COMPARISONS OF LEG, ARM, AND BACK MUSCLE OXYGENATION DURING ROWING EXERCISE USING NEAR INFRARED SPECTROSCOPY

By

LUCAS SAACKS

Honors Thesis

Appalachian State University

Submitted to the Honors College and the Department of Health & Exercise Science in partial fulfillment of the requirements for the degree of

Bachelor of Science

May 2020

Approved by:

Abigail Stickford, Ph.D., Thesis Director

Jennifer Burris, Ph.D., Second Reader

Jefford Vahlbusch, Ph.D., Honors College Director

Herman van Werkhoven, Ph.D., Exercise Science Honors Director

Abstract

Introduction: Indoor rowing is an increasingly popular mode of exercise that provides a total-body workout. In a proper rowing motion, muscles in the leg, back, and arm are utilized sequentially (Secher, 1993). These different muscle groups, which vary in terms of muscle fiber composition, all consume oxygen during rowing exercise. However, it is unknown how changes in muscle oxygenation during an acute bout of rowing may differ between these primary working muscles. **Purpose:** The purpose of this study was to assess the deoxygenation in exercising muscles based on their oxidative properties and to further the research into new near infrared spectroscopy (NIRS) technology.

Methods: Male and female college-age subjects were recruited for this study. NIRS devices were placed on the vastus lateralis, biceps brachii, and erector spinae muscles to measure oxygen saturation during rowing exercise. Subjects rowed for two minutes each at three different relative (i.e., based on percent of maximal power output) exercise intensities, in a randomized order. Muscle oxygen saturation (SmO_2) and total hemoglobin content (THb) were continuously monitored during each stage, as well as in the rest periods between each stage. **Results:** Data indicate strikingly similar trends in muscle oxygen consumption in men and women during rowing. Additionally, SmO_2 in the vastus lateralis decreased to the greatest degree out of the three muscle groups, regardless of intensity. The deoxygenation of the biceps and erector muscles, however, were not significantly different from each other. THb, like SmO_2, increased from rest to exercise, but was not significantly different between the exercise intensities. The difference between male and female THb across all time periods was significant, as males exhibited a higher THb than females. **Discussion:** Many results of the study

proved to be insignificant, most likely due to a multitude of variables, including the small sample size, the untrained status of the subjects, and the low reliability of current NIRS devices at high intensity exercise. More research should be performed to further understand the oxidative properties of various muscles groups during rowing exercise as well as advance the reliability of NIRS technology in an athletic setting.

Table of Contents

Introduction

Indoor rowing is an increasingly popular workout that has the potential to be a more aerobically challenging exercise regime than treadmill or cycling workouts (Hagerman, 1984). One of the primary reasons for the increased oxygen demand during rowing is the utilization of a myriad of muscle groups (Secher, 1993). In a proper rowing technique, muscles of the legs, back, and arms sequentially contract to create a powerful, fluid motion. Due to differences in fiber composition and size of the muscles used during this motion, oxygen consumption will vary across the muscle groups (Mannion, 1999). However, it is unknown how changes in muscle oxygenation during an acute bout of rowing may differ between these primary working muscles; further, whether or not men and women, who tend to have differences in both absolute muscle mass and muscle fiber composition, exhibit different rates and/or magnitude of muscle deoxygenation responses during rowing is not clear.

Using near infrared spectroscopy (NIRS), oxygen saturation and hemoglobin concentration in various muscles can be monitored simultaneously. NIRS uses infrared light to travel through the muscle and back up to the detector on the monitor. Based on the amount of light scattered, how much light was absorbed by oxygen molecules can be calculated, and thus saturation of oxygen in the target tissue can be determined. The MOXY NIRS device (Foritori Design LLC, Hutchinson, MN) is a small, lightweight monitor that is placed directly on the skin to record changes in oxygen saturation and hemoglobin content. Its portability makes it ideal for athlete training programs and exercise research. By utilizing data on real-time O_2 usage during workouts, trainers and coaches can prescribe more accurate training intensity zones to maximize their athletes' exercise potentials.

Indoor rowing utilizes arm, leg, and back muscles - three muscles of particular importance to the movement are the vastus lateralis, biceps brachii, and middle erector spinae. The vastus lateralis is the most lateral muscle of the quadriceps group, and it allows for extension of the leg as well as the body to rise up from a squatting position. Due to its frequent use in quick, forceful contractions, the vastus lateralis has a large muscle belly and a blend of slow- and fast-twitch fibers. The biceps brachii is a two-headed muscle that is primarily utilized for elbow flexion. It has a smaller fiber size than the vastus lateralis and has a higher concentration of type II fast-twitch fibers. The erector spinae muscles are a group of thin muscles that run along the spinal column. They work in tandem to maintain posture and bend the trunk forward. Because of the long contractions required to stand and hold the body upright, the erector spinae muscles have the highest concentration of type I slow-twitch fibers in the entire skeletal muscular system. Due to the differences in oxidative capacity of these muscles, they likely will exhibit unique oxygenation curves, despite all being heavily utilized in the rowing movement, in untrained subjects.

Although much research has been published lately assessing the validity and reliability of NIRS devices, few have used NIRS during rowing exercise. Additionally, limited studies have examined the oxygenation of back muscles during exercise using NIRS technology. As such, this project aims to quantify oxygenation changes in different muscle groups throughout rowing exercise in healthy men and women. This study will further advance the research behind NIRS as an assessment tool, and shed more light on the oxidative properties of various muscle groups during rowing exercise.

The main focus of this research is to quantify changes in oxygen saturation during rowing exercise across various muscle groups and intensities. We hypothesize that the degree of deoxygenation is linked to the muscles' fiber sizes and compositions; therefore, the biceps brachii will experience the greatest decline, the vastus lateralis will have an intermediate decline, and the erector spinae will have the least degree of deoxygenation. We also hypothesize that, regardless of order, the high-intensity interval will present with the greatest degree of deoxygenation in all three muscles.

Review of Literature

Introduction

By utilizing near infrared spectroscopy, muscle deoxygenation trends can be observed during exercise. Modern-day NIRS oximeters are highly reliable during exercise (Crum et al., 2017) but have not been used often in an indoor rowing setting. Because rowing requires activation of almost every muscle group in the body (Secher, 1993), muscle deoxygenation occurs in a myriad of muscle groups during rowing exercise and thus should be investigated to find trends and differences in muscles with varying oxidative characteristics.

This study included multiple foci of interest, such as a practical application of near infrared spectroscopy, indoor rowing as an exercise research modality, and the deoxygenation of various skeletal muscle groups during exercise. Because of these wide-spanning topics, this review of literature is split into three main sections: NIRS technology, biomechanical and physiological aspects of indoor rowing, and the anatomical characteristics of the studied muscle groups. Although much research has been published in these three respective categories, there is very limited literature that has previously tied these topics together. This review of literature aims to provide a background on the main variables of research and synthesize them in an investigative setting.

NIRS technology

Continuous wave near infrared spectroscopy (CW NIRS) is a relatively new method to monitor oxygen saturation in human subjects. Early on in the development of this technology, McCully & Hamaoka (2000) detailed the specific processes of muscle oxygenation monitoring via NIRS. CW NIRS monitors use a continuous stream of infrared light between 700 and 900 nm that penetrates the tissue; in most instances, that specific tissue is skeletal muscle. Heme compounds found in hemoglobin and myoglobin reflect or scatter this stream of infrared light. Because oxygen molecules attach to heme to get carried through the blood, the amount of light absorbed by these compounds can determine how much oxygen is in a given tissue. Using the Beer-Lambert Law, the amount of light scattered by the heme compounds is calculated to determine a percentage of oxygen saturated in that tissue.

NIRS technology has been used to measure muscle oxygenation since the late 1980's (Ferrari et al., 2011). Since then, major improvements have been made in the cost and portability of NIRS-based oximeters (Grassi & Quaresima, 2016). Research using NIRS devices has focused on two main settings: exercise and clinical applications. It has been proven that NIRS technology can be used for a wide array of exercise training modalities (Neary, 2004), such as skiing, speed skating, cycling, running, and rowing. NIRS has also aided in clinical diagnostics. Jobsis (1977) utilized a very early NIRS system to monitor oxygenation in the cerebral circulatory pathways, assisting in patients' diagnoses of a stroke. More recently, NIRS devices have monitored cardiac rehab patients with chronic heart failure during exercise (Mezzani et al., 2013).

The main focus of research today regarding NIRS technology is the performance of NIRS-based oximeters during exercise. Grassi & Quaresima (2016) created a review detailing the extensive uses of NIRS oximeters during exercise as well as the myriad of physiological variables these devices can provide. These variables include: regional blood flow, O_2 consumption, and O_2 extraction at the skeletal muscular level. By utilizing these variables, cardiac output (Q) can then be determined based on NIRS technology alone. In addition, NIRS oximeters also have been shown to align with various physiological thresholds, such as the ventilatory threshold (Bhambhani et al., 1997) and the onset of blood lactate accumulation (Grassi et al., 1999). It is also well known that regional blood flow to the skin increases during exercise due to the increase in body core temperature (Kenney & Johnson, 1992). When NIRS technology started to become more widely available in the early 21st century, researchers tested the effects of the increase of skin blood flow on NIRS oxygenation measures. Buono et al. (2005) state that any increase in skin blood flow, due to heating or exercise, will negatively affect NIRS recordings due to the large increase in hemoglobin. However, Tew et al. (2010) argue that NIRS oxygenation values only lose reliability due to increased skin blood flow during moderate or high intensity exercise.

