Muscle Fatigue Diagnostic Sensor Array

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***Abstract*— Muscle fatigue is a critical factor influencing athletic performance, injury recovery, and neuromuscular health. It extends beyond mere tiredness, serving as an early indicator of underlying muscle health issues. Current research highlights the importance of measuring mitochondrial function in skeletal muscle, typically assessed through complex, invasive methods requiring specialized equipment and expertise. With limited research on quantifying skeletal muscle health, we aim to create a portable, automated device that can safely and accurately measure mitochondrial function in skeletal muscle.**

Due to the limited accessibility, high cost, and technical complexity of existing methods for measuring mitochondrial function, this work proposes the development of a portable, automated, all-in-one device designed for non-invasive measurement of muscle mitochondrial function. This device is engineered specifically to be compatible with the Mito6 protocol, a standardized method for assessing muscle health and mitochondrial function. This device integrates several key functionalities: it employs near-infrared spectroscopy (NIRS) to continuously monitor muscle oxygen levels, while a motorized strap system facilitates controlled blood flow occlusion. Electrical muscle stimulation is delivered via surface electrodes connected to a modified TENS 7000 unit. The entire system is managed through a user-friendly central control box, enabling adjustments to settings and the initiation of measurements with a single START button. By automating the measurement process in line with established research protocols, this device aims to democratize access to advanced muscle diagnostics, making it suitable for both clinical and research applications. Ultimately, our device seeks to enhance the understanding of muscle fatigue and mitochondrial function, contributing to improved athletic performance and recovery strategies.

Keywords—Muscle, fatigue, mitochondria, health

I. Problem Statement

Current muscle fatigue and mitochondrial assessments rely on complex, multi-device laboratory setups that combine blood-flow occlusion, muscle stimulation, and oxygen monitoring. One such approach is the Mito6 protocol, a research method used to evaluate skeletal muscle mitochondrial function through repeated cycles of arterial occlusion and muscle stimulation while monitoring oxygen recovery via near-infrared spectroscopy (NIRS). This method requires precise timing, controlled pressure application, and consistent repetition to produce reliable results.

However, existing implementations of this protocol rely on benchtop research rigs composed of separate components, including blood pressure cuffs, electrical muscle stimulators, and NIRS devices, that are not seamlessly integrated. These systems depend on strict timing, expert operation, and bulky equipment, such as large air pumps required for repeated occlusion cycles. As a result, they are difficult to operate, non-portable, and largely inaccessible to clinicians, trainers, or field researchers.

In addition, consumer-grade wearable devices lack the precision required for research-level mitochondrial assessment, leaving most fatigue evaluation subjective rather than quantitative. This limits the ability to accurately track rehabilitation progress, optimize athletic performance, or conduct field-based studies. Reliable mitochondrial assessment requires precise pressure control, tightly coordinated timing, and highly repeatable cycles—capabilities that are difficult to achieve manually and nearly impossible outside controlled laboratory environments.

To address these limitations, we propose a portable, fully integrated system that combines blood flow occlusion, muscle stimulation, and NIRS-based oxygen monitoring into a single, centrally controlled device. By automating protocol execution and simplifying operation, this design improves measurement consistency and enables objective, quantitative muscle fatigue analysis in clinical, research, and athletic settings.

II. System Overview

The proposed device consists of four integrated subsystems: (1) a motorized constrictor for blood flow occlusion, (2) a modified TENS unit for electrical muscle stimulation, (3) a centralized control box for system automation, and (4) a near-infrared spectroscopy (NIRS) system for oxygen monitoring.

These subsystems operate together to automate the Mito6 protocol. The control box coordinates timing and activation, triggering the constrictor to occlude blood flow, the TENS unit to stimulate muscle contractions, and the NIRS device to record oxygenation changes in real time. By integrating these previously separate systems into a single platform, the design improves repeatability, reduces operator error, and enables portable mitochondrial function assessment.

A. Constrictor

The constrictor subsystem is responsible for controlled blood flow occlusion. Unlike traditional pneumatic cuffs, this design uses a motorized strap tightening system to apply circumferential pressure to the limb.

- *Motor Housing:* The motor housing contains a servo motor, gear train, guide sleeve, and nylon webbing. During operation, the system winds and pulls the webbing inward, tightening the strap around the limb to induce occlusion. This pulling action is achieved through a gear-and-roller mechanism, where the roller grips the webbing while the gear reduction increases torque output from the motor.
- *Clasp:* The clasp is a key safety feature of the system. It is designed to securely hold tension during operation while allowing rapid manual or passive release in the event of excessive force. The clasp uses a side-release buckle mechanism with flexible prongs that lock into a mating housing. It distributes load across the nylon webbing to prevent stress concentration. Importantly, the clasp is designed to fail safely—under excessive tension, the user can quickly disengage it by pinching the side tabs, immediately releasing pressure and preventing injury. This dual behavior—secure under normal loads but easily releasable under abnormal conditions—provides a critical safeguard against over-occlusion.
- *Sleeve:* When a strap is tightened directly against the skin, pinching can occur and may compress the underlying arteries. To prevent this, we added a sewn-in sleeve, made from an 80% nylon 20% spandex knit, around the strap to provide a protective barrier that eliminates pinching and ensures user comfort.

