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TITLE: The Prediction and Evaluation of Strength and Fatigue to Prevent Warfighter Musculoskeletal Injuries

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CONTRACTING ORGANIZATION: University of Alabama, Tuscaloosa, AL

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## 14. ABSTRACT

Musculoskeletal disorders are common for people who work on strenuous and demanding tasks, such as nurses, construction workers, and soldiers. The injuries come from overexertion of the individual's related muscle groups that are required to be activated to complete a specific task in various environments. A current solution is the use of robotic-aid devices. These robotic devices are being investigated to treat musculoskeletal injuries and significantly increase a human's capacity in heavy working conditions. However, the design of the human-machine interaction force remains an obstacle to the implementation of effective assistance to people in practical working scenarios due to the environmental variety, task complexity, and human variation and uncertainty. Previous studies showed that the metabolic cost of exercise will be increased instead of reduced if improper forces are provided by the machine. Thus, accurate estimations of the required machine force application to the individual are critical to labor saving and muscle health.

As an accurate, real-time estimation of the muscle capacity is important to determining the necessary force to be applied by the robotic aid device, factors that affect instantaneous muscle capacity must be comprehensively considered. There are three main factors that relate to muscle capacity: the environment, such as the temperature and humidity, the task, such as the activity patterns and workloads, and the human, such as the weight, age and fatigue state. The hypothesis of this proposal is that, muscle strength and muscle health can be accurately described by a human muscle fatigue model with real-time feedback data from sensors capturing the environmental, work-history, and physiological state of the subject, and the model can enable a smart, robust diagnostic tool. Previous studies have attempted to understand the effect of the wearer's body on the force requirements for effective robotic aid, as well work-related factors like cognitive load, workload, and situational awareness. The relationship between muscle fatigue and the environment has also been studied, particularly with respect to the effects of temperature and humidity may affect worker performance. However, little work has been done understanding the combined effect of the wearer's personal factors, their work history, and the environment on muscle strength, fatigue or health, and no appropriate framework of a mathematical model has been developed to describe the muscle fatigue dynamic process under a practical scenario with a combination of these factors.

In this work, the PIs propose a new muscle fatigue stochastic dynamic model, where inferences of the muscle fatigue state and its evolution equations are based on maximum likelihood estimations of prior hypothesis and posterior corrections from real-time feedback information. In order to derive the model, experiments will be conducted with adult subjects in a controlled environment in this project. The experiments are designed to investigate the coupling effect of work load and environmental factors on muscle fatigue using exercises targeting specific muscle groups. The derived stochastic model will be then used to estimate the muscle force in a more realistic activity in real time, which can be an assessment of the proposed model. An exosuit will be developed as part of the proposed study. Different sensors will be integrated in the exosuit to collect all required data, which will be used as the feedback in the model to infer and predict the dynamic model and current estimation of the muscle fatigue state. The effectiveness of the predictive model and exosuit will be validated using a more realistic, task-based experiment (material handling). If positive results are observed by using the proposed model to estimate the fatigued muscle capacity, more sophisticated and detailed model will be developed in the further work by following the same framework, and a more practical and effective exosuit will be designed to significantly improve soldiers' or other workers' musculoskeletal health.

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## 1. INTRODUCTION

Musculoskeletal disorders are common for those who have physically demanding jobs that including strenuous tasks such as soldiers, nurses, and construction workers. One proposed solution to this challenge is robotic-assistive devices, which provide force to the wearer to either overcome injury or increase strength and longevity. However, current devices, commonly built as exoskeletons or exosuits, often apply improper force to the desired muscle groups. This improper application of force actually increases the metabolic load of the wearing the robotic-assistive device and can increase the likelihood of associated injuries. In order for new devices to appropriately aid the soldier or worker attempting to improve their musculoskeletal performance, information about the wearer must be taken into account before force is applied. Nothing currently available, commercially or in the academic literature, is able to accurately account for all of the necessary factors which will affect muscle performance. These include environmental factors (temperature, humidity), work factors (activity patterns and workloads), and human factors (age, weight, health). The work described here is the first of its kind to perform a real-time estimation of muscle capacity based on all of the relevant environmental, work, and human factors to develop a new muscle fatigue stochastic dynamic model. This is being done through human subject experiment where adults are asked to perform specific exercises that target specific muscle groups while wearing an exosuit outfitted with sensors to detect movement and muscle activity. This data will be fed back into the dynamic muscle fatigue model to provide an accurate estimation of real-time fatigue and thus the appropriate amount of aid required by the wearer.