Although previous literature has debated a possible limitation to determining O_2 extraction via NIRS, there is no doubt that a subcutaneous adipose tissue layer is indeed a limitation of current NIRS technology. There is, however, an ongoing debate in research whether a concrete threshold on the amount of adipose tissue exists or not. Hamaoka et al. (2011) argue that an adipose tissue thickness (ATT) of 5mm will reduce the signal intensity, but is not significantly reduced until the layer of ATT is over 15mm. Niemeijer et al. (2017) expand on this limitation, stating that NIRS signals are altered by an ATT layer of as little as 1mm. Additionally, due to the highly oxygenated blood found in adipose cells, they conclude that a higher ATT will cause NIRS signals to inaccurately report a higher muscle oxygenation value. Some correction algorithms have been created for in-laboratory NIRS monitors. Grieger et al. (2013) recommended a Monte Carlo-based correction model that allows for a greater spectral view when subjects present a large ATT (~15 mm). Although simulations like the Monte Carlo model exist in some settings, they are not widely incorporated in commercial NIRS devices. Therefore, current research in NIRS oximeters is limited to a lean, healthy subject population (Ferrari et al., 2011).

The NIRS device used in this study is the MOXY Muscle Oxygen Monitor (Foritori Design LLC, Hutchinson, MN). Due to its small size (61x44x21 mm) and lightweight design (42g), MOXY oximeters are ideal for athlete training regimens and exercise research, since the devices will not impede on any forceful movements. Its small size also indicates that these devices measure local muscle oxygenation characteristics, instead of whole-body O_2 changes. Crum et al. (2017) determined that, from rest to moderate intensity exercise, MOXY sensors show a high reliability of muscle oxygenation values. At high intensity exercise, however, the sensors become much less reliable. This is a common pattern among all NIRS devices (Thiel et al., 2011), and can be attributed to the increase in muscle contraction causing an impairment in muscle perfusion, leading to a more variable oxygenation recording. When compared to the PortaMon, a NIRS oximeter similar in size and cost, the MOXY sensor showed a greater change in muscle oxygenation values from rest to maximal exercise (McManus et al., 2018). This literature reveals that, at exercise intensities less than maximal, the MOXY muscle oxygen monitor is both a valid and reliable device to measure muscle oxygenation in a training or research setting.

Indoor Rowing

Although rowing has been of interest in an exercise science research setting for over 150 years (Warmenhoven et al., 2018), it has never been as popular as other aerobic exercise modalities, such as running or cycling. Since 2016, 38,100 results appear when searching for “treadmill exercise” publications; 46,000 appear for “cycling exercise”; and 20,000 results appear for “rowing exercise” publications. However, when studied properly, rowing can provide excellent data on a myriad of biomechanical and physiological variables.

When compared to treadmill running or indoor cycling, indoor rowing provides a much more holistic exercise modality. This is because rowing requires activity from almost every muscle group in the body (Secher, 1993). An early study found high muscle activity in major muscles of the arms, legs, and back (Ishiko, 1967). A proper rowing motion utilizes these muscles in a sequential order. According to Concept2 (“Technique Videos”), the leading manufacturer of rowing ergometers and the device used in this study, the motion can be broken down into four segments: the ‘catch’, the ‘drive’, the ‘finish’, and the ‘recovery’. The catch phase is the beginning of the motion. It serves as a baseline position to return to after each stroke. During this phase, the arms are extended, the back is slightly bent, and the handlebar is in its neutral position by the flywheel. The drive is the second, and arguably most important, technique in the motion. The drive involves movement of the legs, arms, and back to pull the handlebar away from the flywheel and towards the chest. The finish phase is a static position to hold the body in an isometric contraction after the drive concludes. The final phase is the recovery, where the body relaxes in the opposite order of the drive and returns to the catch phase to begin the next stroke. Although there is much debate in the time spent in the drive versus the recovery phase, Umar et al. (2019) found in elite rowers a drive to recovery ratio of 1:1 in off-water rowing.

The drive can further be broken down into three distinct movements. First, the legs press to push the body away from the starting point. Then, the back swings to extend the core. Finally, the drive ends with the flexion of the arms, bringing the handlebar towards the body. The drive phase has been the most researched phase within the rowing motion. Many biomechanical studies have compared and contrasted ergometer motions to on-water rowing forms. Although ergometers in many ways accurately simulate on-water rowing, Lamb (1989) found a difference in arm kinematics between the two forms. Bazzucchi et al. (2013) analyzed electromyographic data of eight various muscles to determine that muscle activation is slightly lower in ergometric rowing compared to on-water rowing. Another point of interest has been the differences in kinematics between elite rowers and non-rowers. Non-rowers vary significantly in body posture and stroke technique when compared to elite rowers (Cerne, 2013). Since all subjects of this current study were classified as non-rowers, it was pertinent to advise them on proper rowing techniques based on the Concept2 guidelines.

As with other modes of exercise, there are a plethora of physiological responses to ergometric rowing. The metabolic cost of rowing is split, with 70% of the energy contribution coming from aerobic pathways and 30% coming from anaerobic pathways (Hagerman et al., 1978). This requires the rower to possess both anaerobic power as well as cardiorespiratory endurance. Ventilation (V_E) increases during rowing (Das et al., 2019) and exhibits a non-linear increase after a threshold, similar to other cardiorespiratory workouts (Bunc & Leso, 1992). It has also been observed that the increase in ventilation is associated with a higher breathing frequency and a lower tidal volume (Szal & Schoene 1989). Maximal oxygen consumption (VO_{2max}) is higher in indoor rowing than treadmill running (Yoshiga & Higuchi, 2003) as well as indoor cycling (Lindenthaler et al., 2018). On average, VO_{2max} is typically achieved within two minutes of high-intensity rowing (Hagerman, 1984). It is due to this literature that the workout intervals implemented in this study last two minutes each, as most individuals cannot perform at their capacity for much longer after VO_{2max} is achieved.

The most relevant physiological variable to this study is skeletal muscle oxygenation (SmO_2). Utilizing early NIRS technology, Belardinelli et al. (1995) found that SmO_2 in the vastus lateralis decreases during an incremental cycling exercise. As the subjects neared VO_{2max}, however, the decrease of SmO_2 slows, resulting in a plateau when VO_{2max} was achieved. Immediately following the stoppage of exercise is a phenomenon known as “oxygen debt.” Once exercise stops, the active skeletal muscle continues to demand a great amount of blood flow, causing a sharp increase in oxygen saturation in the beginning stages of recovery (Knuttgen, 1970). Oxygen debt has been observed in recovery from ergometer rowing as well (Chance et al., 1992). Using NIRS, Zhang et al. (2010) compared the changes of muscle oxygenation in the vastus lateralis and biceps brachii during an incremental rowing exercise. They found that both the “breaking point”, the point in which muscle oxygenation severely drops at the beginning of an exercise, and the “leveling-off point”, the point in which oxygenation plateaus at the end of the interval, occur earlier in the biceps brachii than in the vastus lateralis. This allows us to infer that various muscle groups have differing oxidative capacities, and these capacities can be determined through the observation of muscle oxygenation during exercise.

Fiber Characteristics of the Vastus Lateralis, Biceps Brachii, and Erector Spinae

Scott et al. (2001) outlined seven different types of human skeletal muscle, all placed on a spectrum from slowest-twitch to fastest-twitch. Of these seven types, three are most commonly seen: type I, type IIa, and type IIb (Simoneau & Bouchard, 1989). Type I fibers are considered slow-twitch yet have a bountiful network of capillary beds providing oxygen; it is because of this high oxygen content that type I fibers are linked to endurance exercises. Coyle et al. (1992) found a high percentage of type I fibers in the vastus lateralis of trained cyclists. Type II fibers, both IIa and IIb, are less oxidative than type I but are faster-twitch, allowing for more power to be generated. Type II fibers are more commonly found in athletes utilizing short, quick movements, such as power lifters (Fry et al., 2003). For this study, the fiber type characteristics of the vastus lateralis, biceps brachii, and erector spinae should be taken into consideration. Each muscle has a unique size and fiber composition, thus allowing for differing oxidative capacities.

The erector spinae muscles are a group of skeletal muscles that run down both sides of the spine, mainly functioning to keep the upper body in an upright position. These muscles also assist in forward bending and lifting (Bogduk, 2005), activating them during the drive and catch of the row. Because of the long, low-force contractions required to maintain posture, type I slow-twitch fibers are the main paraspinal muscle fiber. On average, type I fibers comprise 62.0% of the erector spinae in men and 67.8% in women (Mannion, 1999). The predominance of type I fibers make the erector spinae unique to most other muscle groups.

Contrary to the erector spinae muscles, the biceps brachii have a much lower concentration of type I fibers. Klein et al. (2003) found that type II fibers make up about 60% of the biceps brachii in both young and elderly males. This fiber concentration allows for higher force generation yet faster fatigue (Gerdle et al., 1990). As the muscles mainly responsible for elbow flexion (Nygaard et al., 1983), the biceps brachii are essential to the rowing stroke.

The vastus lateralis muscle, the main driving force of the rowing stroke, has a unique blend of fast- and slow- twitch fibers. Of the three main fiber types, Staron et al. (2000) discovered that approximately 40% of the muscle is made up of type I fibers, 30% is type IIa, and 20% is type IIb in both male and female subjects. A more homogenous mix of fiber types grants the vastus lateralis a higher force production than erector spinae muscles as well as less fatigability than the biceps brachii. Along with this blend of fibers is the overall size of the vastus lateralis. The vastus lateralis has a considerably larger cross-sectional area than the biceps brachii (Miller et al., 1993) as well as the group of erector spinae muscles (Delp et al., 2001). This larger size will also lead to a greater force production (Tonson et al., 2008).

