SEX DIFFERENCES IN MUSCLE FATIGUE AMONG COMPETITIVE ROWERS DURING A 2000M TIME TRIAL

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ABSTRACT

The goal of this master's project was to examine sex differences in rowing-related fatigue, as well as muscle activation and oxygenation among competitive rowers. Varsity rowers with previous and current competition experience completed maximal voluntary muscle contractions followed by an all-out 2000m time trial on a Concept 2 rowing ergometer. These athletes are classified under the 3rd tier of sports participant classification framework (highly trained/national level)(McKay et al., 2022). Patterns of muscle activation, using surface electromyography (EMG), and quadriceps (vastus lateralis) muscle oxygenation, using near infrared spectroscopy (NIRS), were measured continuously throughout the row. Five strokes were averaged at 7 fixed distances to assess how these measures progressed with fatigue. The EMG root mean square (RMS) of middle trapezius, biceps brachii, rectus femoris, lumbar and thoracic erector spinae muscles all saw significant decreases throughout the trial in females, but not in males. Females also had significantly greater initial muscle activation from the start of the trial compared to males for biceps brachii, vastus lateralis, and rectus femoris. Additionally, females maintained a greater oxygenation level in vastus lateralis compared to males. This observation, combined with females demonstrating significantly greater heart rates compared to males throughout the trial, would suggest that females rely on the cardiovascular system significantly more than males to complete the row. These results are likely caused by greater type I muscle fibers within the vastus lateralis for females. Fiber type disparity could offer an explanation as to why females are experiencing exhaustion in certain muscle groups while males are not. The results from this study can help identify differences between male and female rowers and create the foundation for future studies to adapt training and decrease risk of injury.

RÉSUMÉ

L'objectif de ce projet de maîtrise était d'examiner les différences entre les sexes en ce qui concerne la fatigue liée à l'aviron, ainsi que l'activation et l'oxygénation des muscles chez les rameurs compétitif. Des rameurs varsity ayant une expérience antérieure et actuelle ont effectué des contractions musculaires volontaires maximales suivies d'une course contre la montre de 2000 m sur un ergomètre de type concept 2. Les patrons d'activation musculaire par électromyographie de surface (EMG) et l'oxygénation musculaire du quadriceps (vastus lateralis) par spectroscopie proche infrarouge (NIRS) ont été mesurés en continu tout au long de l'épreuve, et la moyenne des derniers 5 coups a été calculée sur 7 distances fixes afin d'évaluer l'évolution de la fatigue. La moyenne quadratique EMG du trapezius moyen, du biceps brachii, du rectus femoris et des muscles erector spinae lombaires et thoraciques a diminué de manière significative tout au long de l'essai chez les femmes, mais pas chez les hommes. Les femmes avaient également une activation musculaire initiale significativement plus élevée dès le début de l'essai comparativement aux hommes pour le biceps brachii, le vastus lateralis et le rectus femoris. En outre, les femmes ont maintenu un niveau d'oxygénation plus élevé dans le vastus lateralis comparativement aux hommes. Ces résultats, combinés à une fréquence cardiaque nettement plus élevée chez les femmes que chez les hommes tout au long de l'épreuve, suggèrent que les femmes font davantage appel au système cardiovasculaire que les hommes pour terminer l'épreuve d'aviron. Ces résultats sont probablement dus à la présence d'un plus grand nombre de fibres musculaires de type 1 dans le vastus lateralis chez les femmes. Cette disparité de type de fibres pourrait expliquer pourquoi les femmes éprouvent de l'épuisement dans certains groupes musculaires alors que les hommes n'en éprouvent pas. Ces résultats peuvent aider à déterminer les stratégies d'entraînement qui devraient être adoptées par les deux sexes afin de réduire les blessures et d'améliorer les performances.

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CONTRIBUTION OF AUTHORS

Luke Spagnuolo, the candidate, oversaw the research design, setup, recruitment, data collection, analysis, writing, and all steps necessary to complete the research study and submit the thesis as per McGill University requirements.

Julie N. Cote, Ph.D., Professor, Department of Kinesiology and Physical Education, McGill University, the candidate's supervisor, was actively involved in every step and decision made regarding the research study and completion of thesis submission.

Samuel Lamanuzzi, Research Assistant, assisted with the research design, data collection, and analysis.

Jean-Matin Huaman, B. Sc. Kin student, assisted with the data collection.

INTRODUCTION

Modern research is evolving towards studies that involve both female and male participants. It has become evident that research on males is not necessarily applicable to females. Females remain an underrepresented population among modern sport science research (Smith et al., 2022). Recent studies have determined that female participants accounted for only 34% of over 12.5 million total participants across six sport science and sports medicine journals (Cowley et al., 2021). Additionally, 31% of studies focused solely on males while only 6% examine females in isolation. Including both sexes and allowing for their comparison presents an opportunity for the discovery of sex-specific injury prevention and performance benefits.

Competitive rowing falls into a unique category of sport where ample full-body strength and endurance are necessary to compete at the highest level. The most common form of rowing competition occurs over a 2000m racecourse where rowers use up to 70% of their entire body's muscle mass to propel a boat toward the finish line (Smith & Hopkins, 2012; Steinacker, 1993). Rowers push their body to the absolute maximum in order to reach the finish line in as little time as possible. Training for competitive rowing is just as vigorous. Elite young rowers (aged approximately 20) averaged 10.6 training session a week (Arne et al., 2009) consisting of on water rowing, resistance training, and many other alternative training methods. This training frequency, as well as the repetitive nature of the sport, have led to a high incidence of overuse injuries (Hosea & Hannafin, 2012; Newlands et al., 2015). In rowing, females are injured more often than males (Smoljanovic et al., 2009), however there are minimal rowing studies that compare the sexes and the mechanisms that may predispose them to greater risks of injury.

Muscle fatigue plays a significant role in increasing the likelihood of injury. Sex-specific fatiguability characteristics and adaptations to fatigue have been noted. More specifically, females have demonstrated a greater resistance to fatigue compared to males when completing tasks at the same intensity (Albert et al., 2006; Hunter, 2016; Minoshima et al., 2022). Increased fatigue resistance however, does not align with the increased rate of injury among females. Certain studies have noted that accounting for total work performed mitigated any previously noted differences in fatiguability between the sexes (Billaut & Bishop, 2012). Sex differences in fatiguability during high-intensity full-body tasks such as rowing have not yet been investigated. Given the disparity between the sexes within the realm of injury, understanding any differences in how the sexes fatigue may offer an indication of how they get injured.

The objective of this thesis was to compare male and female competitive rowers in their full body muscle activity and muscle oxygenation to evaluate their fatigue across a 2000m time trial. We hypothesized that females would demonstrate more electromyographical manifestations of fatigue across the body while maintaining a greater muscle oxygenation. This research will offer a better understanding of the mechanisms that underlie sex differences in fatigue during whole-body tasks such as rowing. The results will allow for adaptation to training methods to prevent future injuries among this group of athletes and improve performance.

LITERATURE REVIEW

Biomechanics and Physiology of Rowing

Rowing is both an anaerobic and aerobic exercise. Using metabolic and bioptic measurement methods during a 2000m time trial, it was determined that 67% of the work required was created aerobically while 33% was created anaerobically (Steinacker, 1993). This anaerobic to aerobic ratio occurs because of the strategic pattern that rowers use during the race as well as the nature of the movement itself. The 2000m race begins with a vigorous sprint, causing extreme demand on the athletes' anaerobic metabolism. This is followed by a high aerobic steady-state section, and another sprint near the finish (Hagerman, 1984). This physiological pattern means that rowers need both large muscle strength to accelerate the boat forward during the sprints, and high oxidative capacity to maintain the speed throughout the duration of the race. The 2000m race typically takes around 7 minutes with the most elite rowers completing the race in 5.5 minutes.

When examining the underlying biomechanics of the cyclical and repetitive sport of rowing, it is important to understand the breakdown of the stroke and the techniques implemented. A single rowing stroke can be divided into two phases (Dawson et al., 1998). The first phase, or drive phase, involves the propulsion of the boat with the rower extending their legs and trunk then flexing their arms to pull on the oar. The highest intensity muscle contractions occur during the drive phase (Dawson et al., 1998). The second phase, or recovery phase, of a rowing stroke consists of the extension of the arms, followed by the flexion of the trunk and legs to return the oar to the starting, or catch, position prior to its re-entry into the water. There are several main agonist muscles that actively contribute to the drive phase due to the complexity of the movement. The three different portions of the drive phase each have their own muscle groups acting as the main force producers (Tachibana et al., 2007). For the initial push known as the leg drive, the quadriceps muscles, especially the rectus femoris, act as the main agonist. For the trunk swing portion, the muscles of the lower back including erector spinae are the main agonists. Finally, for the arm pull, the elbow flexors including biceps brachii and brachioradialis are the main agonist muscles. Given the number of muscle groups, the large amount of muscle mass, and the intensity of the sport and competition, muscle fatigue is likely to occur in these athletes.