## 2. KEYWORDS

Musculoskeletal disorder
Exosuit
Muscle fatigue
Robotic assistive device
Metabolic load
Stochastic dynamic model
Movement sensors
Electromyography

## 3. ACCOMPLISHMENTS

*Completed*
Major Task 1: Determine optimal frequency for using dynamometer (DM) to determine submaximal muscle contractile force (MVC)

**1. Develop protocol for experiment and obtain UA IRB approval [Target completion period: 2months]**
The PIs have successfully developed a protocol for this study that has been given UA IRB approval. Official IRB approval notification was sent to the PIs on March 13, 2020. This application has been reapproved as of March 12, 2021.

PI and graduate students responsible for the running of experiments have been trained in how to respond to an overheating episode during an experiment.

**2. Obtain approval from HRPO for experiment protocol [Target completion period: 1 month]**

The PIs have successfully obtained approval from HRPO. The PIs were notified of this approval on June 11, 2020. This approval was based on a re-submission of the protocol to the UA IRB to align the needs of HRPO with the UA IRB. The revised IRB protocol was approved by the UA IRB on May 28, 2020.

**3. Recruit participant for the experiments. Recruitment will continue until the sample size is obtained (after attrition) [Target completion period: 3 months]**

The PIs have identified eight potential participants for the first experiment. Although not officially recruited, these individuals have agreed to participate in the study once we begin experiments in the summer. The PIs will keep identifying and recruiting potential participants until we achieve the sample size for the first experiment.

*Not completed*
**4. Conduct experiment to ascertain the optimal density of MVC test using a DM during an exercise session [Target completion period: 3 months]**

The experiment is scheduled to take place between May and June 2021, as UA returns to Full Business Operations.

*Not completed*
**5. Assess relationship between MVC (dynamometer) and EMG data and determine appropriate density of MVC test [Target completion period: 1 month]**
*Not completed*

Milestones:
IRB and HRPO approval **[Achieved]**

Identified optimal frequency for DM test and relationship between EMG and MVC **[Not Achieved]**

Opportunities for training and professional development: Nothing to Report

Results disseminated: Nothing to Report

Plan for next reporting period: As will be discussed in Section 5, the PIs are waiting for the resumption of Full Business Operations at the University of Alabama in order to begin subject recruitment and exercise experimentation. Once UA resumes Full Business Operations, the PIs plan to rapidly recruit human subjects from Tuscaloosa to participate in the exercise trials described under Major Task 1. Working closely with the Department of Kinesiology here in UA, the PIs have put together an alternative plan to recruit students who meet the study requirements. In the meantime, the PIs are preparing the facility where the exercise experiments will take place, particularly with respect to new safety requirements associated with COVID-19, required safety equipment (as described in overheating safety protocols), temperature control, and humidity control. The PIs are in the process of acquiring the necessary equipment and accessories to be present in the experiment space as well as the sensors needed to outfit subjects. If UA returns to Full Business Operations, it is fully expected that Major Task 1 will be completed during the next reporting period and work will have begun on Major Task 2.

## 4. IMPACT

Nothing to report.

## 5. CHANGES/PROBLEMS

This study has run into and overcome three significant challenges.

1. **Measuring core body temperature:** As mentioned in the previous technical report for W81XWH-20-1-0030 [03/2020-09/2020], in order to measure muscle fatigue in human subjects, the experimental protocol details an exercise program that is designed to fatigue certain muscle groups while the subject is in a controlled temperature and humidity environment. The environmental temperatures to be used are 15 °C, 25 °C, and 35 °C [59 °F, 77 °F, and 95 °F]. The exercise monitoring sessions are expected to last roughly 1.5 hours. Knowing that it was critical to maintain a safe experimental environment and protect subjects from overheating, the PIs developed the proposal based on the understanding that subject safety would be monitored through (a) continuous communication with the subject and (b) measuring of body temperature through external temperature monitoring (skin temperature sensors), which can be correlated to core body temperature. If the subject expressed any discomfort or their internal temperature began to approach unsafe levels, the experiment would be terminated, and the subject would be immediately cooled down (in-line with a heat stroke protocol approved by UA IRB). The budget for the initial proposal was also based on this experimental design. While this protocol and method of measuring core temperature was based on previous literature and interactions with colleagues performing similar experiments, the UA IRB disagreed with the method suggesting that measuring temperature externally and correlating it to core temperature was not acceptable. Two alternative methods were suggested: rectal thermometer or orally administered core temperature sensing pills. As the PIs are uncomfortable with and untrained to do rectal temperature measurements, the orally administered core temperature sensing pills became the only option. These pills, however, carry significant expense that was not originally budgeted for.