When the vastus lateralis, biceps brachii, and erector spinae muscles are ordered by type I fiber concentration, the erector spinae would be highest, the vastus lateralis would be in the middle, and the biceps brachii would be the lowest. Ordered by type II fiber concentration, these muscles would be in the exact opposite order. This means that the erector spinae should have the highest oxidative capacity and should fatigue the least during exercise. In contrast, the biceps brachii should fatigue the quickest, due to its higher concentration of type II fibers. Amann et al. (2006)

established a connection between muscle fatigue and oxygen saturation; therefore, the rate of deoxygenation should coincide with the fatigability of the observed muscle groups.

Summary

This review of literature aimed to provide a history of research on the various topics pertinent to this study. It is clear that there is a link between the use of NIRS technology, indoor rowing exercise, and the oxidative properties of muscles. However, we have not seen an all-encompassing synthesis of these topics. Studies have linked a few of these themes that create a prominent background for this current investigation. By observing the deoxygenation trends during rowing using NIRS devices, Zhang et al. (2010) provided the most relevant data for this investigation, but did not study the erector spinae muscles. Chance et al. (1992) also observed oxygenation trends during rowing, but limited their scope to the quadriceps muscle using outdated NIRS technology. A widespread viewpoint of current literature was necessary to gather information across multiple scientific topics, with the aim to bring them into one cohesive research project.

Methods

Subjects

All study protocols were approved by the Appalachian State University Institutional Review Board (IRB# 19-0289). Twelve healthy subjects (6 women) of varying fitness levels participated in this study. All subjects were between the ages of 18 and 35 and had an adipose tissue thickness of less than 13 mm at the vastus lateralis, biceps brachii, and middle erector spinae, as measured via ultrasound (GE Vivid 7, Chicago, IL). Subjects were free from cardiovascular, metabolic, or renal disease as well as suggestive signs and/or symptoms of disease.

Experimental Design

Following screening and consent, subjects came to the lab for a single visit. To assess the subject's level of physical fitness, the International Physical Activity Questionnaire (IPAQ) (Booth, 2000) was administered at the beginning of the visit. After completing the IPAQ, anthropometry was assessed using a weight scale and stadiometer, and adipose tissue thickness (ATT) was measured via ultrasound at the three target sites. According to the literature, an ATT layer of 13 mm or more will significantly affect the muscle oxygenation measures. Therefore, any subject with 13 mm or more of ATT at any of the three muscle sites was excluded from the study. The ultrasound sites of the vastus lateralis, biceps brachii, and erector spinae muscles were based off of guidelines provided by SENIAM (SENIAM, Enschede, NL). These sites were marked after measuring to ensure placement of the NIRS oximeters aligned with the ultrasound images.

For the full-body exercise stimulus, subjects rowed on an indoor rowing ergometer (Concept2 ©, Morrisville, VT). Due to the flywheel mechanism of a rowing ergometer, it is not possible to set a certain power output like a bike ergometer. The power, measured in watts, is based on the force at which the user rows. Therefore, this study used intervals based on a relative percentage of the subject's individual maximum power output.

Before the subject begins rowing, a familiarization period was administered to inform the subject on a proper rowing motion. After observing the researcher, the subject then practiced this motion, while being observed and receiving feedback from the investigator, for five minutes at a very low intensity. This practice also serves as a warm-up before the maximal power output test. After familiarizing themselves with the rowing motion, the subject then performed a maximal power output test, wherein they were instructed to row as forcefully as possible. Their power output was observed on the P5 monitor attached to the rower (Concept2 ©, Morrisville, VT). The power typically increased with each row for about 5 strokes. Then, once the power starts to decrease, the subject was informed to stop and the highest wattage was recorded as their max. This process typically took about 15 seconds.

Percentages of the recorded max were then calculated. Since it is virtually impossible to row at a singular power value, ranges of power were calculated and the subject was instructed to row within that range for 2 minutes. The ranges are: 20-30% (light), 40-50% (moderate), and 60-70% (vigorous) of the subject's maximal wattage.

After a short rest period following the max test, the three NIRS devices were placed on the subject's vastus lateralis (VL), biceps brachii (BB), and erector spinae

(ES) muscles. MOXY muscle oximeters were used in this study to measure muscle oxygenation and hemoglobin (Foritori Design LLC, Hutchinson, MN), and PeriPedal software was used to measure and record this data (Peripedal ©, 2018). All devices were placed on the right side of the body according to the sites imaged by the ultrasound earlier in the visit. To ensure a tight fit and continuous monitoring, the oximeters were attached with MOXY adhesives (Foritori Design LLC, Hutchinson, MN), as well as reusable cotton wraps.

After placement of the oximeters, estimates of muscle oxygenation (SmO_2) and total hemoglobin (THb) were continuously recorded. Resting values were recorded for five minutes. The order of the three exercise intervals was randomized. After the five minute rest period, the subject then rowed at each of the exercise intensities, with five minute rest periods separating each workload. After the final rest period, recording was stopped and the devices were removed. MOXY oximeters collect and report data every second. For this investigation, averages based off of these data were calculated.

Data Analysis

Data are presented as means ± standard errors. Statistical analysis was performed using IBM SPSS Statistics 26 (Armonk, NY). To determine differences in the dependent variables between the various intensities and muscle groups, two-way repeated measures ANOVA tests were performed. Specifically, we examined SmO_2 and THb of three muscle groups (VL, BB, ES) and four time points: the average of the first rest period and the average of the second minute of each interval: 20%, 40%, and 60%. Furthermore, because sex is known to affect total hemoglobin, sex was used as a between-subjects factor for analysis of changes in THb. When a significant interaction was found, simple main effects were examined with adjustment for multiple comparisons. Significance was set at $\alpha = 0.05$.

Results

Seven subjects consented to participate in this study and completed the exercise in its entirety. Four subjects were male and three were female. Using International Physical Activity Questionnaire (IPAQ) criteria, four subjects were classified as 'highly physically active' and three were classified as 'moderately physically active'. Every participant was able to achieve the average wattage range required to row for each interval, except for one subject who did not reach within 60% of their final interval, but rowed for two minutes at a perceived high intensity regardless. Table 1 describes the body composition and characteristics of the seven subjects.

Subject	**Sex**	**Age (yr)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**	**ATT_VL (mm)**	**ATT_BB (mm)**	**ATT_ES (mm)**	**Max (W)**
001	M	21	184.1	71.4	21.1	5.2	3.6	4	473
002	F	27	165	72.6	26.7	9.5	7.3	12.1	265
003	F	22	162.9	62.1	23.4	7.3	5.8	2.8	144
004	M	22	174.1	71.9	23.7	3.9	4.1	2.9	498
005	M	21	195	72.9	19.2	4.4	2.4	4.1	475
006	M	21	191	91.6	25.1	6.6	4.1	7.1	768
007	F	22	175.2	56.2	18.3	6.4	2.7	5.9	200
Mean		**22.3**	**178.2**	**71.2**	**22.5**	**6.2**	**4.3**	**5.6**	**403.3**
SD		**2.1**	**12.3**	**11.0**	**3.1**	**1.9**	**1.7**	**3.3**	**215.9**

Table 1. Subject body composition and characteristics. BMI: body mass index. ATT: adipose tissue thickness. VL: vastus lateralis. BB: biceps brachii. ES: erector spinae. Max: maximal power.

The average age was 22.3 years (±2.1). The average height was 178.2 cm (±12.3) and the average weight was 71.2 kg (±11.0), leading to an average BMI of 22.5 (±3.1) kg/m^2. Five subjects were either in the underweight or normal weight range for

BMI, and two were in the bottom tier of the overweight range. None were classified as obese. The average adipose tissue thickness (ATT) measured via ultrasound at the three sites were 6.2 mm (±1.9) at the vastus lateralis, 4.3 mm (±1.7) at the biceps brachii, and 5.6 mm (±3.3) at the erector spinae; these ATT were not significantly different from each other (p=0.091).

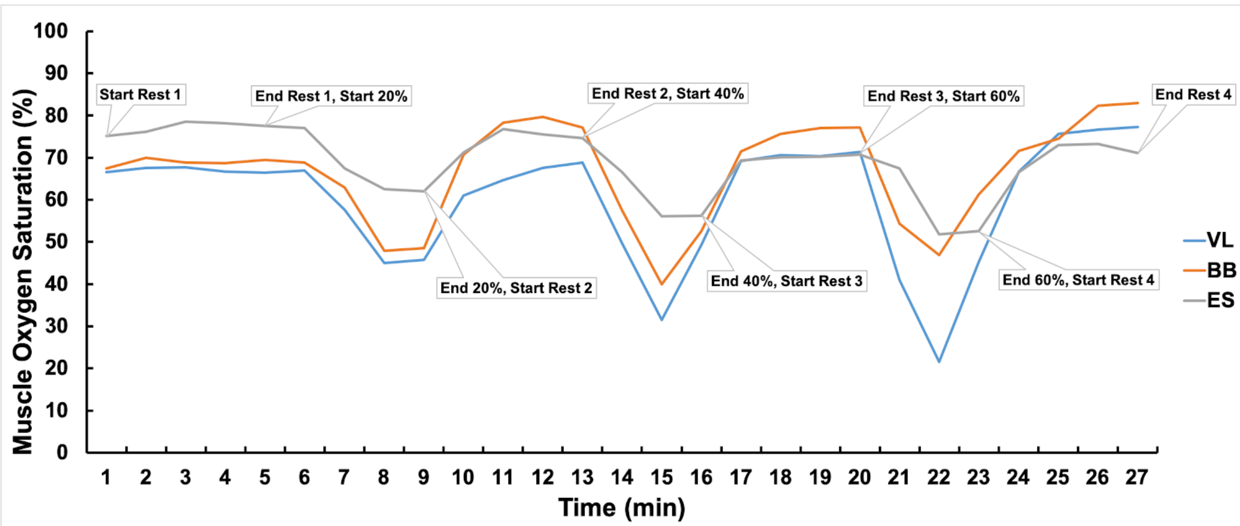

Figure 1. Minute average of muscle oxygenation of vastus lateralis (VL), biceps brachii (BB), and erector spinae (ES) during rowing exercise. An average was calculated each minute throughout both the rest periods and rowing intervals. The start and end of each interval and rest period is labeled.