Defining and Measuring Fatigue

Defining Fatigue

An individual's fatigue may be influenced by several physiological systems including the cardiovascular and respiratory systems, the neuromuscular system and even including one's psychological state (Enoka & Duchateau, 2016). Fatigue of the neuromuscular system can be categorized into peripheral or contractile function fatigue and central or muscle activation fatigue (Enoka & Duchateau, 2016). Performance fatiguability, as it pertains to the neuromuscular system, refers to the decline in performance metrics or the reduction in muscle activation, causing a loss in force production over a discrete amount of time (Enoka & Duchateau, 2016). The loss of force production inhibits the maintenance of the same degree of task performance. This is the definition of fatigue that is used throughout this review.

Electromyography

Surface electromyography (EMG) is a non-invasive tool used to measure muscle activity and infer muscle fatigue. Electrodes placed on the skin detect and measure electrical activity of the superficial muscles. The amplitude of the signal, often calculated using the root mean squared (RMS), can be identified to reflect the number of action potentials in the muscle (Vøllestad, 1997). The RMS acts as an indicator of the recruitment strategy that the neuromuscular system is using to accomplish the task. As a muscle is used continuously over time, the recruitment within that muscle or muscle group must change to adapt to fatigue and the loss of force production in order to maintain performance. Often as fatigue begins to set in, the body will begin to recruit additional and larger motor units to compensate for the loss of force production. Increased recruitment is reflected by an increase in EMG RMS (Vøllestad, 1997). This compensatory strategy will continue to the point at which the neuromuscular system becomes exhausted and is no longer able to maintain task performance despite the already increased motor unit recruitment. Now exhausted, a drop in the EMG RMS is known to occur as the system simply cannot maintain the action potential production required (Mendez-Villanueva et al., 2007).

An additional and insightful interpretation of the EMG data is an analysis of the power frequency. Power frequency offers insight into the type of muscle being recruited. Often represented by the mean or median, changes in the power frequency over time can also indicate muscle fatigue. More precisely, deceases in the median or mean of the power frequency are evidence of the muscle reaching its exhaustion point (Cifrek et al., 2009). Frequency change occurs due to a reduction in signal conducting velocity within the muscle as a result of fatigue. Using both changes in RMS and power frequency analysis provides the most accurate representation of muscle performance fatigue.

EMG Manifestations of Fatigue in Rowing Studies

Studies examining EMG outcomes of rowers have noted significant indicators of muscle fatigue across multiple rowing tasks. One study demonstrated a significant drop in EMG RMS in the rectus femoris of males during isometric and concentric maximal contractions performed before and after a 2000m time trial (Husmann et al., 2017). Similarly, another study examining the EMG median power frequency of the erector spinae and multifidus muscles found a significant decrease during maximal contractions performed before and after a 2000m time trial. The participants in this study included young rowers age 15-17, both male (n = 8) and female (n = 8), and saw significant drops in the median frequency of the iliocostalis and longissimus erector spinae muscles (Caldwell et al., 2003). Another study had recreational males, with only ergometer rowing experience, completing a 2000m maximal time trial. This study found a drop in mean power frequency for the latissimus dorsi, trapezius, and posterior deltoids at the completion of the time trial (Willwacher et al., 2021). Taken together, studies on rowing and EMG have found that muscles in the back and legs demonstrate characteristics of fatigue. However, there are no studies to date that have examined EMG across the legs, back, and arms throughout a rowing task.

Near Infrared Spectroscopy

Similar to electromyography, near infrared spectroscopy (NIRS) offers a distinct way of analyzing a muscle's oxygen use during an exercise task and how it changes with fatigue. NIRS uses near-infrared light in the range 700-1000nm to detect changes in hemoglobin and myoglobin oxygenation (Boushel & Piantadosi, 2000). By placing a NIRS probe on the belly of a muscle, total hemoglobin (THb) as well as deoxygenated hemoglobin (HHb), oxygenated hemoglobin (O_2Hb) and the tissue oxygenation index (TOI%, i.e. the percent of the THb that is O_2Hb) can be measured. During high-intensity muscle use, a common pattern in the NIRS data emerges for muscle oxygenation. At the beginning of high-intensity exercise, there is a very clear drop in oxygenation levels, reflecting a sudden deficit in oxidative capacity, followed by a plateau for the remainder of the exercise, reflecting the triggering of mechanisms to urgently increase delivery of oxygen and thereby restore homeostasis (Ansdell et al., 2020). Thus, using the information provided through NIRS and EMG measurements, we can accurately describe muscle use and changes in oxygen usage to better understand fatigue and adaptation throughout a task.

NIRS Rowing Studies

Previous studies have examined NIRS in rowers during rowing tasks. One such study demonstrated that the biceps brachii muscles of rowers have a low oxidative capacity compared to the vastus lateralis during an incremental rowing task. This finding was based on the biceps reaching the maximal oxygen uptake faster than the vastus lateralis (Zhang et al., 2010), indicating differences in the functional capacity of the different muscle groups during the maximal capacity rowing exercise. Another study examines NIRS in the quadriceps of world class rowers and described a typical drop plateau for oxygenated hemoglobin concentration (Klusiewicz et al., 2021). The drop plateau denotes a rower reaching maximal oxygen uptake in their quadriceps during a row. No previous studies have examined NIRS measures during a 2000m time trial nor have previous studies combined NIRS and EMG results.

Injuries

Overuse Injuries

Overuse injuries are defined by Krivickas et al. (1997) as injuries that are caused by cumulative repetitive force greater than what the tissue can withstand. These injuries most commonly affect the musculotendinous unit and are often associated with a gradual increase in pain which oftentimes prevents athletes from being aware of the seriousness of the injury. Musculotendinous injuries are not always associated with a single identifiable event and are often a result of repetitive training (Yang et al., 2012). A certain amount of microtrauma and discomfort is necessary during training to achieve physical improvement, however adequate recovery time is necessary to replenish the muscles and prevent injury (Côté, 2014; Sub Kwon & Kravitz, 2006). Thus, these injuries typically occur in muscles that have not adequately recovered (Edwards, 2018). Muscle fatigue can also lead to an increased risk in muscle strain and injury since fatigued muscles absorb less energy before reaching the degree of stretch that causes muscle strain (Murgia, 2013). Additionally, fatigued muscle cannot efficiently transfer stress from the joints and bones like unfatigued muscle can, thereby creating further potential for injury. Finding and understanding the balance between muscle use and the extent of oxygen dependency at a muscular level is key for the athletes and researchers to improve performance and prevent injury. Using tools such as EMG and NIRS to measure muscle use and muscle fatigue can offer further insight into this topic.

Injury Prevalence in Rowing

Given the intensity of the sport of rowing, it comes as no surprise that injuries are a common complication for these athletes. A survey administered to 217 elite level junior rowers reported 398 injuries over the course of the 2006-2007 rowing season. This survey produced an aggregate annual injury rate of 0.99 injuries per rower or 2.1 injuries per 1000 training sessions (Smoljanovic et al., 2009). Furthermore, the study found 73.8% of injuries were overuse injuries whereas the minority of the reported injuries were related to a single traumatic event. The two most common injury sites among rowers are the low-back and the knees, accounting for more than 50% of all reported rowing injuries (Hosea & Hannafin, 2012; Smoljanovic et al., 2009).

There are multiple mechanisms that lead to overuse injuries among rowers. Primarily, as training frequency increases, so does the rate of injury. However, training frequency must also increase as the level of competition increases. One study noted that the prevalence of low back pain had a significantly high correlation to total training hours per month, average training hours per month, and average kilometers rowed per month in competitive rowers. (Newlands et al., 2015). When a group of rowers was compared to age- and sex-matched subjects in the general population, the injury prevalence among the rowers was more than 50% greater. It was determined that 82% of rowers reported low back pain, sciatica, or both, while in the general population only 25-30% of individuals reported the same pain and injuries (Howell, 1984). Another study found that 32% of individuals developed back pain during their collegiate rowing careers (Teitz et al., 2002). Low back injuries among a group of national level rowers were also reportedly caused the greatest number of absences from training that exceeded 5 days (Verrall & Darcey, 2014). Knee overuse injuries often present as pain on the anterior knee and are usually caused by training activities designed to increase quadriceps strength, especially those loading the patellar tendon (Hosea & Hannafin, 2012). These injuries, excluding the most severe cases, allow for the rowers to continue training while implementing a few minor treatments (stretching, and non-steroidal anti-inflammatory medications).

During the rowing stroke, significant spinal loading forces can occur. One study found that peak compressive forces were equivalent to 4.6 times the person's body weight (Morris et al., 2000). Additionally, significant shear forces (693 ± 11N) were also noted. Muscle fatigue in the lower back increases the risk of injury associated with shear force. Muscle fatigue increases the lumbar flexion of a rower thus increasing the bending moments and creating additional strain on passive structures such as the ligaments and vertebrae (Reid & McNair, 2000). Prevention of these injuries in the future requires an understanding of the fatigue present within the athletes. The use of EMG and NIRS to better this understanding should be a priority.

Sex Differences in Sport-Related Injury

Sex Differences in Injury Mechanisms

An important topic of modern sports science research is examining the differences between the biological sexes, especially as they pertain to injuries. Previous literature has suggested that female tendons have a greater tendency for overstretching and that female joints are also more flexible, especially in the pelvic and lumbar region (Burgess et al., 2009; Peharec et al., 2007). Additionally, due to less strength, height, and segment size differences, females often must approach tasks with different techniques and exert greater physical effort to accomplish the same task (Yehoyakim et al., 2016). These factors could be a potential mechanism for the greater injury risk of females as compared to their male counterparts.