   After significant discussion with the UA IRB, it was determined that the only way to move forward with this study in a safe manner was to utilize the orally administered core temperature pills. As such, Dr. Koh, Dr. Nnaji, and Dr. Martelli worked with their respective departments at the University of Alabama to find additional resources to put towards this work. All three departments agreed to split the cost of the core temperature pills after Dr. Koh and Dr. Nnaji were able to negotiate a reduced price for the devices (approximately $12,500). The core temperature pills have now been purchased and are safely housed in Dr. Nnaji's lab ready for the start of testing.

2. **PI Change**: In January 2021, Dr. Xuefeng Wang, one of the original PIs on this grant, resigned from his position at the University of Alabama. This left the team without the ability to perform the modeling originally proposed for the grant. Thankfully, Dr. Dario Martelli (UA Department of Mechanical Engineering), whose research focuses on biomechanics and rehabilitation robotics, agreed join the team and bring his expertise to the project. With the addition of Dr. Martelli to the proposal, the team not only has the expertise in modeling that is needed but gains a deeper ability to characterize and understand the physical motion of the human subjects that will lead to a stronger final muscle fatigue model and greater potential for future application of this model to the health challenges of the US warfighter

3. **COVID-19 Restrictions**: Due to national, state, and university-level COVID-19 restrictions on in-person experimentation as well as general population hesitancy with in-person activities, human subject recruitment was not possible for most of 2020 and has been slow during 2021. Dr. Nnaji has been able to jump start recruitment this year, however, and the team is on pace to accomplish Major Task 1 this summer.

## 6. PRODUCTS

Nothing to report.

## 7. PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

| | |
|---|---|
| Name: | Dr. Amanda S. Koh |
| Project Role: | Principal Investigator |
| ORCID: | 0000-0003-3960-3872 |
| Nearest person month worked: | 1 |
| Contribution to project: | Dr. Koh was in charge of facilitating HRPO approval of the experiment protocol. Dr. Koh has also helped Dr. Nnaji in the submission of the UA IRB protocol and determination of needed body temperature technology updates as per UA IRB requirements. Dr. Koh facilitated the pooling of department funds to purchase the need core temperature pills and the subsequent purchasing. Dr Koh has been in charge of all US CDMRP required reporting. |

| | |
|---|---|
| Name: | Dr. Chukwuma Nnaji |
| Project Role: | Principal Investigator |
| ORCID: | 0000-0002-3725-4376 |
| Nearest person month worked: | 1 |
| Contribution to project: | Dr. Nnaji developed and revised the research protocol to ensure conformance with meet UA's IRB and HRPO requirement. Dr. Nnaji has managed all interactions with UA IRB. Working closely with the Department of Kinesiology, Dr. Nnaji has identified individuals who meet the participation criteria for the first experiment. Dr. Nnaji developed an estimate for the pills required for the study. |

| | |
|---|---|
| Name: | Dr. Dario Martelli |
| Project Role: | Principal Investigator |
| ORCID: | |
| Nearest person month worked: | 1 |
| Contribution to project: | Dr. Dario's student has taken classes in machine learning to prepare to develop the muscle fatigue model as human subject experiments get underway such as "Introduction to Machine Learning" offered by Duke University [focuses on the foundational understanding of machine learning models (logistic regression, multilayer perceptions, convolutional neural networks, natural language processing, etc.) as well as demonstrate how these models can solve complex problems in a variety of industries, from medical diagnostics to image recognition to text prediction] as well as "Machine Learning: Regression" offered by the University of Washington [focusing on exploring regularized linear regression models for the task of prediction and feature selection to handle very large sets of features and select between models of various complexity]. |