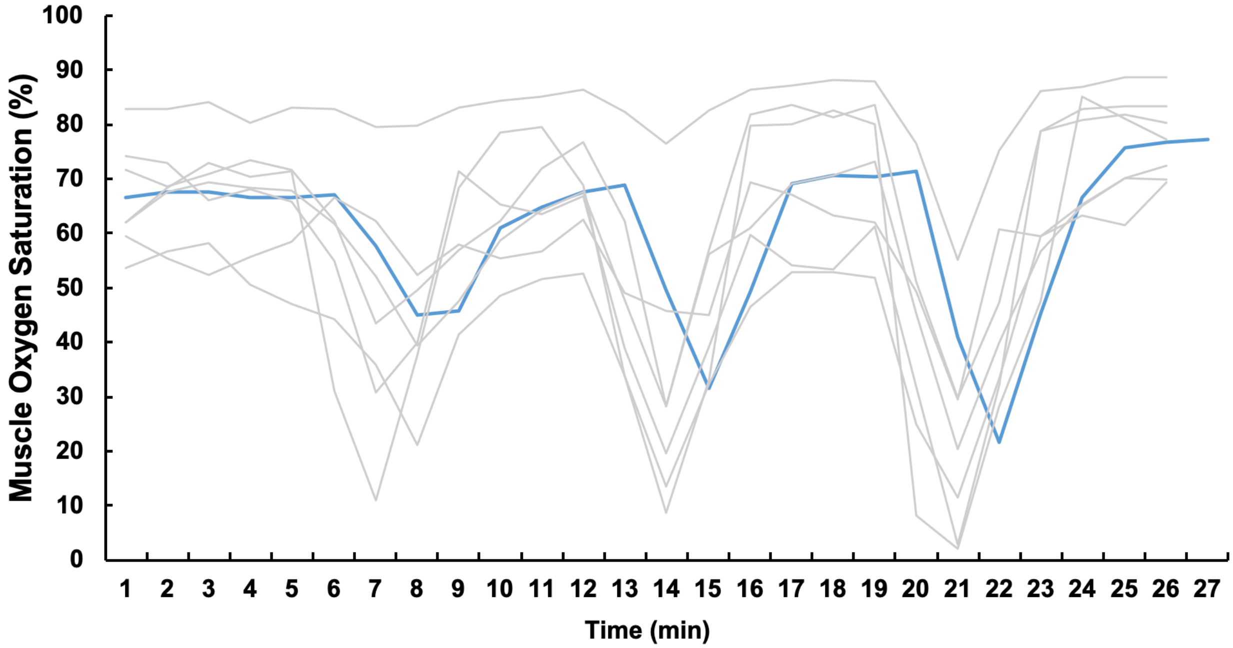

Figure 2. Minute average of muscle oxygenation of vastus lateralis during rowing exercise. The solid blue line represents the average of all seven subjects; each grey line represents the minute average of an individual subject.

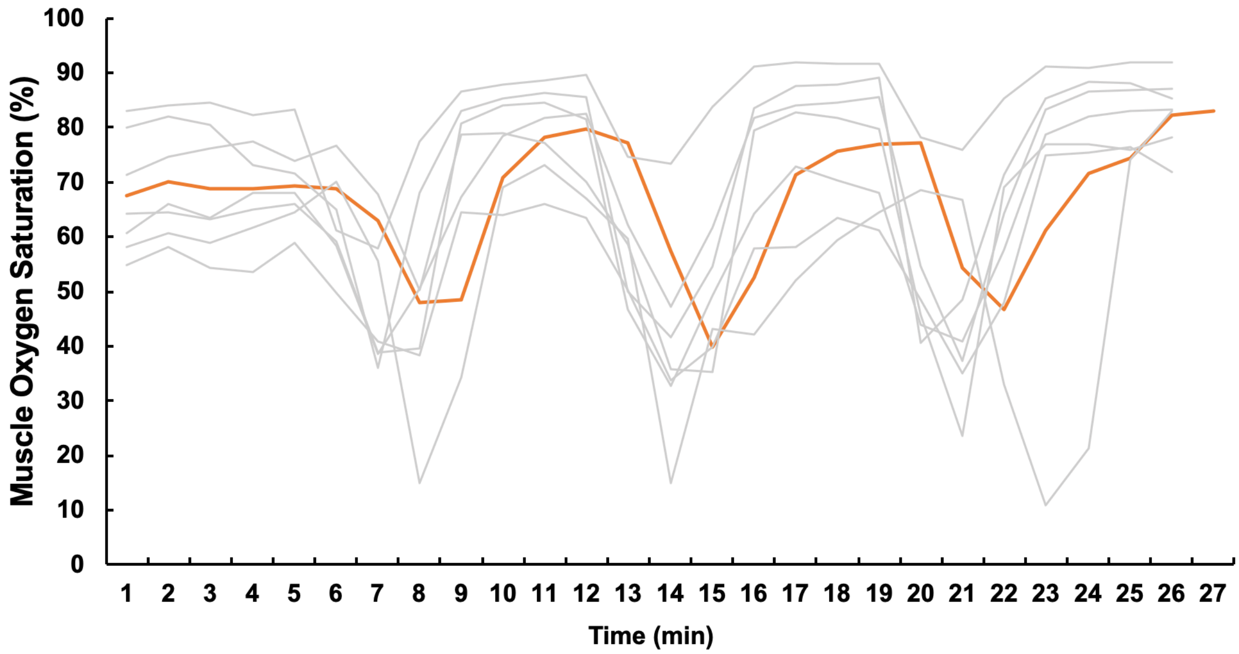

Figure 3. Minute average of muscle oxygenation of biceps brachii during rowing exercise. The solid orange line represents the average of all seven subjects; each grey line represents the minute average of an individual subject.

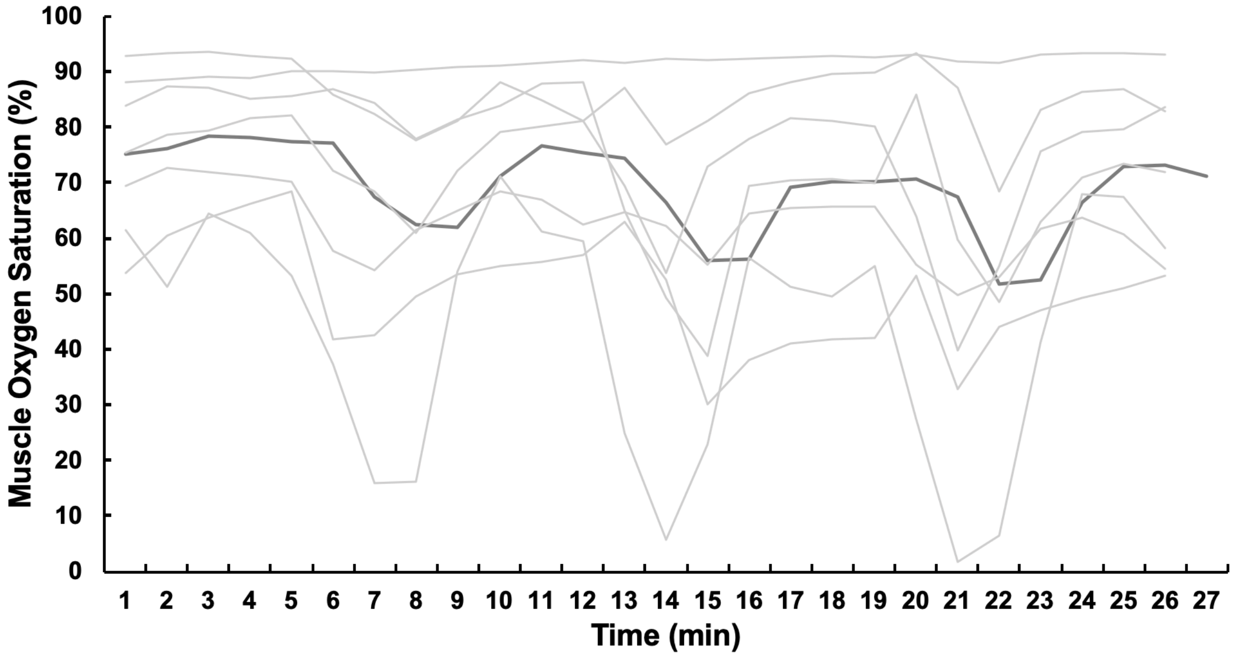

Figure 4. Minute average of muscle oxygenation of erector spinae during rowing exercise. The solid black line represents the average of all seven subjects; each grey line represents the minute average of an individual subject.

Figure 1 shows a comparison of the oxygenation of the vastus lateralis (VL), biceps brachii (BB), and erector spinae (ES) muscle groups during the rowing exercise. NIRS data collection began after the subject performed a maximum power test and wattages were calculated for their three intervals. Resting values were recorded for five minutes after the subject's oxygen characteristics returned to a baseline after the maximum power test. Then, the subject rowed at three varying intensities for two minutes each, with a five minute rest period in between each interval. Another five-minute rest period was recorded after the final interval. Averages of muscle oxygen saturation (SmO_2) were taken every minute in each of the three muscle groups.