Sex Differences in Neuromuscular Fatigue

Sex Differences in Fatiguability

It has previously been established that females are less fatigable than males during tasks of similar intensity relative to individual strength (Albert et al., 2006; Fedorowich et al., 2013; Hunter, 2016; Minoshima et al., 2022; Srinivasan et al., 2016). These studies also suggest that contractile mechanisms are responsible for these differences. Fatigability in these studies was examined through change in voluntary force production, change in twitch force, as well as EMG measures such as change in frequency. It has however been noted that certain fatiguability differences are negated when the sexes are matched for strength. Factors such as time to task failure, change in torque, and EMG burst rate demonstrated no sex-specific differences when matched for strength (Hunter et al., 2004).

While these differences have been mostly observed in low to medium intensity tasks, there has also been evidence of fatiguability differences in tasks of higher intensity such as cycling (Billaut & Bishop, 2009). However, further investigation using absolute mechanical work completed as a covariate concluded that females are not always more fatigue-resistant than males and use similar recruitment strategies to complete the same task (Billaut & Bishop, 2012). Additionally, it has been suggested that sex differences in fatigue resistance could be muscle group-dependant. A study using EMG measurements found that females had a greater fatigue resistance than males in elbow flexors, but not in the ankle dorsiflexors (Avin et al., 2010). Cumulatively, the aforementioned evidence is inconclusive with regards to fatigability between the sexes. Further investigation, especially within the sport of rowing, is required for definitive conclusions.

Sex Differences in Muscle Oxygenation

Similarly, sex differences have been observed in muscle deoxygenation during high-intensity tasks. In a high intensity cycling sprint study, male participants displayed a drastic drop in oxygenation (TOI% and O_2Hb of vastus lateralis) while females did not elicit a significant deoxygenation during the same task (Ansdell et al., 2020). This result encourages the idea of less fatiguability in female leg muscle. Similarly in another study, females experienced less muscle deoxygenation in vastus lateralis during high-intensity sprint exercises compared to males (Smith & Billaut, 2012). It is however, unclear whether these differences were impacted by the established sex differences in adipose tissue thickness (ATT). It is well-documented that females tend to have a greater ATT than males (Westerbacka et al., 2004) and that greater ATT causes a decrease in observed concentrations of heme compounds (Bowen et al., 2013; Niemeijer et al., 2017). Cumulatively there is an indication that further studies are required to understand the true mechanisms of oxygenation especially during rowing tasks.

Sex Differences in Rowing

Sex Differences in Rowing-Related Injury Prevalence

Previous research has concluded significant sport-specific differences between the sexes in many features of performance, technique, and injury prevalence. Most significantly, there are multiple established differences in injury prevalence and injury type between the sexes. For instance, a study on NCAA athletes examining 16 (8 male and 8 female) teams, found that females in comparable sports reported a higher incidence of overuse injuries than males (Yang et al., 2012). This same study also noted female rowers had the highest incidence of overuse injuries across all sports teams, with over 56 of the 98 injuries reported by the rowing team attributed to overuse. These female NCAA rowers accounted 14.5% of overuse injuries reported throughout the entire study. Within junior elite rowers, overuse injuries were significantly more common among females as well, with 81% of female injury reports being overuse injuries. Comparatively, males only reported a 67.5% rate of overuse injuries (Smoljanovic et al., 2009). The same study found that females were generally injured more often than males, with females reporting 110.2 injuries per 100 rowers and males reporting 90.5. All these studies help conclude that female rowers are more likely to be injured and are more likely to suffer an overuse injury compared to male rowers of the same level.

Sex Differences in Rowing Performance

In the sport of rowing, males out-perform females significantly and maintain a significantly greater performance even after the sexes are matched for different anatomical and physiological factors. In Yoshiga et al. 2003, male and female performance was based on time in a 2000m time trial. Each participant (71 females and 120 males) completed an all-out 2000m row on a concept 2 rowing ergometer. Males and females were matched for height, body mass, fat free body mass, and maximal oxygen uptake. Despite being matched for these different factors, males still out-performed females significantly (C. Yoshiga & M. Higuchi, 2003). The sexes showed the least difference when matched for maximal oxygen uptake; however, the performance differences were still significant (by approximately 20 seconds). There are no studies to date that have explained this performance difference, and further investigation into the sex-specific mechanisms of rowing-related performance are necessary.

Sex Differences in Rowing Kinematics

Sex differences in kinematics and range of motion during rowing have also been described in the literature. A previous study examined kinematics of the lower thoracic, lumbar, and sacral spine during the first and twentieth minute for 10 males and 10 females during a 20-minute steady state row. Results showed that females rowed with their pelvis significantly more anteriorly tilted than males (Ng et al., 2013). This could potentially be explained by the greater hamstring flexibility, as well as greater hip mobility of females compared to their male counterparts (Ng et al., 2013). Additionally in another study, females were found to have greater lumbar extension, thoracic extension, and shoulder flexion at the finish position (end of the stroke) (Li et al., 2020). All of these contributed to an overall greater range of motion in the previously mentioned joint angles. This study examined 31 females and 27 males across three different steady state trials. Range of motion (ROM) data was examined using inertial measurement units placed on the S1, L1, and T2 vertebrae. What these studies indicate is that there are significant differences in the stroke motion pattern of female and male rowers. What is unclear is whether these differences are maintained at different stages of fatigue during a typical rowing race, and whether they have a significant effect on injury prevalence. It is possible that the greater mobility and range of motion is increasing the likelihood of injury among female rowers. Indeed, one of the aforementioned studies noted that low back range of motion increased with fatigue, further exposing the joints to overstretching and damage (Ng et al., 2013). Whether or not this might be compensated for at other joints as fatigue evolves, is unknown.

Sex Difference Knowledge Gaps

To date, studies examining neuromuscular fatigue and the response to fatigue have been carried out in an almost entirely male population. In the rowing literature, there are no studies that analyzed sex differences in full body EMG responses to rowing activities. Sex-specific fatigue responses in EMG for the muscles of the legs, upper body, and the entire trunk (lumbar and thoracic regions) within the same participants have not been examined. There is opportunity to observe the effect of the previously described rowing kinematic sex-based differences on the neuromuscular system. Similarly, the NIRS studies within rowing have only been completed using male participants. While there are few studies examining NIRS in rowers there are none, to our knowledge, that examined sex differences in muscle oxygenation during rowing tasks. By researching the fatigue and oxygenation pattern differences between the sexes during rowing, we gain a more comprehensive understanding for how these differences affect the athletes and may contribute to the disparity in injury prevalence and performance.

Summary

Competitive rowing requires a very diverse and comprehensive set of physical abilities combined with considerable amounts of physical training. Due to the highly intense and repetitive nature of the sport, rowers experience a high incidence of overuse injuries, especially in the low back and knee regions. Certain biomechanical and physiological differences have been noted between the sexes, such as greater flexibility and tendencies for overstretching in ligaments and tendons among female rowers, especially those of the lower back and pelvis.

While male rowers outperform female rowers, despite being matched for multiple physical characteristics, females are more likely to experience an overuse injury. Muscle fatigue is linked with overuse injuries, as a fatigued muscle cannot absorb as much energy, which places additional strain on the passive structures (ligaments and tendons) and the joints. Fatigue can be observed using EMG measures where changes in amplitude and power frequency demonstrate fatiguability over time. Additionally, muscle oxygenation can be determined using NIRS and these two measurement outcomes offer unique insights into how the muscles of the body are used and adapt during rowing. Finally, there is minimal research regarding sex differences in NIRS and EMG measurements during rowing tasks, despite well documented sex differences in other aspects such as performance, kinematic patterns, and injury prevalence. By investigating both NIRS and EMG data from male and female rowers, insight explaining the mechanisms of these well documented sex-based differences could be discovered. Additionally, identifying which muscles may show the largest sex differences in their use patterns and fatigue responses may be possible. These insights could contribute to a better understanding of the whole-body neuromuscular mechanisms most responsible for the larger injury prevalence in female rowers.

RESEARCH ARTICLE

Sex Differences in Muscle Fatigue Among Competitive Rowers During a 2000m Time Trial

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Abstract

Rowing is a repetitive, whole-body, high-intensity sport in which, overuse injuries are common. Female rowers are known to have a greater injury rate compared to males. However, what remains to be understood is whether these injuries are related to any sex-specific changes in how muscles fatigue during high-intensity rowing. Sixteen varsity rowers (9F/7M) completed a 20-minute self-selected warm-up and 2000m time trial on a Concept 2 rowing ergometer. A near infrared spectroscopic (NIRS) probe was placed on VL to measure muscle oxygenation. EMG surface electrodes were placed on 10 muscles of the right upper and lower limbs, as well as the trunk. The muscle activity was recorded during maximal voluntary isometric contractions (MVICs) and at 7 time points during the time trial. MVICs signals were used to normalize the EMG signals from the time trial. Results show two interaction effects (Sex x Time). Females maintained a greater oxygenation index (%TOI) than males that varied with time (Females approximately 8% TOI greater than males throughout the warmup and first 1100m of the 2000m trial, $p < 0.001$). Females also demonstrated a significant drop in RMS of middle trapezius (from approximately 42% MVIC to about 24% MVIC, $p = 0.015$) and biceps brachii (from approximately 23% MVIC to about 15% MVIC, $p = 0.009$) from 350m to 1850m while males did not experience any significant change. Females also had greater activation of vastus lateralis than males (Males approximately 11% MVIC, Females approximately 25% MVIC, $p < 0.001$). Vastus lateralis EMG and oxygenation results could reflect the greater proportion of type I muscle fibres in female leg muscle and thus a greater oxidative capacity and larger reliance on the aerobic system. This could explain a lower force generating capacity for females leading to earlier damage and thus a greater injury incidence that could target these female muscles.