Our design consists of a 161 × 102.5 × 88 mm box that houses a motor, metal axle, and gear system. The motor drives the gear assembly, which rotates the axle to tension and retracts the strap. We used a 100 Kg·cm servo motor along with a gear ratio of 1.2 for more torque. This achieves enough torque to apply 300 mmHg or 5.8 psi. The servo motor allowed us to control how much of the strap we are pulling and therefore control the pressure of the constrictor. Also, as you can see in the image below, we also have rollers below the motor and main axle that help manage the strap when retracting and expelling. We made the axles out of aluminum so that it could withstand the stresses acting on it by the strap.

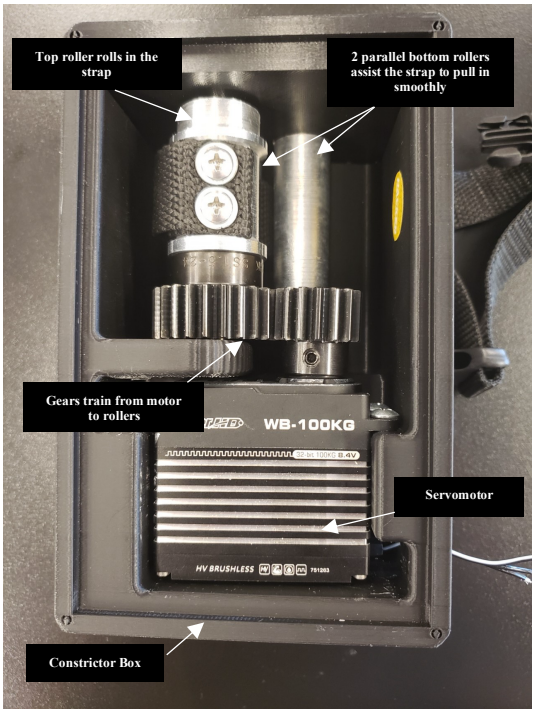

Fig. 1. Constrictor Box Inside Illustration Top Angle. *The constrictor utilizes a 1:1.2 gear mechanism that uses the motor to pull the strap on to a roller and occlude blood flow. The automation of this constriction is controlled using a control box.*

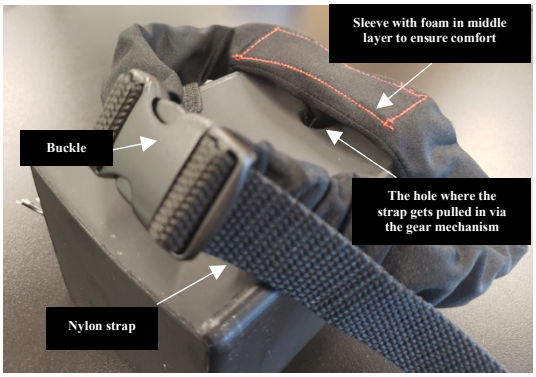

Fig. 2. Constrictor Box Outside Illustration. *The constrictor box is attached to a nylon strap. The nylon strap is surrounded by a sleeve to ensure patients more comfort.*

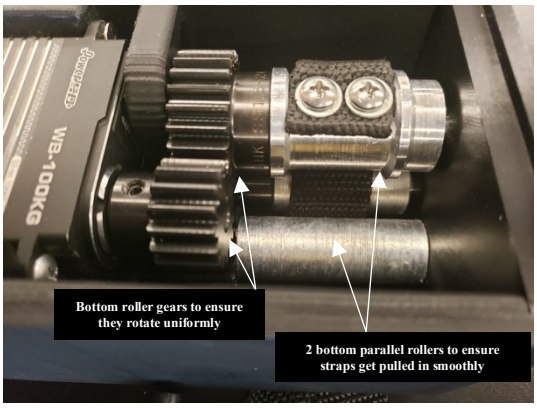

Fig. 3. Constrictor Box Inside Illustration Side Angle. *A look at the inside of the constrictor box from the side angle. The bottom rollers are connected via a 1:1 gear ratio to uniformly and smoothly pull the strap in.*

B. TENS Unit

The TENS (Transcutaneous Electrical Nerve Stimulation) subsystem provides controlled electrical stimulation to induce muscle contractions during the protocol.