Figures 2, 3, and 4 outline the oxygenation of each muscle group during rowing exercise. Each sharp decline indicates a period of exercise, while the subsequent increases represent the beginning of the following rest period. There was a significant main effect of time (i.e., interval/intensity). Across all muscle groups, SmO_2 in each interval showed a significant difference from the rest period (rest vs. 20%: p=0.004, rest vs. 40%: p=0.001, rest vs. 60%: p<0.001). The SmO_2 during the 20% interval was also significantly higher than the 60% interval (p=0.017) and, while not statistically different (p=0.051), tended to be higher than the 40% interval. There was no difference in SmO_2 during the 40% compared to the 60% interval (p=0.474).

The repeated measures ANOVA test was performed for three muscles (VL, BB, ES) and four major time points (average of first rest period, and minute 2 of 20%, 40%, and 60% intervals). The test indicated a significant main effect of muscle group. Across each time period, the oxygenation of the VL was significantly less than both the BB (p=0.027) and the ES (p=0.050). The BB and the ES, however, were not significantly different from one another (p=0.176). When observing both time and muscle, the SmO_2 of the VL was different at all four time points. The SmO_2 of the BB was different from rest to each of the exercise intensities, but was not different from one exercise intensity to another. As with the BB, The ES SmO_2 was different from rest to each of the exercise intensities, but was not different from one interval to another. Figure 5 shows the SmO_2 of muscle groups at each of the four time periods.

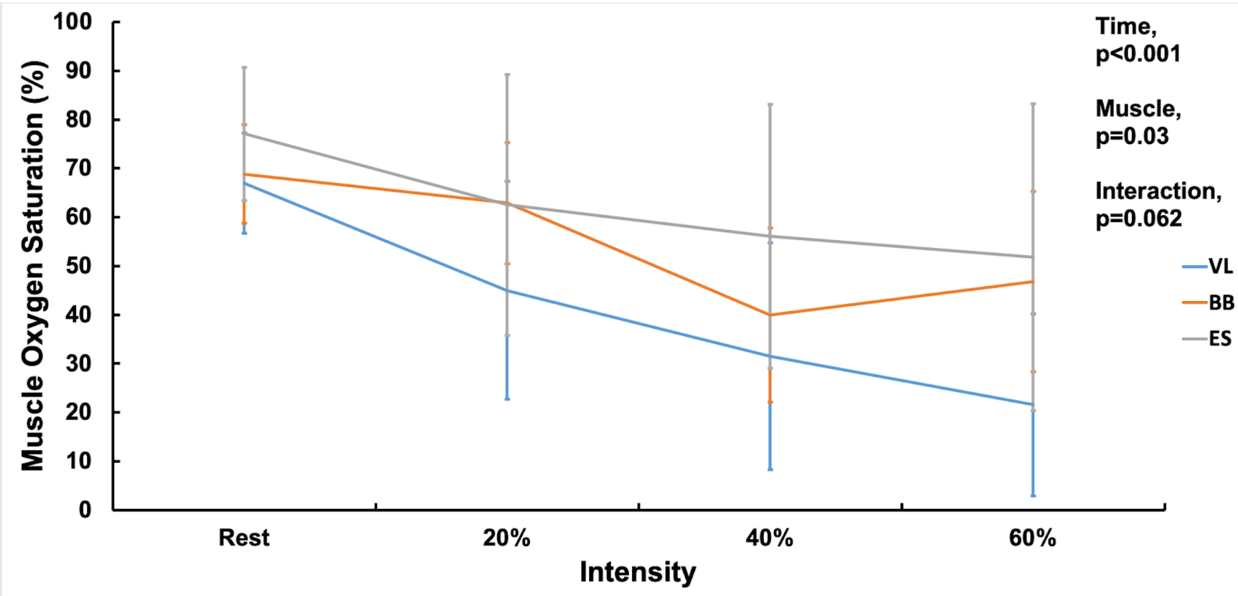

Figure 5. Minute averages (± SE) of vastus lateralis (VL), biceps brachii (BB), and erector spinae (ES) muscle oxygenation during four major time periods.

As for total hemoglobin (THb), there were fewer significant differences between intensities and muscle groups than what was observed in SmO_2 (Fig 6). There was no significant difference in THb between the time points (p=0.094), but there was a significant main effect between the muscle groups (p=0.039). The THb of the BB was found to be greater than the ES (p=0.021) and tended to be higher than the VL as well (p=0.06). No difference was found in THb between the ES and the VL. As would be expected, there was a significant effect of sex (p=0.039), with men (12.648 g/dL) (Fig 7) having higher estimates of THb than women (11.932 g/dL) (Fig 8). A comparison of the two sexes is displayed in Figure 9. There was no time x muscle interaction (p=0.106), muscle x sex interaction (p=0.271), or time x muscle x sex interaction (p=0.093).

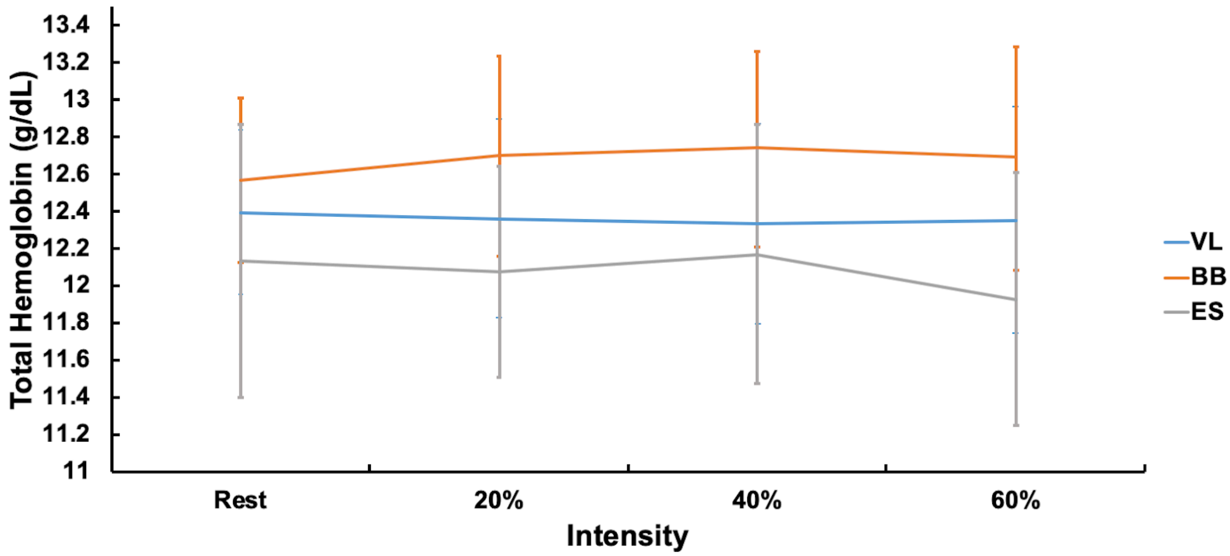

Figure 6. Minute averages (±SE) of total hemoglobin content of the vastus lateralis (VL), biceps brachii (BB), and erector spinae (ES) during four major time periods.

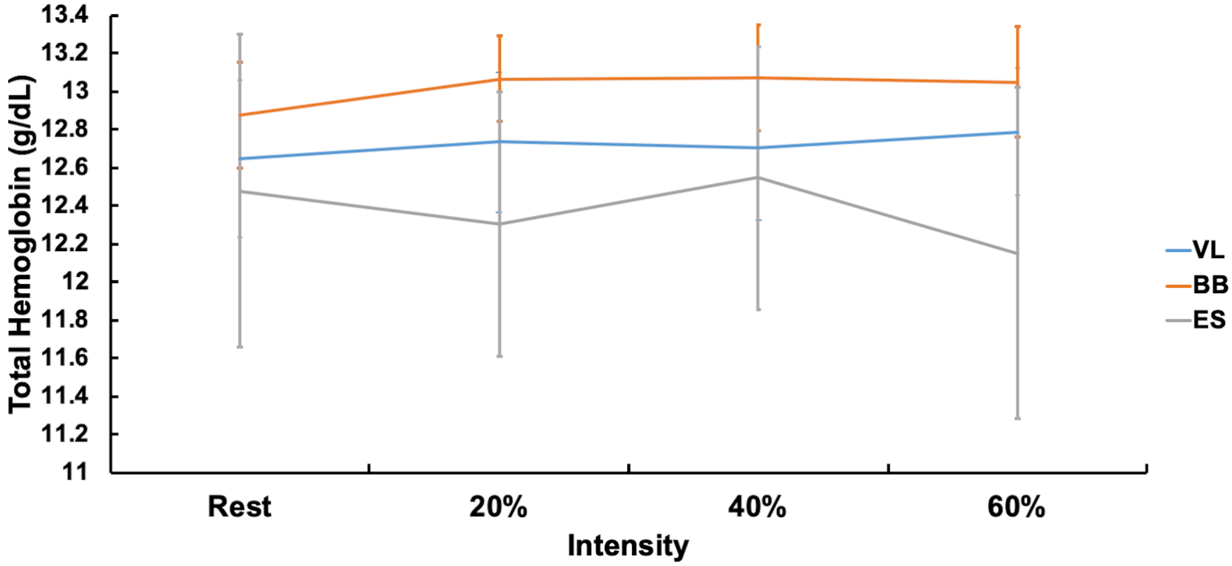

Figure 7. Minute averages (±SE) of total hemoglobin content of the vastus lateralis (VL), biceps brachii (BB), and erector spinae (ES) of male subjects during four major time periods.