Keywords: Electromyography, Near Infrared Spectroscopy, Rowing, Sex Differences

Introduction

Competitive rowing requires both a high level of aerobic and anaerobic capacity and forces athletes to push themselves to the point of physical exhaustion. The most common form of rowing competition is the 2000m racecourse, during which rowers use up to 70% of their body's muscle mass to propel a boat towards the finish line (Smith & Hopkins, 2012; Steinacker, 1993). The intensity, combined with the repetitive motions of the rowing stroke, causes a high incidence of injury among competitive rowing athletes. An annual rate of 0.99 injuries per rower was reported among elite junior level rowers (Smoljanovic et al., 2009). The same studies also noted that over 70% of rowing injuries are classified as overuse related injuries, and that female rowers typically report a significantly greater number of injuries than males (Hosea & Hannafin, 2012; Smoljanovic et al., 2009).

Fatigue is often mentioned as one of the main risk factors for muscle injury (Murgia, 2013). Fatigued muscle is more prone to injury and strain, since it is not able to absorb as much energy prior to reaching the degree of stretch that leads to strain, nor can it effectively mitigate stress from the joints and passive structures (Murgia, 2013). Thus, muscle fatigue is associated with increased risk of injury. Muscle fatigue is defined by Enoka and Duchateau (2016) as both the reduction in contractile function and the reduction in muscle activation causing a loss in force production.

Previous studies provided evidence to suggest that females were more fatigue resistant than males, which has been suggested to be partially due to a difference in muscle fiber type, with females generally showing a greater proportion of type I muscle fibres (Albert et al., 2006; Hunter, 2016; Minoshima et al., 2022). The same observation of higher fatigue resistance in females was found in a high-intensity cycling task (Billaut & Bishop, 2009). However, these differences in cycling were mitigated when the sexes were matched for total work (Billaut & Bishop, 2012). Other studies have found that sex differences in fatiguability are muscle group-dependant, such that female elbow flexors were fatigue resistant compared to males while ankle dorsiflexors were not (Avin et al., 2010).

Previous studies have noted kinematic and technical differences between the sexes during rowing (Li et al., 2020; Ng et al., 2013) including a greater range of motion in the rowing stroke among female rowers as well as a difference in pelvic positioning. However, there is minimal literature regarding the differences between the sexes within whole body muscle activation and oxygenation. Moreover, the previous studies in rowing have noted evidence of leg fatigue using electromyography (EMG) whereas muscles such as rectus femoris saw reductions in EMG amplitude (Caldwell et al., 2003; Husmann et al., 2017; Willwacher et al., 2021). However, these studies included only male participants, and did not examine full-body EMG. Significant oxygenation responses in rowing have also been observed using near infrared spectroscopy (NIRS) (Zhang et al., 2010) where the maximal O_2 uptake was reached faster in the biceps than in the quadriceps. There are no studies that compare any sex-specific NIRS results during rowing.

The objectives of this study were to examine leg oxygenation and whole-body electromyographic manifestations of muscle fatigue during a 2000m rowing time trial and compare the results from EMG and NIRS measures between the sexes. We hypothesized that females would likely display evidence of a greater muscle oxygenation within the quadriceps while sustaining greater evidence of muscle fatigue across the whole body. Despite females having higher fatigue resistance, especially in low to medium intensity tasks, we predict that the intensity of the time trial and the muscle recruitment required will have a larger fatiguing effect on the muscles of females due to their lower overall muscle mass.

Methods

Participants

Sixteen healthy young competitive rowers (7 males, 9 females; age: males = 21.7yrs, female = 21.1yrs, $p = 0.03$; height: male = 182.07cm, female = 172.33cm, $p = 0.42$; weight: male = 77.6kg, female = 70.2kg, $p = 0.36$) were recruited on a volunteer basis through coordination with the McGill Varsity Rowing Team and other local rowing teams. The participant inclusion criteria required them to be between the ages of 18 and 30, have previous experience competing in at least one rowing regatta, and to be enrolled and training regularly in a competitive rowing team at the time of the experiment. Participants were excluded if they were not currently training due to an injury or medical condition that could prevent them from producing true maximal exertion. Participants signed a written informed consent form and filled out a PAR-Q activity questionnaire prior to participating to ensure safe participation (Thomas et al., 1992). A sample size of 34 healthy rowers ($n = 17$ females) with an effect size of 0.43 powered for ANOVA was calculated using G*Power software. These values were calculated from previous studies involving vigorous exercise that compared EMG signals of the rectus femoris muscle between the sexes (Billaut & Bishop, 2012). The study was approved by the Research Ethics Board 2 of the McGill University, REB file #: 22-06-032.

Instrumentation

<u>Electromyography</u>

Electromyographic (EMG) signals were recorded via wireless bipolar surface electrodes (Trigno Avanti, Delsys, Natick, MA, USA; double-differential bar (Ag) electrodes 2.7 cm x 3.7cm; common-mode rejection ratio = 80 dB) Sensors were placed following SENIAM guidelines and those established by Pollock et al. (2009) (Table 1). Electrode position with respect to innervation zones of upper limb muscles can be found in Barbero et al. (2012). The sensors were placed on the anterior deltoid (AD), posterior deltoid (PD), biceps brachii (BB), middle trapezius (MT), latissimus dorsi (LT), thoracic erector spinae (TES), lumbar erector spinae (LES), rectus femoris (RF), vastus lateralis (VL) and gastrocnemius (GS). Prior to electrode placement, the skin was shaven and abraded with alcohol to minimize signal interference. Sensors were placed parallel to the direction of the muscle fibres and in the corresponding locations as listed in Table 1 on the right side of the body.

Table 1. Surface Electrode Placements

Muscle	Placement
Anterior Deltoid	One fingerbreadth distal and anterior to the acromion
Posterior Deltoid	Two fingerbreadths behind the angle of the acromion, on the line with the little finger
Biceps Brachii	1/3 the distance of a line from the fossa cubit to the acromion
Middle Trapezius	Halfway between the medial border of the Scapula and the spine, at the level of T3
Latissimus Dorsi	4cm below the inferior tip of the scapula midway between the spine and the lateral edge of the torso
Lumbar Erector Spinae	Two fingerbreadths lateral from the spinous process of L1
Thoracic Erector Spinae	Two fingerbreadths lateral from the spinous process of T9
Gastrocnemius	On the most prominent bulge of the muscle in the direction of the leg
Rectus Femoris	Halfway between the anterior spina illicia superior to the superior part of the patella
Vastus Lateralis	2/3 from the anterior spina illicia superior to the lateral side of the patella

Near Infrared Spectroscopy and Ultrasonography

A frequency-domain multi-distance NIRS system (OxiplexTS, ISS, Champaign, IL, USA) with LED-detector fiber bundle separation distances of 2.0, 2.5, 3.0, and 3.5 cm was used to measure the microvascular hemoglobin + myoglobin concentration of VL. The NIRS probe was calibrated prior to each use via the manufacturer supplied phantom block. Using a brightness-mode Doppler Ultrasound (logiq @7, GE Healthcare, Chicago, IL, USA) subcutaneous adipose tissue thickness (ATT) was obtained under the location of the NIRS probe. Images were taken twice while the participant was seated in an upright position with the quadriceps relaxed. During the ultrasound procedure, two images were captured. The NIRS probe was positioned 15cm above the proximal border of the patella on the VL muscle belly (Smith & Billaut, 2012) and secured using medical tape and covered with an opaque cloth. Oxygenation data was recorded for 30 s in the same seated position to create a baseline.

Heart Rate

A commercially available heart rate (HR) monitor (Polar Verity Sense, Polar Electro, Kempele, Finland) was fitted to the subject's left forearm. HR and NIRS data were recorded at baseline as well as for the warm-up and throughout the 2000m time trial.

Maximum Voluntary Isometric Contractions (MVICs)

The participant was instructed to complete 8 sets of MVICs with 2 repetitions each. EMG was measured for each muscle during each repetition. To ensure maximal force production, the researchers gave verbal encouragement. Each repetition consisted of a 5-second (ramp up – hold – ramp down) maximal voluntary isometric contraction. One minute of rest was given between each repetition. MVIC guidelines from Hermans et al. (2000) were followed. The 8 different exercises offered maximal reference EMG signals for each muscle being tested (Table 2.).

Table 2 Procedure used to administer the MVICs.

