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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.

15. SUBJECT TERMS
None listed.

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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]

Complete. The PIs successfully recruited 25 participants, with 15 completing the required sessions.

4. Conduct experiment to ascertain the optimal density of MVC test using a DM during an exercise session [Target completion period: 3 months]

Completed. Participants completed four sessions. The first session focused on capturing the 1RM and Manual Muscle Testing (MMT) using a handheld dynamometer. Session two to four captured data on muscle fatigue (EMG, heart rate, core temperature, estimated core temperature) while increasing the number of 1RM and MMT checks.

5. Assess relationship between MVC (dynamometer) and EMG data and determine appropriate density of MVC test [Target completion period: 1 month]

PIs and graduate students developed MATLAB routines to analyze EMG data. EMG data from deltoid and biceps muscles during the Objective Failure Cycles (OFC) have been analyzed for all 13 participants. To address the non-stationarities of the EMG signal during dynamic contractions, we used time-frequency techniques to determine the instantaneous mean frequency (IMF), average rectified value, root mean square, and wavelet spectral parameters over time. As expected, we found changes of these parameters over time that are reflective of peripheral muscle fatigue before the participants were not able to maintain the same performance on the task.
The same outcome parameters were calculated for the four cycles performed Sessions 3 and the ten cycles performed in Session 4.

Pearson coefficient was used to correlate the EMG outcomes with the results outcome of the maximum voluntary contraction (MVC) testing performed with the muscle mass tester (MMT). Results suggested that it is not necessary to perform multiple MVC testing during the course of the experiment: EMG parameters are sufficient to detect those peripheral changes in muscle performance that will be used to develop our prediction model. In addition, since we are aiming to predict muscle fatigue while the subjects are performing the exercise, the results of the MVC tests cannot be used as input parameters to our model.

Milestones:
Identified optimal frequency for DM test and relationship between EMG and MVC **[Achieved]**

Major Task 2: Evaluate relationship between environmental, workload and physical condition
Recruit participant for the experiments. Recruitment will continue until the sample size is obtained (after attrition) [Target completion period: 1-3 month]

PIs successfully recruited 26 students to participate in the experiment. Given the length of the experiment (10 sessions over 10 – 12 weeks), the PIs recruited 11 additional participants (15 +11) to account for potential attrition.

Conduct experiment to ascertain the coupling effect of temperature and load variation on muscle fatigue [Target completion period: 3 months]
The experiments consists of visiting the laboratory 10 times. The first visit focuses on collecting baseline data (MVC, etc.) and familiarizing participants with the research process. The subsequent 9 session focus on exposing the participants to a specific condition (3 temperatures X 3 weights). Presently, ten participants have completed the fifth session and five have completed the sixth session. The PIs expect that 15 participants should have completed all sessions by the end of April 2022.

Major Task 3: Develop prediction model
Develop a muscle fatigue model using the data from the second task to incorporate factors of working, environmental and human physiological parameters [Target completion period: 2 months]
PIs and graduate students are currently collecting data for Experiment 2. In the meanwhile, we are in the process of developing a muscle fatigue model based on the results of Experiment 1 that does not take in account temperature and working load. The EMG outcome parameters estimated during the OFC of Experiment 1 will be used to train a supervised machine learning classifier aimed at identifying muscle fatigue. We assumed that the outcome parameters of the first and last contractions of the OFC could be labeled as non-fatigue and fatigue status, respectively. The parameters from these cycles will be used to train a 3-layer feedforward neural network with tangent hyperbolic transfer function. The model will be then tested using the remaining contractions of the OFC. The same model will be used also for the data collected in Experiment 2 with temperature, heart rate, and working load as additional inputs of or classifier.

Plan for next reporting period: Two tasks are planned for Major Task 3. Under "Develop a muscle fatigue model using the data from the second task to incorporate factors of working, environmental and human physiological parameters," the muscle fatigue model will be modified to also include temperature, working load, and working history. The model will be trained using the data of Experiment 2. Three fatigue states will be identified: No Fatigue (start till local muscle fatigue from EMG, Pre-Fatigue: local muscle fatigue till objective task failure; Fatigue: task failure till unable to lift the load with the right posture or the subject end the exercise because exhausted). Under "Develop a real-time muscle fatigue estimation method based on the fatigue model and real-time feedback of personal and environmental factors," The model will be tested with leave- one-out cross validation (LOOCV). For each LOOCV iteration, all but one dataset M (Training Set) will be selected to train the model, whereas the excluded dataset (Test Set) will be adopted to test its performance. The multi-categorical classification model will be evaluated by the sensitivity and specificity of each possible class, and time delay to alert pre-fatigue or fatigue sates.

With respect to Major Task 4, The PIs will develop and submit an experiment protocol for Experiment 3 (assessing the wearable device in real time) to the Institutional Review Board (IRB) in May 2022. Commercial and experimental environmental, motion, and muscle status sensors will be evaluated and integrated into an exosuit for Experiment 3 to collect realistic exercise data. Participant recruitment for the third experiment will begin August 2022 and will continue until the required sample size (15 participants) is obtained. The goal of Experiment 3 is to evaluate the effectiveness of the proposed wearable device and model. As part of the experiment, participants will be asked to complete a material handling exercise aimed at inducing fatigue. The experiment will begin in September 2022.

4. IMPACT
Nothing to report.

5. CHANGES/PROBLEMS
The study has had no new challenges during this last reporting period. Below are three significant challenges that the study has already encountered and overcome.

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's graduate student is helping facilitate human subject studies for Major Task 1 and 2. Dr. Koh oversees the exosuit sensor development and validation. 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 and recruited individuals who meet the participation criteria for Major Tasks 1 and 2. Dr. Nnaji and his graduate students have run human subject trials and collected data for Major Task 1.

Name:	Dr. Dario Martelli
Project Role:	Principal Investigator
ORCID:	
Nearest person month worked:	1
Contribution to project:	Dr. Dario Martelli and his graduate student conducted data analysis. They have developed Matlab scripts to quantify fatigue during dynamics contractions from EMG data, correlate the muscle fatigue parameters with the MVC tests, and the machine learning classifier to detect state of fatigue. These scripts are being validated with EMG data from Experiment 1.