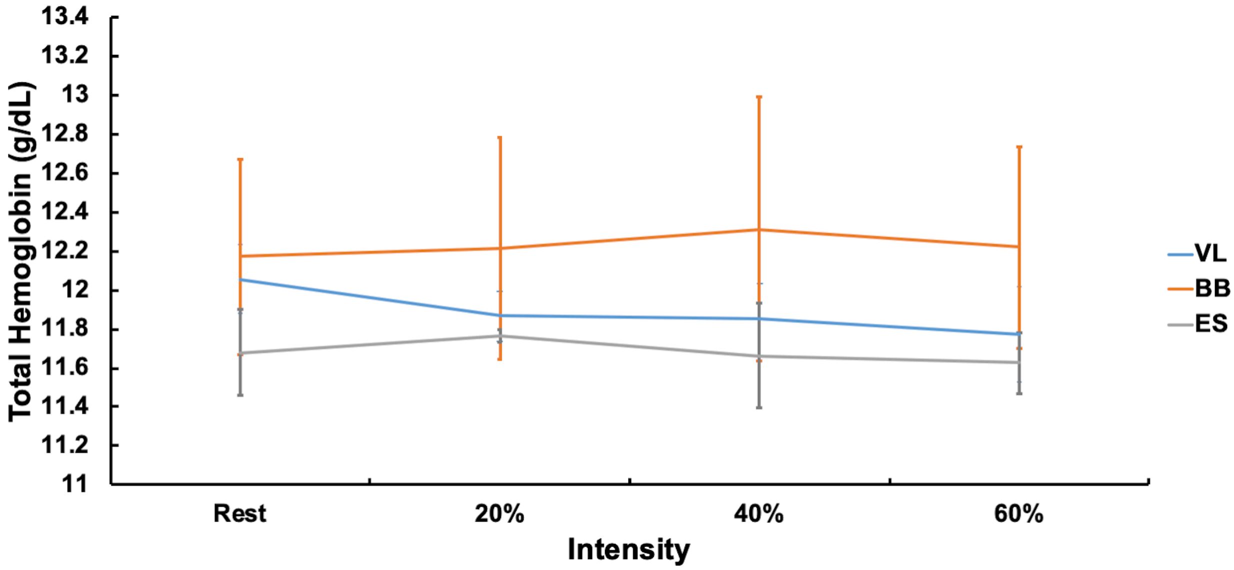

Figure 8. Minute averages (±SE) of total hemoglobin content of the vastus lateralis (VL), biceps brachii (BB), and erector spinae (ES) of female subjects during four major time periods.

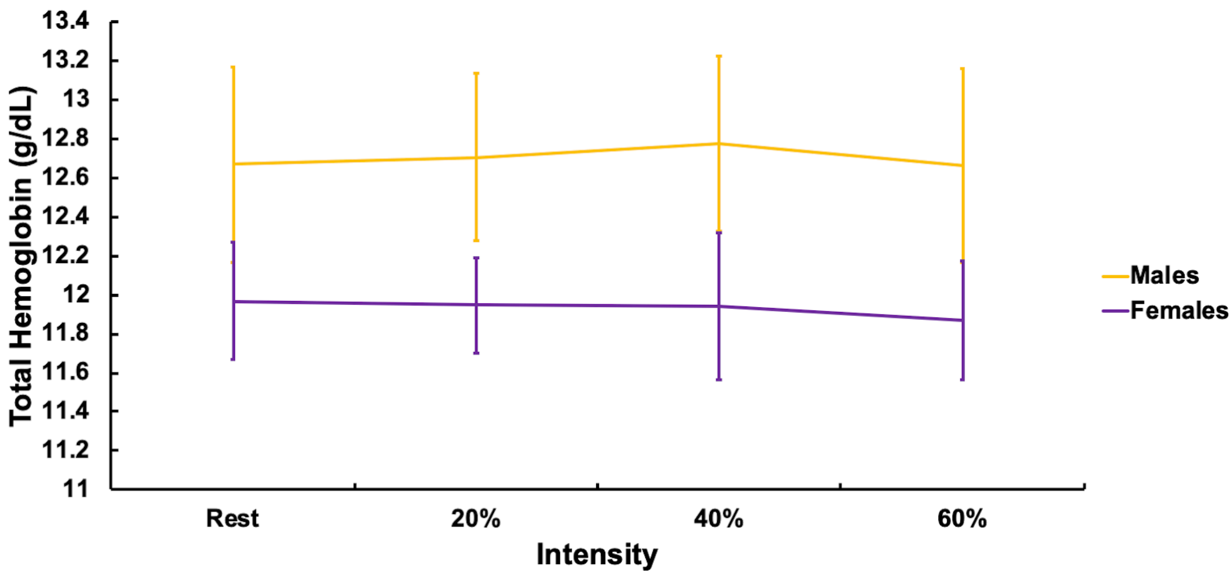

Figure 9. Minute averages (±SE) of total hemoglobin content of male and female subjects during four major time periods.

Discussion

The purpose of this study was to assess the deoxygenation in exercising muscles based on their oxidative properties. Utilizing near infrared spectroscopy (NIRS) during rowing exercise, we were able to monitor oxygen saturation trends in the vastus lateralis (VL), biceps brachii (BB), and erector spinae (ES) muscles in healthy young men and women. It was hypothesized that 1) the degree of deoxygenation would be, from largest to smallest: BB, VL, then ES, and 2) the high intensity rowing interval will cause the greatest degree of deoxygenation in all three muscle groups. Seven subjects successfully completed the study. Based on the results, the hypotheses were only partially true. In contrast to our hypothesis, the BB did not experience the most deoxygenation; in all three exercise intervals, the VL had the fastest and most severe decline in oxygen saturation. This aligns with the data and conclusions from Zhang et al.'s (2010) study, which stated that, although it has a greater oxidative capacity than the BB, the VL has prominent deoxygenation and post-exercise reoxygenation trends when studied via NIRS. Consistent with our hypothesis, the ES did, however, experience the slowest and least severe deoxygenation. Prior studies have also found this trend of low deoxygenation in paraspinal muscles (Vrana et al., 2018).

As for the second hypothesis, the high-intensity interval, where subjects were required to row within 60%-70% of their maximum wattage for two minutes, did not prove to be the most deoxygenating section of the exercise test for each muscle group. The VL exhibited its greatest deoxygenation during this interval, but the BB and ES showed no difference between the exercise intervals. Only from rest to exercise did the BB and ES show any significant difference in oxygenation. This contrasts studies that have found that O_2 kinetics directly correlates with exercise intensity (McKay et al., 2009). However, this anomaly is most likely a cause of the low reliability of NIRS oximeters at high-intensity exercise (Crum et al., 2017; Tew et al., 2010) as well as the inexperience of rowing mechanics for the untrained subjects. Most studies, like Zhang et al. (2010), target elite competitive rowers as their subjects. Their high level of stroke repeatability allows for less erratic movements, thus leading to more direct physiological changes in the main muscle groups. Trained rowers are also more likely to retain the ideal drive to recovery ratio of 1:1, as outlined by Umar et al. (2019). Untrained rowers will likely spend more time in the drive than the recovery, causing quicker fatigue and inconsistent form (Shaharudin & Agrawal, 2015). With this previous literature in mind, the unreliable trends in deoxygenation found in this study are most likely due to a multitude of variables- inconsistent movements during the rowing stroke, a greater workload placed on the BB than what is normative, and a low drive to recovery ratio causing greater fatigue at high intensity, leading to low reliability in the MOXY device.

Secher (1993) detailed how consistent training alters the rower's form. With training, the stroke of the rower utilizes less upper body movement and focuses more on the drive of the legs. This trend was not particularly seen in the results of this study; anecdotally, it appeared that the subjects used their arms more than what is required, yet the data show a greater deoxygenation in the VL than the BB, representing increased activity in the legs rather than the arms at higher exercise intensities. It is this unreliable data caused by inconsistent form that leads many researchers to focus on a trained subject population instead of untrained when utilizing rowing exercise.

Zhang et al. (2010) stated that, because of its size and oxygen consumption, the VL is the ideal muscle to measure via NIRS. This is evident in the vast amount of physiology literature that monitors the VL during exercise. In this current investigation as well, the VL exhibited the most evident changes during exercise, as it was the only muscle observed that had significantly different oxygen saturation at rest, low-intensity, medium-intensity, and high-intensity exercise. Both the ES and BB muscles showed a decrease in oxygenation from rest to exercise, but there was no difference between the various intervals. Other muscle groups that are utilized in the rowing stroke, such as the rhomboids, hamstrings, and abdominal muscles should also be observed to achieve a more holistic view of the oxygen kinetics applied to indoor rowing.

This study provided some insight into the changes in oxygenation in the erector spinae muscles during exercise. Compared to the vastus lateralis and the biceps brachii, the erector spinae muscle group is vastly lower in terms of investigative research. This is especially true in exercise studies. This study showed that, while lesser in degree than the other two muscle groups, the erector spinae muscles decrease in oxygen saturation during rowing, proving their function in the stroke. More research should be done on the paraspinal muscles to further understand their oxidative properties and responses to whole-body exercise.