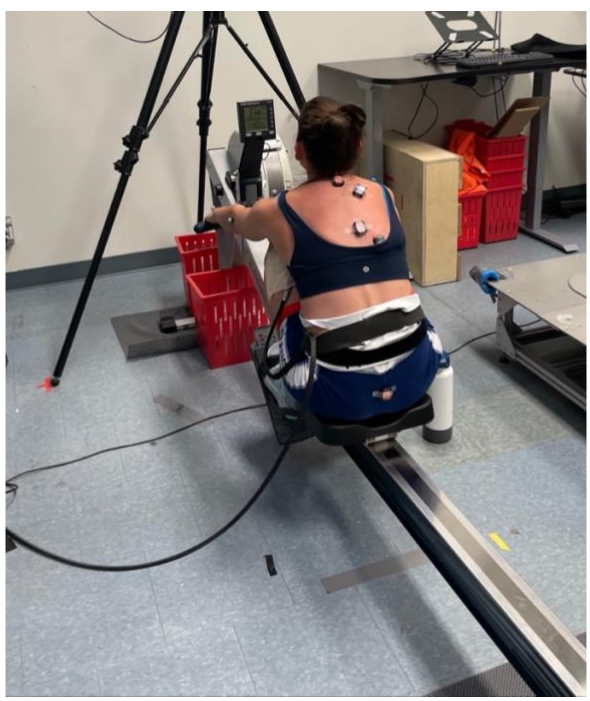
Muscle(s)	Posture	Direction of Effort
Anterior Deltoid	Seated; 45° shoulder flexion palm facing down	Primary researcher applied pressure on the arm in the direction of shoulder extension
Posterior Deltoid	Seated; Horizontal abduction in the sagittal plane at 90° shoulder abduction with forearm pronated (bend elbow), palm facing down	Primary researcher applied pressure on the arm in the direction of horizontal adduction
Biceps Brachii	Seated; Elbow flexion at 90° with forearm supinated and shoulder in pendant position in neutral humeral rotation, palm facing up	Primary researcher applied pressure on the forearm in the direction of elbow extension
Latissimus Dorsi	Standing; flex at the hips with feet on the floor, and place their torso prone atop of massage table, hand in fist	Primary researcher applied pressure as the participant attempt a row
Middle Trapezius	Prone; shoulder horizontally abducted and externally rotated	Primary researcher applied pressure on the arm above the elbow in the direction of scapular adduction
Lumbar Erector Spinae and Thoracic Erector Spinae	Prone; upper body off the physio table at the level of ASIS, lower body secured, Strap around back at the level of T5 attached to the floor, maximal back extension against strap at body position parallel to ground (180 degrees)	N/A
Gastrocnemius	Prone plantarflexion	Primary researcher applied pressure on the foot in the direction of dorsiflexion
Rectus Femoris and Vastus Lateralis	Seated; Knee joint angle of 90°, ankle strap attached proximal to the lateral malleolus, knee extension	N/A

Data Acquisition

<u>2000m Time Trial</u>

The participant preformed a 2000m time trial on a Concept 2 rowing ergometer (Model D, Morrisville, VT, USA). Drag factors on the ergometer were set at 110 for females and 120 for males as was standard with the McGill rowing team. They were instructed to complete the trial to the best of their ability as though it were a competitive race, thus ensuring a maximal effort. All rowers had experience with this type of test and were expected to use their typical competitive race strategy given the nature of the test. The aim for each participant, being to achieve their fastest time, would have them reach exhaustion by the end of the task. Surface EMG, NIRS and heart rate signals were collected continuously throughout the 2000m time trial. Electrical current signal markers were manually placed by the experimenter within the data at 250m intervals starting from 100m continuing until 1850m during the task using an analog touch sensor.

Figure 1**.** Experimental Setup



Data Analysis

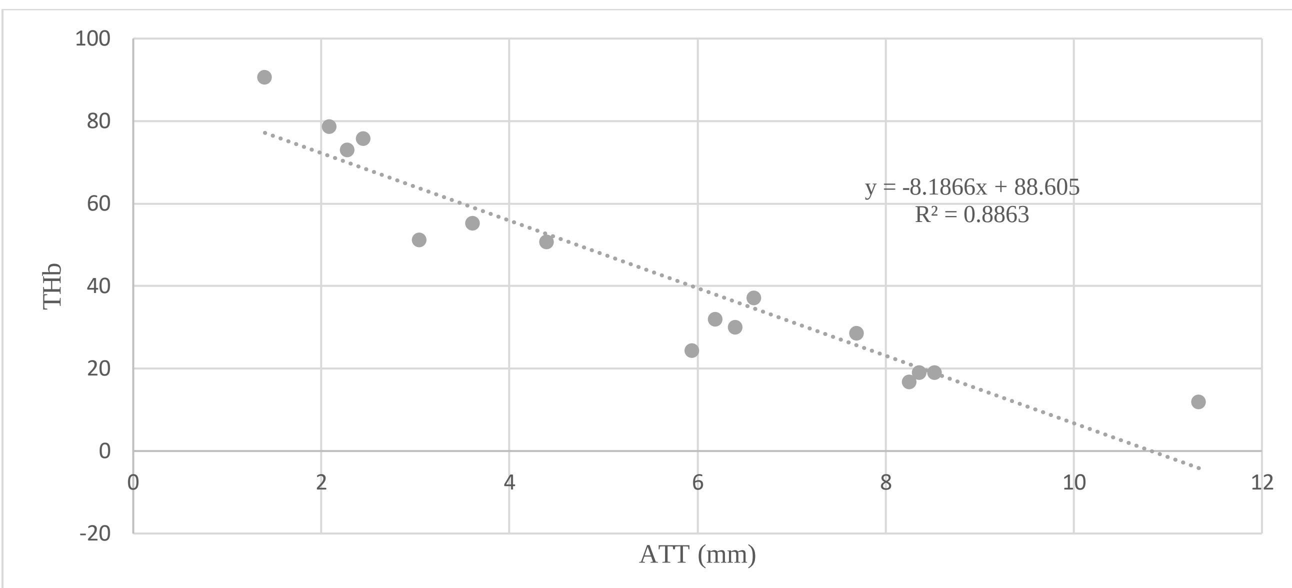
The EMG recordings were bandpass filtered, smoothed using a 4th order Butterworth filter with a frequency range between 10 - 500Hz, and full-wave rectified. The signals were normalized to the peak amplitude calculated from the MVIC recordings. The peak amplitude was visually selected to ensure the values represented the true maximum voluntary RMS. The data was partitioned using a passive reflective marker attached to the ergometer handle to separate the drive and recovery phases of the rowing stroke. The kinematics of the handle were recorded using an 8-camera motion capture system (MX3 VICON, Oxford Metrics Ltd., Oxford, UK). The forward-backward motion of the handle in the sagittal plane was used to define the phase of the stroke. EMG amplitude values were calculated by taking the average of the RMS values of the drive phase of the last five strokes at each 250m interval. A Fast Fourier Transform was applied to the filtered EMG data to obtain the median power frequency (MdPF). MdPF was determined also by averaging the individual MdPF values from the drive phases of the last five strokes at each 250m interval.

Ultrasound images were analyzed in Image J (Laboratory of Optical and Communication, University of Wisconsin-Madison, WI, USA) to obtain a measurement of ATT. All images from all subjects were analyzed by the same researcher.

NIRS parameters including the concentration of oxygenated hemoglobin-myoglobin (O_2Hb), deoxygenated hemoglobin-myoglobin (HHb), total hemoglobin-myoglobin (THb), and tissue oxygenation index (TOI%) were extracted from the NIRS data series and quantified by the NIRS system. The NIRS data was sampled at 50Hz and the scattering (μ_s) averaging window was 2s. The data was resampled offline to 10Hz then filtered via 10th order zero-lag low-pass Butterworth filter to remove any artefacts of movement (Rodriguez et al., 2018). To correct the

NIRS data for ATT, a correction factor based on the relationship between THb and ATT was created. Following procedures outlined by Bowen et al. (2013), a linear regression to the above-mentioned relationship was performed (Figure 2 ($y = -8.1866x + 88.605$, $r = 0.941$[a] $p < 0.01$)). The correction factor was then determined by solving for the THb at the subject ATT then dividing this value from the common ATT of 0 mm. The correction factor value (group mean ± SD) was 1.36 ± 0.18 for males and 3.81 ± 1.83 for females. All the NIRS signals, apart from TOI% as it is a percentage, were multiplied by the correction factor. Normalizing NIRS signals for muscle thickness allows for inter-subject comparisons of all NIRS values (Bowen et al., 2013). NIRS and heart rate data was averaged over the last 30s of each 250m interval to obtain a single value for each distance.

Figure 2 ATT Linear Regression



Statistical Analysis

Mean and standard deviation for both males and females were determined for age, weight, and height, and were compared using Independent-Samples T-Tests between sexes. A p-value < 0.05 indicated a significant difference.

EMG (RMS and MdPF) and NIRS (THb, HHb, O_2Hb, and TOI%) data were statistically analyzed using Generalized Estimating Equations (GEE; Zeger & Liang, 1986) in SPSS (v23, IBM Corporation), via the Ballinger et al. (2004) methods. Time (7 distance markers for EMG, 9 for NIRS due to baseline and warmup values) and muscle (each muscle location for EMG) were modelled as within-subject factors and sex (male and female) as a between-subject factor. Sequential Bonferroni corrections were performed on statistically significant effects using pairwise comparisons (Wald X2). Hedge's g effect size calculations were done for the data with main Sex effects. Hedge's g effect size values of $g \geq 0.8$ denote a large effect size, $g = 0.05$ denotes a medium effect size, and values $g < 0.2$ are considered small effect sizes.

