foundation for active wearable robots that reduce fatigue-induced medical errors, extend surgical careers, and ultimately improve patient safety.</u> This technology could allow surgeons to perform lengthy procedures without their precision being affected by muscular strain, and without chronic pain and burnout diminishing their quality of life outside the operating room. Beyond surgery, the design and control strategies developed here will guide future wearable systems for professions facing similar physical and cognitive demands, such as dentistry, radiology, and pathology. Moreover, these technologies will support greater inclusivity by helping practitioners of various body types, ages, and physical abilities maintain their careers in surgery and related fields. To encourage students from diverse disciplines to apply their skills to translational biomedical research, I will mentor undergraduate students assisting me with biomechanical modeling, exoskeleton fabrication, and data analysis. All designs, datasets, and control algorithms will be open source to ensure these findings can accelerate progress across academia, medicine, and industry toward assistive technologies that enhance human performance.

References: [1]Costa, A.D.S. *Einstein (Sao Paulo)*. 2017. [2]Schlussel, A.T., et al. *Clinics in Colon and Rectal Surgery*. 2019. [3]Aaron, K.A., et al. *Public Library of Science One.* 2021. [4]Shanafelt, T.D., et al. *Annals of Surgery.* 2010. [5]Makary, M.A., et al. *The British Medical Journal*. 2016. [6]Gräf, J., et al. *Frontiers in Neurology.* 2024.