Although it was not a primary focus of this study, total hemoglobin (THb) estimates were also determined via NIRS. An increase in THb during exercise was expected (Novosadova, 1977) because the overall hematocrit in active skeletal muscle increases. However, no significant increase of THb was observed in any muscle at the four time points, though the BB had lower THb than the other muscle groups. This is likely because the BB has a higher concentration of type II anaerobic muscle fibers in comparison to the VL and the ES (Nygaard et al.,1983). Therefore, the VL and the ES both have a greater oxidative blood supply, thus causing an increase in hematocrit and THb. The main finding regarding THb in this study was the difference in THb between the sexes. Despite a small sample size, the average THb of the four male subjects was significantly higher than the average THb of the three female subjects. This sex difference in THb is found in previous literature as well (Sugisaki, 2000). Theories on the reason behind the increased THb in males vary in literature. The most common and widely accepted theory refers to the increase in androgens in males. Murphy (2014) explains how the sex hormone, which is naturally higher in almost all mammalian males, causes an increase in erythropoiesis, otherwise known as red blood cell production. When red blood cell production increases, hematocrit also increases, thus leading to greater levels of THb in males.

Unlike THb, no difference in SmO_2 was found between sexes. Smith & Billaut (2012) found a similar conclusion when comparing deoxygenation and fatigue in men and women after sprint exercises. Although Beltrame et al. (2017) found higher oxygen consumption (VO_2) in men than women during exercise, deoxygenation is simply a percentage of O_2 saturation, correlating more with fitness level and exercise intensity than sex (Grassi & Quaresima, 2016).

Limitations

The main limitation of this study was the small sample size. Due to the university closure, subject recruitment was fully terminated. Seven subjects completed the study before the university closure and thus created the sample pool for this study. This small size resulted in relatively high measures of variability, which negatively impacted our statistical power and ability to detect differences. This investigation should be further carried out in a larger study to allow for a greater sample size and more reliable results.

Another limitation of this study, as outlined earlier, is the use of untrained rowers as subjects. Although a vast majority of users of rowing ergometers are untrained, very few rowing exercise studies utilize untrained subjects. Most research focuses on the physiological changes observed in elite competitive rowers. When comparing oxygenation results of the current investigation to the results of Zhang et al. (2010) and Chance et al. (1992), it is clear that trained rowers can provide more reliability. Even on an ergometer, the form of the stroke is highly reproducible for trained rowers. This allows for clearer results and more accurate changes between exercise intensities. Unlike untrained rowers, the trained rower's stroke will not alter significantly from one intensity to the next. Muscle force is the only differing factor, leading to more direct physiological changes.

Another limitation of this study is the low reliability of current NIRS oximeters at high intensity exercise. This issue was outlined in Crum et al.'s (2017) study that found great validity and reliability in the MOXY device from rest to moderate exercise, but concluded that, due to increased movement and changes in O_2 kinetics, the device becomes significantly less reliable at high intensity exercise. This was exemplified in our study as well; the largest standard errors for both THb and SmO_2 of all three muscle groups occurred during the 60%-70% interval.

Conclusion

This study was the first to examine the oxygenation of multiple muscle groups during rowing exercise using portable NIRS technology. Although the hypotheses were not fully met, this investigation showed some promising data for further research. As NIRS technology continues to become the paramount tool to measure muscle oxygenation during athletic activities, more research will have to be performed in modalities other than cycling, such as treadmill running and rowing, to determine normative values. While a few unforeseen limitations ultimately affected the significance of the results, highlighting changes in oxygenation in various muscles simultaneously allows us gain a deeper understanding of the effects of muscle fiber size and composition on athletic performance. This knowledge can subsequently lead to more targeted training programs with underlying muscle exercise physiology in mind. As NIRS technology improves in portability, cost, and reliability, future research should be performed to further quantify deoxygenation trends in various exercise modalities.

References

Amann, M., Romer, L. M., Pegelow, D. F., Jacques, A. J., Hess, C. J., & Dempsey, J. A. (2006). Effects of arterial oxygen content on peripheral locomotor muscle fatigue. *Journal of Applied Physiology*, *101*(1), 119–127. doi: 10.1152/japplphysiol.01596.2005

Andrea, B. E., Ward, J. L., & Mahler, D. A. (1986). Comparison Of Exercise Performance On Rowing And Cycle Ergometers. *Medicine & Science in Sports & Exercise*, *18*(supplement). doi: 10.1249/00005768-198604001-00403

Bazzucchi, I., Sbriccoli, P., Nicolò, A., Passerini, A., Quinzi, F., Felici, F., & Sacchetti, M. (2012). Cardio-respiratory and electromyographic responses to ergometer and on-water rowing in elite rowers. *European Journal of Applied Physiology*, *113*(5), 1271–1277. Doi: 10.1007/s00421-012-2550-2

Belardinelli, R., Barstow, T. J., Porszasz, J., & Wasserman, K. (1995). Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. *European Journal of Applied Physiology and Occupational Physiology*, *70*(6), 487–492. doi: 10.1007/bf00634377

Beltrame, T., Villar, R., & Hughson, R. L. (2017). Sex differences in the oxygen delivery, extraction, and uptake during moderate-walking exercise transition. *Applied Physiology, Nutrition, and Metabolism*, *42*(9), 994–1000. doi: 10.1139/apnm-2017-0097

Bhambhani, Y. N., Buckley, S. M., & Susaki, T. (1997). Detection of ventilatory threshold using near infrared spectroscopy in men and women. *Medicine & Amp Science in Sports & Amp Exercise*, *29*(3), 402–409. doi: 10.1097/00005768 199703000-00017

Booth, M.L. (2000). Assessment of Physical Activity: An International Perspective. *Research Quarterly for Exercise and Sport, 71*(2), 114-20.

Bunc, V., & Leso, J. (1993). Ventilatory threshold and work efficiency during exercise on a cycle and rowing ergometer. *Journal of Sports Sciences*, *11*(1), 43–48. doi: 10.1080/02640419308729962

Buono, M. J., Miller, P. W., Hom, C., Pozos, R. S., & Kolkhorst, F. W. (2005). Skin Blood Flow Affects In Vivo Near-Infrared Spectroscopy Measurements in Human Skeletal Muscle. *The Japanese Journal of Physiology, 55*(4), 241–244. doi: 10.2170/jjphysiol.t649

Černe, T., Kamnik, R., Vesnicer, B., Gros, J. Ž., & Munih, M. (2013). Differences between elite, junior and non-rowers in kinematic and kinetic parameters during ergometer rowing. *Human Movement Science*, *32*(4), 691–707. doi: 10.1016/j.humov.2012.11.006

Concept2. (2019, August 2). Technique Videos. Retrieved from https://www.concept2.com/indoor-rowers/training/technique-videos

Cooper, C. E., Penfold, S.-M., Elwell, C. E., & Angus, C. (2010). Comparison of Local Adipose Tissue Content and SRS-Derived NIRS Muscle Oxygenation Measurements in 90 Individuals. *Advances in Experimental Medicine and Biology*.

Coyle, E. F., Sidossis, L. S., Horowitz, J. F., & Beltz, J. D. (1992). Cycling efficiency is related to the percentage of Type I muscle fibers. *Medicine & Science in Sports & Exercise*, *24*(7). doi: 10.1249/00005768-199207000-00008

Crum, E. M., O'Connor, W. J., Loo, L. V., Valckx, M., & Stannard, S. R. (2017). Validity and reliability of the Moxy oxygen monitor during incremental cycling exercise. *European Journal of Sport Science*, *17*(8), 1037–1043. doi: 10.1080/17461391.2017.1330899

Das, A., Mandal, M., Syamal, A. K., & Majumdar, P. (2019). Monitoring Changes of Cardio-Respiratory Parameters During 2000m Rowing Performance. *International Journal of Exercise Science*, *12*(2), 483–490.

Delp, S. L., Suryanarayanan, S., Murray, W. M., Uhlir, J., & Triolo, R. J. (2001). Architecture of the rectus abdominis, quadratus lumborum, and erector spinae. *Journal of Biomechanics*, *34*(3), 371–375. doi: 10.1016/s0021-9290(00)00202-5

Ferrari, M., Muthalib, M., & Quaresima, V. (2011). The use of near-infrared spectroscopy in understanding skeletal muscle physiology: recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *369*(1955), 4577–4590. doi: 10.1098/rsta.2011.0230

Fry, A. C., Webber, J. M., Weiss, L. W., Arber, M. P. H., Vaczi, M., & Pattison, N. A. (2003). Muscle Fiber Characteristics of Competitive Power Lifters. *Journal of Strength and Conditioning Research*, *17*(2), 402–410. doi: 10.1519/00124278-200305000-00031

Geraskin, D., Boeth, H., & Kohl-Bareis, M. (2009). Optical measurement of adipose tissue thickness and comparison with ultrasound, magnetic resonance imaging, and callipers. *Journal of Biomedical Optics*, *14*(4).

Gerdle, B., Eriksson, N. E., & Brundin, L. (1990). The behaviour of the mean power frequency of the surface electromyogram in biceps brachii with increasing force and during fatigue, with special regard to the electrode distance. *Electromyography and Clinical Neurophysiology*, *30*(8), 483–489.

Grassi, B., & Quaresima, V. (2016). Near-infrared spectroscopy and skeletal muscle oxidative function in vivo in health and disease: a review from an exercise physiology perspective. *Journal of Biomedical Optics*, *21*(9), 091313. doi: 10.1117/1.jbo.21.9.091313

Grassi, B., Quaresima, V., Marconi, C., Ferrari, M., & Cerretelli, P. (1999). Blood lactate accumulation and muscle deoxygenation during incremental exercise. *Journal of Applied Physiology*, *87*(1), 348–355. doi: 10.1152/jappl.1999.87.1.348

Grieger, S., Geraskin, D., Steimers, A., & Kohl-Bareis, M. (2013). Analysis of NIRS-Based Muscle Oxygenation Parameters by Inclusion of Adipose Tissue Thickness. *Advances in Experimental Medicine and Biology*, 131–136.