Results

Performance and Participant Characteristics

Table 3 presents the participant characteristics and performance metrics for the 2000m time trial. The time indicates the duration it took for the participants to complete the time trial, while the stroke rate and power metrics are averaged across the entire trial. Independent Sample, Two Tailed T-Tests indicated that males were significantly taller than females. Males also finished the 2000m time trial faster than females and generated more power on average.

Table 3. Male and female averages (SD) and mean differences [95% CI] of participant characteristics and 2000m time trial performance metrics.

Characteristic	Males (N = 7)	Females (N = 9)	Diff. [95% CI]	*p*-value
Age (years)	21.7 (3.0)	21.1 (1.5)	.603 [-2.28, 3.48]	= .612
Height (cm)	182.1 (8.0)	172.3 (5.5)	9.73 [1.91,17.57]	**= .02**
Weight (kg)	77.6 (9.7)	70.2 (8.4)	7.4 [-2.64, 17.44]	= .134
Time (min:sec)	6:45.3 (22.1)	8:03.2 (23.1)	77.9 [-102.67, -53.13]	**< .001**
Power (watts)	341.1 (49.9)	201.2 (30.2)	139.92 [91.85, 187.99]	**< .001**
Stroke rate (strokes/min)	31.4 (3.1)	30.1 (1.8)	1.32 [-1.65, 4.29]	= .341
Rowing Experience (years)	5.8 (4.1)	3.9 (2.7)	1.89 [-2.14, 5.93]	= .319

Heart Rate (Figure 3)

There was a significant Sex x Distance interaction effect within the heart rate data (Wald X^2 = 52.94, p < .001). Heart rate increased for both sexes from baseline to all other distances. Females' heart rate increased from warm up to the trial phase, while males did not. Males' heart rate only increases from 350m and 600m to 850m. Additionally, females' heart rate was significantly greater than males' at all distances of the trial phase except 1850m.

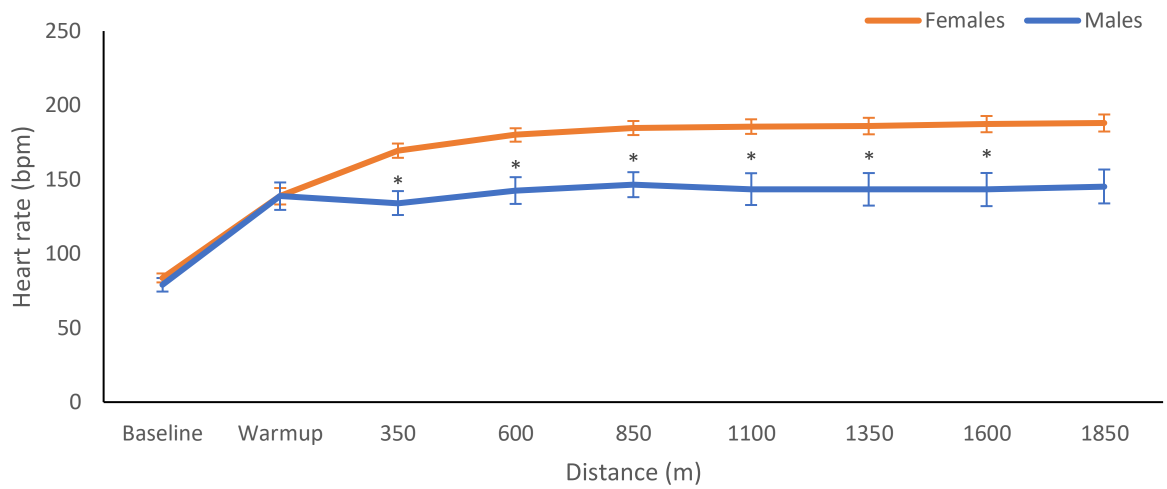


Figure 3. Heart rate recorded during baseline, warm up, and the duration of the 2000m time trial. A significant Sex x Distance interaction effect ($p < 0.001$) is present. (* indicates a significant post-hoc pairwise comparison)

Muscle Oxygenation (Figure 4)

There were Sex x Distance interaction effects for 3 out of the 4 NIRS metrics: TOI% (Wald $X^2 = 44.1$, $p < .001$), THb (Wald $X^2 = 28.5$, $p < .001$), and HHb (Wald $X^2 = 72.5$, $p < .001$). As seen on Fig. 4C, females' (TOI%) was higher during the warm up and until 1350m, after which the sex difference was non-significant. As for THb, females demonstrated a significant increase from 350m to 1850m, while males did not experience a significant change. For HHb, males' values are greater during warm up and at 350m. Finally, there was a significant main effect of Distance for the O_2Hb (Wald $X^2 = 682.7$, $p < .001$), where values at warm up were greater than at all distances of the trial phase (350m-1850m).

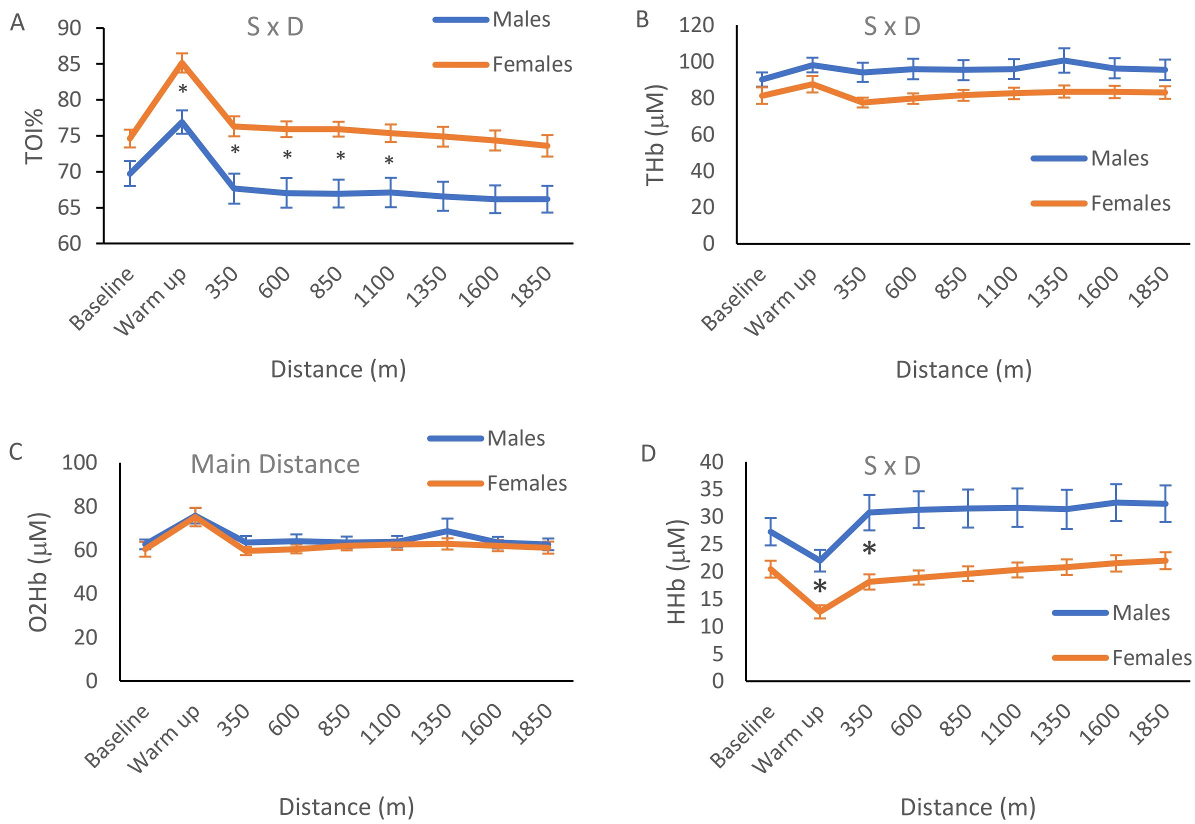
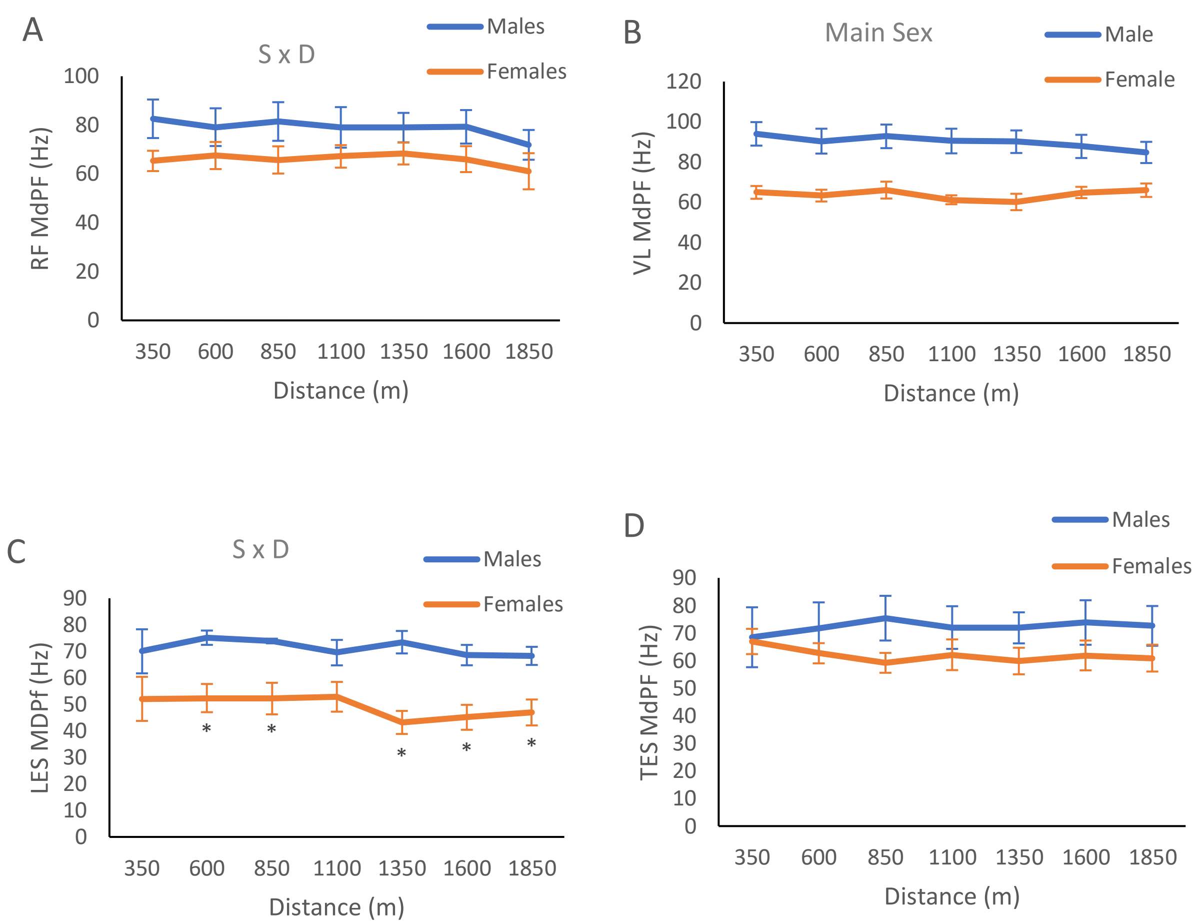