In this design, a commercial TENS unit has been modified by replacing its manual control knobs with a digitally controlled potentiometer, allowing full integration with the control box. This enables precise, repeatable adjustment of key stimulation parameters, including:

- Output voltage and current (intensity)
- Pulse width
- Pulse frequency
- Stimulation duration

By integrating control digitally, the system eliminates manual adjustments and ensures that stimulation is applied consistently across trials, which is critical for reliable mitochondrial assessment.

Additionally, this modification allows stimulation sequences to be automated and synchronized with occlusion timing, aligning with the requirements of the Mito6 protocol.

C. Control Box

The role of the control box is to house the Arduino microcontroller and features two manual buttons used to operate the constrictor. The current configuration offers limited functionality, with no automated timing or control features.

- *LCD Screen:* Displays the current settings and the values being adjusted.
- *Matrix Keypad:* Enables user input and precise control over settings.
- *Up/Down Buttons:* Adjust specific values, such as electrode voltage or constrictor pressure.
- *Start/Stop Button:* Initiates or halts automated operations.
- *Arduino Control:* Powers and manages all functions of the control box.

D. NIRS

Near-infrared spectroscopy (NIRS) is used to monitor muscle oxygenation throughout the protocol. The sensor is placed directly over the target muscle and continuously measures changes in oxygen levels during occlusion and recovery phases.

Data from the NIRS device is transmitted to an external laptop, where it is displayed as real-time graphs representing muscle oxygen dynamics and mitochondrial function.

By synchronizing NIRS data collection with automated occlusion and stimulation cycles, the system enables objective, quantitative analysis of muscle fatigue and recovery.

The electrical system of the blood occlusion device is powered by a 12 V, 10 A primary power supply, which serves as the central source for all subsystems. This input is divided into multiple branches using both linear voltage regulation and switching conversion to meet the varying electrical requirements of the system.

A 9 V rail is generated from the 12 V supply using a linear voltage regulator, and this rail serves as the primary power line for the control electronics. Both the Arduino microcontroller and the TENS unit share this 9 V regulated line, meaning they are powered from the same branch. The Arduino receives this 9 V input through its VIN pin and internally regulates it to 5 V and 3.3 V logic levels for operation. Low-power components such as the biosensor and OLED display are powered from the Arduino's regulated outputs and communicate via a shared I²C bus.

The servo motor, which drives the occlusion mechanism, is powered through a separate high-current branch. A buck converter steps the 12 V supply down to approximately 9 V, providing sufficient current capacity of approximately 6–7 A required for servo operation under load. This prevents excessive current draw through the linear regulator branch and isolates the high-current demands of the actuator from the control electronics. The servo is controlled using a PWM signal from the Arduino, while its power is delivered independently through the buck converter.

User input buttons are connected directly to the 12 V supply, with resistor networks used to step down the sensed voltage to approximately 5 V before interfacing with the Arduino's digital input pins. This ensures compatibility with the microcontroller while allowing the buttons to operate within the higher-voltage domain.

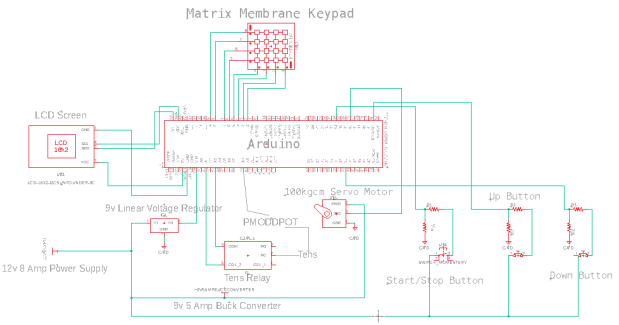

Fig. 4. Circuit Diagram of Muscle Fatigue Device. *The control box is powered by a 12V power supply and connects to the constrictor box to implement occlusion. It features a membrane keypad, start/stop and directional buttons, an LCD screen, and a built-in TENS unit, providing the user with full control over the system.*

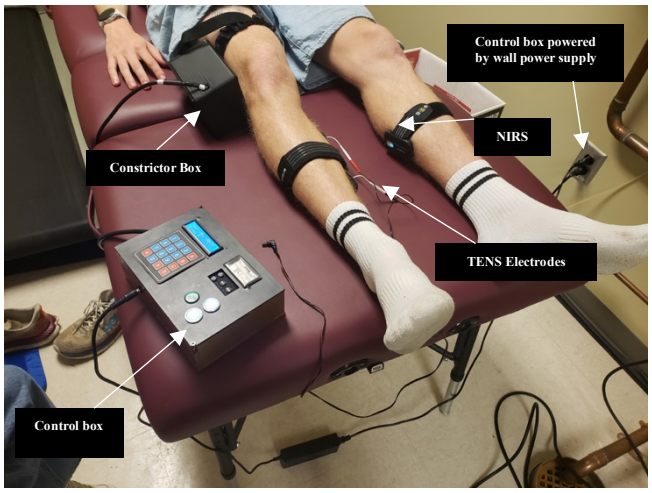

Fig. 5. Device Set-up on patient featuring a control box, constrictor box, NIRS device, and TENS electrodes.