Grieve, G. P. (1997). Clinical Anatomy of the Lumbar Spine and Sacrum. *Physiotherapy*, *83*(9), 495. doi: 10.1016/s0031-9406(05)65639-8

Hagerman, F. C. (1984). Applied Physiology of Rowing. *Sports Medicine*, *1*(4), 303 326. doi: 10.2165/00007256-198401040-00005

Hagerman, F. C., Connors, M. C., Gault, J. A., Hagerman, G. R., & Polinski, W. J. (1978). Energy expenditure during simulated rowing. *Journal of Applied Physiology*, *45*(1), 87–93. doi: 10.1152/jappl.1978.45.1.87

Hamaoka, T., Mccully, K. K., Niwayama, M., & Chance, B. (2011). The use of muscle near-infrared spectroscopy in sport, health and medical sciences: recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *369*(1955), 4591–4604. doi: 10.1098/rsta.2011.0298

Ishiko, T. (1967). Application of Telemetry to Sports Activities. *Medicine and Sport Science Biomechanics*, 138–146. doi: 10.1159/000387168

Jobsis, F. F. (1977). Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. *Science*, *198*(4323), 1264–1267.

Kenney, W. L., & Johnson, J. M. (1992). Control of skin blood flow during exercise. *Medicine & Science in Sports & Exercise, 24*(3). doi: 10.1249/00005768 199203000-00005

Klein, C. S., Marsh, G. D., Petrella, R. J., & Rice, C. L. (2003). Muscle fiber number in the biceps brachii muscle of young and old men. *Muscle & Nerve*, *28*(1), 62–68. doi: 10.1002/mus.10386

Knuttgen, H. G. (1970). Oxygen debt after submaximal physical exercise. *Journal of Applied Physiology*, *29*(5), 651–657. doi: 10.1152/jappl.1970.29.5.651

Lamb, D. H. (1989). A kinematic comparison of ergometer and on-water rowing. *The American Journal of Sports Medicine*, *17*(3), 367–373. doi: 10.1177/036354658901700310

Lindenthaler, J. R., Rice, A. J., Versey, N. G., Mckune, A. J., & Welvaert, M. (2018). Differences in Physiological Responses During Rowing and Cycle Ergometry in Elite Male Rowers. *Frontiers in Physiology*, *9*. doi: 10.3389/fphys.2018.01010

Mannion, A. F. (1999). Fibre type characteristics and function of the human paraspinal muscles: normal values and changes in association with low back pain. *Journal of Electromyography and Kinesiology*, *9*, 363–377.

McCully, K. K., & Hamaoka, T. (2000). Near-Infrared Spectroscopy: What Can It Tell Us About Oxygen Saturation in Skeletal Muscle? *American College of Sports Medicine*, 123–127.

Mckay, B. R., Paterson, D. H., & Kowalchuk, J. M. (2009). Effect of short-term high-intensity interval training vs. continuous training on O_2 uptake kinetics, muscle deoxygenation, and exercise performance. *Journal of Applied Physiology*, *107*(1), 128–138. doi: 10.1152/japplphysiol.90828.2008

Mcmanus, C. J., Collison, J., & Cooper, C. E. (2018). Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise. *Journal of Biomedical Optics*, *23*(01), 1. doi: 10.1117/1.jbo.23.1.015007

Mezzani, A., Grassi, B., Jones, A. M., Giordano, A., Corrà, U., Porcelli, S., Giannuzzi, P. (2013). Speeding of pulmonary VO_2 on-kinetics by light-to-moderate-intensity aerobic exercise training in chronic heart failure: Clinical and pathophysiological correlates. *International Journal of Cardiology*, *167*(5), 2189–2195. doi:10.1016/j.ijcard.2012.05.124

Miller, A. E. J., Macdougall, J. D., Tarnopolsky, M. A., & Sale, D. G. (1993). Gender differences in strength and muscle fiber characteristics. *European Journal of Applied Physiology and Occupational Physiology*, *66*(3), 254–262. doi: 10.1007/bf00235103

Murphy, W. G. (2014). The sex difference in haemoglobin levels in adults — Mechanisms, causes, and consequences. *Blood Reviews, 28*(2), 41–47. doi: 10.1016/j.blre.2013.12.003

Niemeijer, V. M., Jansen, J. P., Dijk, T. V., Spee, R. F., Meijer, E. J., Kemps, H. M. C., & Wijn, P. F. F. (2017). The influence of adipose tissue on spatially resolved near-infrared spectroscopy derived skeletal muscle oxygenation: the extent of the problem. *Physiological Measurement*, *38*(3), 539–554. doi: 10.1088/1361-6579/aa5dd5

Novosadova, J. (1977). The changes in hematocrit, hemoglobin, plasma volume and proteins during and after different types of exercise. *European Journal of Applied Physiology and Occupational Physiology*, *36*(3), 223–230. doi: 10.1007/bf00421753

Nygaard, E., Houston, M., Suzuki, Y., Jørgensen, K., & Saltin, B. (1983). Morphology of the brachial biceps muscle and elbow flexion in man. *Acta Physiologica Scandinavica*, *117*(2), 287–292. doi: 10.1111/j.1748-1716.1983.tb07208.x

Rantanen, J., Rissanen, A., & Kalimo, H. (1994). Lumbar muscle fiber size and type distribution in normal subjects. *European Spine Journal*, *3*(6), 331–335. doi: 10.1007/bf02200146

Scott, W., Stevens, J., & Binder–Macleod, S. A. (2001). Human Skeletal Muscle Fiber Type Classifications. *Physical Therapy*, *81*(11), 1810–1816. doi: 10.1093/ptj/81.11.1810

Secher, N. H. (1993). Physiological and Biomechanical Aspects of Rowing. *Sports Medicine*, *15*(1), 24–42. doi: 10.2165/00007256-199315010-00004

Shaharudin, S., & Agrawal, S. (2015). Muscle synergies during incremental rowing VO_{2max} test of collegiate rowers and untrained subjects. *The Journal of Sports Medicine and Physical Fitness*, *56*(9), 980–989.

Simoneau, J. A., & Bouchard, C. (1989). Human variation in skeletal muscle fiber-type proportion and enzyme activities. *American Journal of Physiology-Endocrinology and Metabolism*, *257*(4). doi: 10.1152/ajpendo.1989.257.4.e567

Smith, K. J., & Billaut, F. (2012). Tissue Oxygenation in Men and Women During Repeated-Sprint Exercise. *International Journal of Sports Physiology and Performance*, *7*(1), 59–67. doi: 10.1123/ijspp.7.1.59

Staron, R. S., Hagerman, F. C., Hikida, R. S., Murray, T. F., Hostler, D. P., Crill, M. T., Toma, K. (2000). Fiber Type Composition of the Vastus Lateralis Muscle of Young Men and Women. *Journal of Histochemistry & Cytochemistry*, *48*(5), 623 629. doi: 10.1177/002215540004800506

Sugisaki, M., Misawa, A., Ikai, A., Young-Sung, K., & Tanabe, H. (2000). Sex differences in the hemoglobin oxygenation state of the resting healthy human masseter muscle. *Journal of Orofacial Pain*, *15*(4), 320–328.

Szal, S. E., & Schoene, R. B. (1989). Ventilatory response to rowing and cycling in elite oarswomen. *Journal of Applied Physiology*, *67*(1), 264–269. doi: 10.1152/jappl.1989.67.1.264

Tew, G. A., Ruddock, A. D., & Saxton, J. M. (2010). Skin blood flow differentially affects near-infrared spectroscopy-derived measures of muscle oxygen saturation and blood volume at rest and during dynamic leg exercise. *European Journal of Applied Physiology, 110*(5), 1083–1089. doi: 10.1007/s00421-010-1596-2

Thiel, C., Vogt, L., Himmelreich, H., Hübscher, M., & Banzer, W. (2011). Reproducibility of Muscle Oxygen Saturation. *International Journal of Sports Medicine*, *32*(04), 277–280. doi: 10.1055/s-0030-1269922

Tonson, A., Ratel, S., Fur, Y. L., Cozzone, P., & Bendahan, D. (2008). Effect of Maturation on the Relationship between Muscle Size and Force Production. *Medicine & Science in Sports & Exercise*, *40*(5), 918–925. doi: 10.1249/mss.0b013e3181641bed

Umar, M. A., Zainuddin, F. L., Razman, R. M., & Shaharudin, S. (2019). Changes of drive to recovery ratio during 2000m ergometer rowing among Junior National rowers. *Malaysian Journal of Movement, Health & Exercise*, *8*(1), 33–43.

Vrana, A., Scholkmann, F., Wirth, B., Flueck, M., & Humphreys, B. K. (2018). Changes in spinal muscle oxygenation and perfusion during the Biering-Sorensen Test: preliminary results of a study employing NIRS-based muscle oximetry. *Advances in Experimental Medicine and Biology*, *40*, 103–109.

Warmenhoven, J., Cobley, S., Draper, C., & Smith, R. (2018). Over 50 Years of Researching Force Profiles in Rowing: What Do We Know? *Sports Medicine*, *48*(12), 2703–2714. doi: 10.1007/s40279-018-0992-3

Yoshiga, C. C., & Higuchi, M. (2003). Oxygen uptake and ventilation during rowing and running in females and males. *Scandinavian Journal of Medicine and Science in Sports*, *13*(6), 359–363. doi: 10.1046/j.1600-0838.2003.00324.x

Zhang, Z., Wang, B., Gong, H., Xu, G., Nioka, S., & Chance, B. (2010). Comparisons of muscle oxygenation changes between arm and leg muscles during incremental rowing exercise with near-infrared spectroscopy. *Journal of Biomedical Optics*, *15*(1), 017007. doi: 10.1117/1.3309741