Figure 4. Muscle Oxygenation recorded from the left Vastus Lateralis of males and females throughout the duration of baseline, warm up, and the 2000m time trial phase. TOI%: Total Oxygenation Index, THb: Total Hemoglobin, O_2Hb: Oxygenated Hemoglobin, HHb: Deoxygenated Hemoglobin. S x D: significant Sex x Distance interaction effect; Main Distance: significant main effect of Distance; *: significant post-hoc pairwise comparison.

Muscle Activation Frequency (Figure 5)

There were Sex x Distance interaction effects for 3 of the 10 muscles: RF (Wald $X^2 = 14.3$, $p = .027$), LES (Wald $X^2 = 28.3$, $p < .001$), and PD (Wald $X^2 = 17.2$, $p = .009$). In all cases, activation frequency was generally higher in males, with a group difference that varied with time. In RF (Fig. 5A), male MdPF significantly dropped from 1600m to 1850m. In LES (Fig.

5C), male MdPF was significantly greater than that of females at 600m, 850m, 1350m, 1600m, and 1850m. In PD (Fig. 5G), only male MdPF dropped from 350m to 1600m. There were also some main Sex effects for the VL (Fig. 5B) and BIC (Fig. 5H) muscles, with generally higher MdPF in males (VL: Wald X^2 =16.6, g = 2.03, p < .001; BIC: Wald X^2 = 14.3, g = 1.67, p < .001). There were no other significant effects.



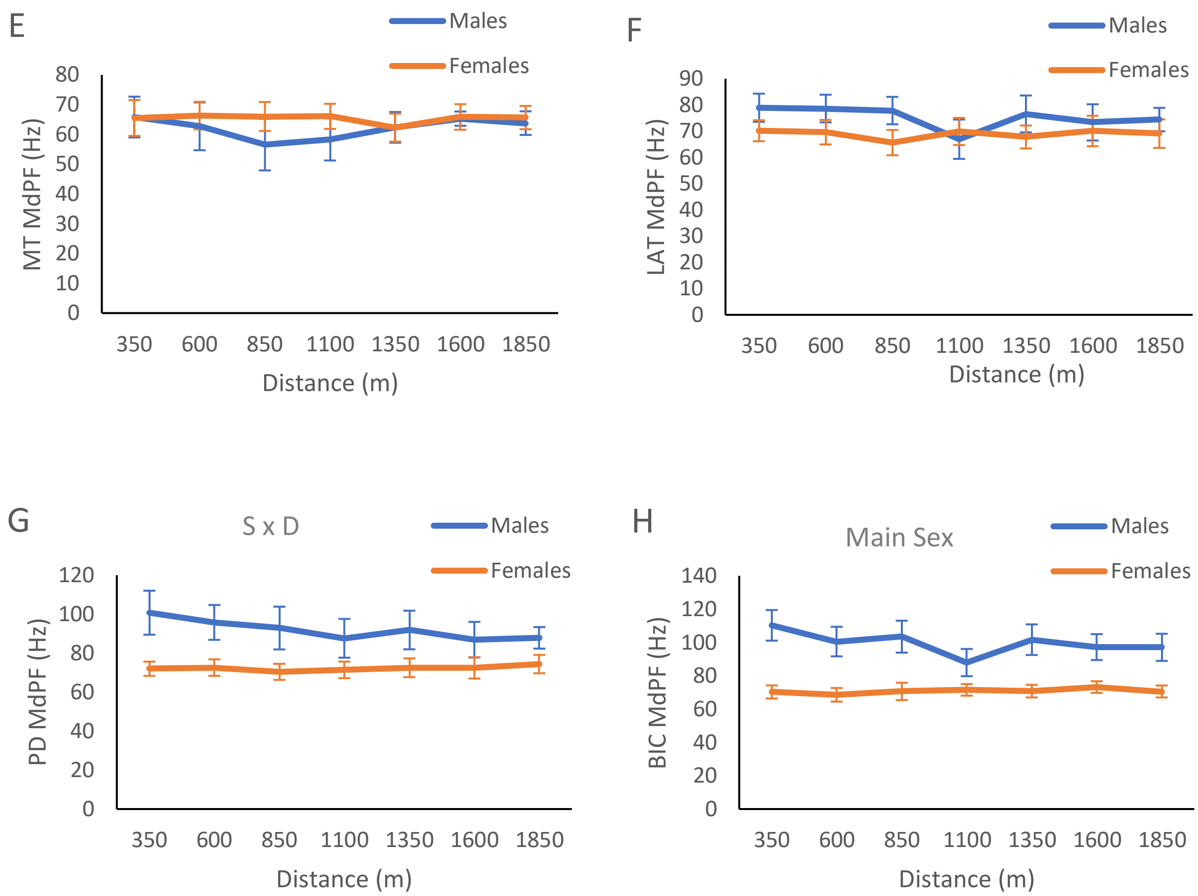


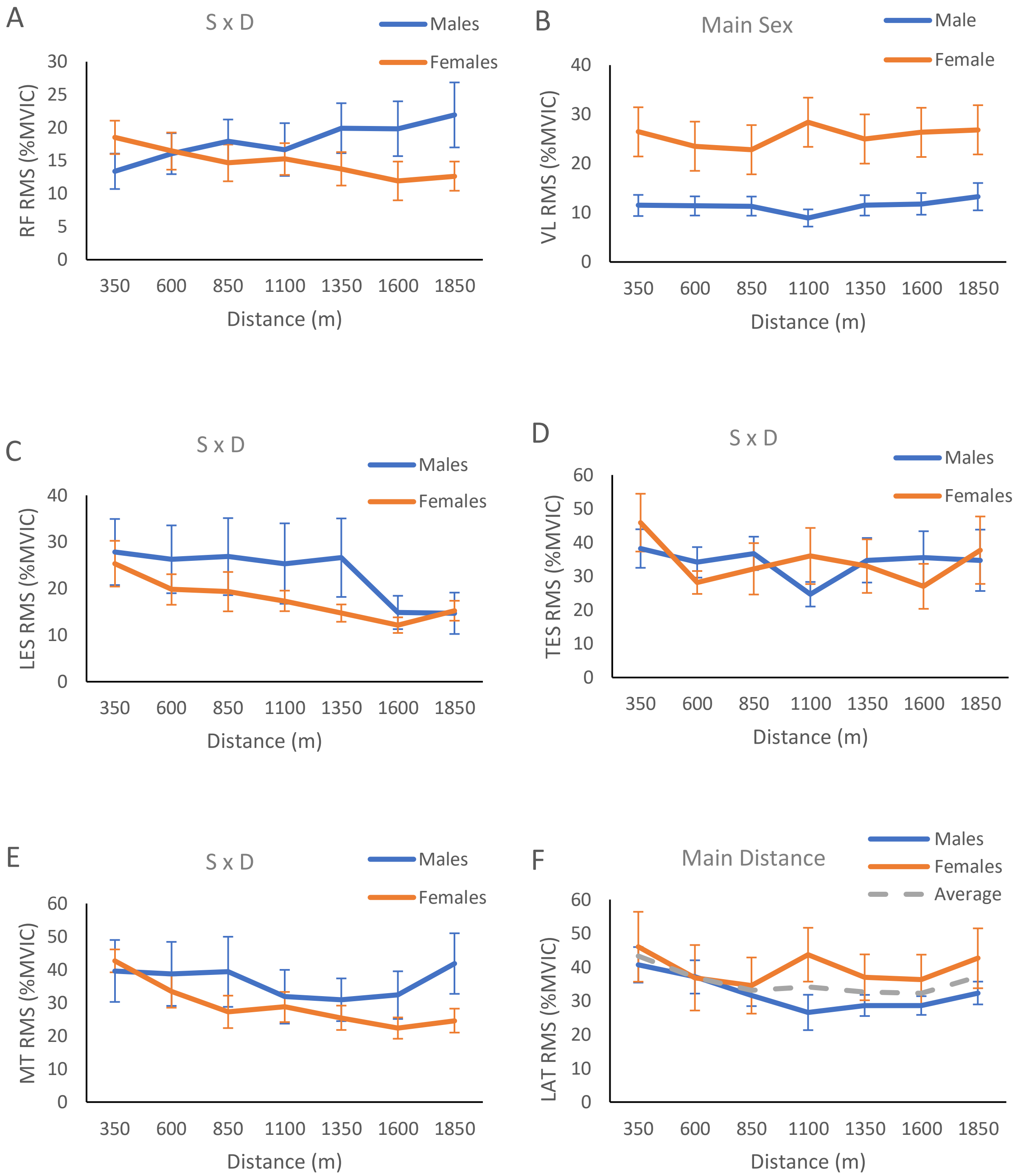
Figure 5. EMG median power frequency (MdPF) recorded for the duration of the 2000m time trial throughout the body. RF: Rectus Femoris, VL: Vastus Lateralis, LES: Lumbar Erector Spinae, TES: Thoracic Erector Spinae, MT: Middle Trapezius, LAT: Latissimus Dorsii, PD: Posterior Deltoid, BIC: Biceps Brachii. S x D: significant Sex x Distance interaction effect; Main Sex: significant main effect of Sex; *: significant post-hoc pairwise comparison.