III. Validation

To evaluate the performance of the proposed system, testing was conducted to assess occlusion capability, repeatability, and system integration, with results compared against a traditional benchtop research rig used for mitochondrial assessment following the Mito6 protocol. This comparison establishes whether the proposed portable system can achieve functionally equivalent performance.

The constrictor subsystem was evaluated against a standard pneumatic blood pressure cuff used in benchtop systems. Both systems were applied to a comparable limb model, and occlusion levels were assessed relative to the target pressure of approximately 300 mmHg.

Occlusion Performance:

The constrictor subsystem successfully achieved pressures comparable to the target value of approximately 300 mmHg required for arterial occlusion. While the benchtop system achieves this using pneumatic pressure, the proposed system uses mechanical tension. Despite this difference in mechanism, both systems produced functionally equivalent occlusion levels.

Response Time:

The motorized strap system demonstrated faster response times during both tightening and release phases compared to the pneumatic cuff. This is due to the elimination of delays associated with air compression, tubing, and valve control. Faster response improves timing accuracy within the Mito6 protocol.

System Integration and Usability:

The benchtop system requires manual coordination of multiple independent devices, increasing setup complexity and potential for user error. In contrast, the proposed system integrates all subsystems into a single platform controlled through a centralized interface.

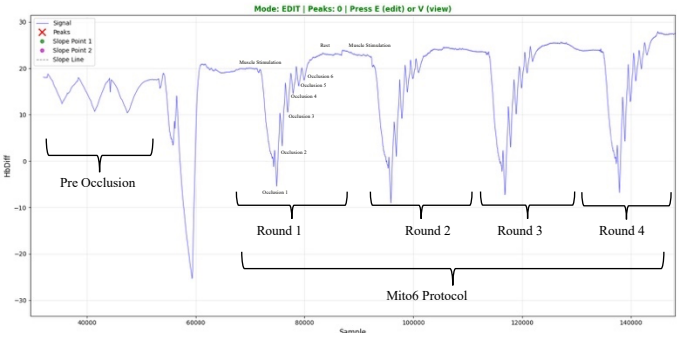

Fig. 6. Data from current device.

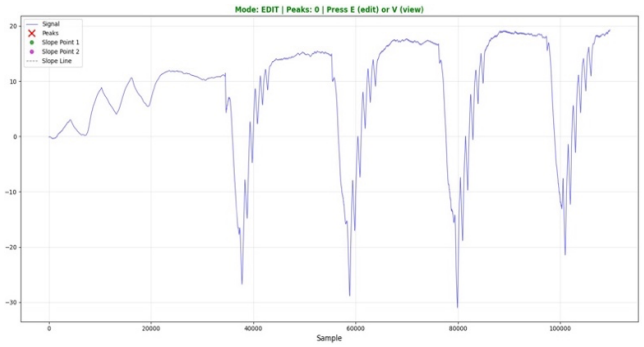

Fig. 7. Data from our new device.

Testing confirmed that the device could successfully execute synchronized occlusion and stimulation cycles without manual intervention. This represents a significant improvement in usability and repeatability.

Comparative tests were conducted on the same subject using both devices, with the resulting graphs displayed above. The trend lines differ slightly due to variations in testing

procedure; however, the new device's occlusion mechanism performs as intended, producing a clear dip in the data at each occlusion event. Overall, both devices yield comparable trends throughout the Mito 6 protocol, which consists of four rounds of electrical stimulation, six occlusions, and a resting period, as illustrated above.

Validation was further conducted by comparing the k-values derived from both devices. The k-value quantifies how quickly muscle tissue returns to its resting slope following blood occlusion. In other words, k-value is a constant rate at which mitochondria return to metabolic equilibrium. A higher k-value indicates a greater capacity for the mitochondria to restore their metabolic rate. The current device yielded a k-value of 0.027, while the new device yielded 0.024, a difference of approximately 10%. This variation falls within the accepted range of physiological and instrumentation variability, as muscle metabolism data is known to fluctuate day-to-day.

IV. Conclusion

This project presents the development of a portable, automated device designed to safely and accurately assess skeletal muscle mitochondrial function using the standardized Mito6 protocol. By integrating near-infrared spectroscopy (NIRS), controlled blood flow occlusion, and electrical muscle stimulation into a single, user-friendly system, the device addresses many of the limitations associated with current complex and invasive measurement techniques.

With built-in safety mechanisms, including pressure monitoring through motor resistance and durable, protective housing materials, the system prioritizes both reliability and user protection. By automating key components of the testing process, this device improves consistency, reduces operator variability, and enhances accessibility to advanced muscle diagnostics.

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