Muscle Activation Amplitude (Figure 6)

There were Sex x Distance interaction effects for 5 of the 10 muscles: RF (Wald $X^2 = 22.0$, $p < .001$), LES (Wald $X^2 = 87.0$, $p < .001$), TES (Wald $X^2 = 49.5$, $p < .001$), MT (Wald $X^2 = 41.6$, $p < .001$), and BIC (Wald $X^2 = 17.0$, $p = .009$). In RF (Fig. 6A), as the time trial advanced, RMS values generally increased in males, and conversely, decreased in females. Post-hoc pairwise comparisons showed that RMS significantly increased for males from 350m to 600m while significantly decreasing in females from 1100m to 1350m. In LES (Fig. 6C), TES (Fig. 6D), MT (Fig. 6E) and BIC (Fig. 6H), activity stayed constant in males for the majority of the time, whereas it gradually decreased in females. Pairwise post-hoc tests revealed that LES RMS values decreased significantly only for females, and from 350m to 1600m. In TES (Fig. 6D), RMS significantly decreased in females only and from 350 to 1350m. In MT (Fig. 6E) and in BIC (Fig. 6H), RMS decreased significantly only for females, and from 350m to 1850m. There were no other significant Sex x Distance interaction effects.

There was also a main Sex effect in only the VL muscle (Fig. 6B), where RMS was greater in females (Wald $X^2 = 10.8$, $g = 1.17$, $p < .001$). It should however be noted that for this muscle, females' MVIC maximum RMS was significantly smaller than males' ($p = 0.03$) see figure 7 in supplemental material.

Finally, there were main Distance effects in the PD (Wald $X^2 = 29.0$, $p < .001$) and LAT (Wald $X^2 = 106.3$, $p < .001$) muscles. In PD (Fig. 6G), there was a significant drop in RMS from 350m to 1350m. In LAT (Fig. 6F), there was a significant increase from 1600m to 1850m.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S x D
Males
Females
RF RMS (%MVIC)
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25
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Distance (m)
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Main Sex
Male
Female
VL RMS (%MVIC)
40
30
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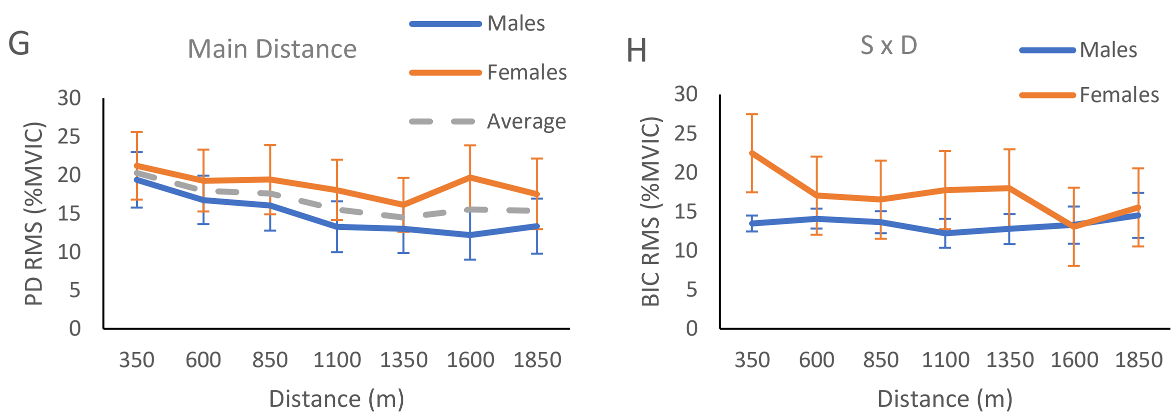

Figure 6. EMG root mean squared (RMS) recorded for the duration of the 2000m time trial throughout the body. RF: Rectus Femoris, VL: Vastus Lateralis, LES: Lumbar Erector Spinae, TES: Thoracic Erector Spinae, MT: Middle Trapezius, LAT: Latissimus Dorsii, PD: Posterior Deltoid, BIC: Biceps Brachii. S x D: significant Sex x Distance interaction effect; Main Sex: significant main effect of Sex; Main Distance: significant main effect of Distance

Discussion

This study examined the electromyographic and muscle oxygenation patterns of competitive rowers during a 2000m time trial and looked specifically for sex differences in these patterns. Electromyography from the upper limb, trunk, and lower limb, as well as oxygenation of the vastus lateralis, was recorded at 7 distance points during the time trial and were compared among male and female athletes for the first time. The novel findings during the rowing task were that females demonstrated generally lower activation frequency and more evidence of gradual decrease in recruitment amplitude in the legs, arms, shoulders, and trunk as the time trial progressed. In comparison, males showed fewer decreases in activation amplitude across the majority of muscles, even showing the opposite phenomenon (i.e. increased activation amplitude with time) in the lower limbs. Finally, females demonstrated greater heart rate and oxygenation with less deoxygenation of the vastus lateralis throughout the task. These findings align with our hypothesis and could potentially explain the greater incidence of injury among females due to greater evidence of fatigue.

Females' Greater Reliance on the Cardiovascular System

Females throughout the 2000m time trial demonstrated numerous characteristics indicating a greater reliance on the cardiovascular system then males. The first indicator was an elevated heart rate compared to males at the outset of the time trial. A higher initial heart rate and a greater increase in heart rate with time, especially in the first half of the task, means that females can deliver more oxygen to the muscles. In turn, allowing for greater use of oxidative force production pathways, potentially indicating a fatigue-preventing strategy among females. A previous study has noted similar maximal heart rates between the sexes during rowing (C. C. Yoshiga & M. Higuchi, 2003) however this study did not examine sex differences in heart rate during a 2000m rowing time trial. The second indicator of the female rower's greater reliance on the cardiovascular system to compensate for rowing-related fatigue is the significantly greater muscle oxygenation found in the quadriceps, i.e. a main task agonist. Females maintained a greater total oxygenation index during warm-up and throughout much of the time trial. It is important to note that females, despite having a lower total hemoglobin than males, maintained the same oxygenated hemoglobin concentration, and thus a lower deoxygenated hemoglobin than their male rowing counterparts. Previous studies have noted similar muscle oxygenation results where females displayed greater oxygenation in vastus lateralis during high intensity cycling (Ansdell et al., 2020; Smith & Billaut, 2012). A possible explanation for this could be differences in muscle fibre type between the sexes. Previous studies have indeed shown that females have a greater proportion of type I fibres in the leg muscles (Nuzzo, 2023; Roepstorff et al., 2006; Simoneau & Bouchard, 1989), resulting in a greater oxidative capacity (Russ et al., 2005). Few studies have examined fiber type differences outside of the leg muscles (Fournier et al., 2022). A study that examined sex differences in biceps brachii found similar fiber type proportions between males and females (approx. 50% type I for both sexes) (Miller et al., 1993). This study did however note that males had significantly greater type I fiber area within the biceps brachii. Together, a higher heart rate, combined with more oxidative muscle fibers in the main agonist muscles, could be evidence of a greater reliance on oxidative pathways to deal with, or even delay, rowing-related fatigue in females.

Sex Differences in Muscle Activation Within the Quadriceps

The quadriceps provide the greatest source of power in rowing. The muscles of the quadriceps are the source of approximately 45% of the total stroke power compared to the trunk and arms making up approximately 30% and 20% respectively (Kleshnev, 2002). Sex differences in quadriceps activation were evident throughout the trial. Over the course of this study females displayed a significantly smaller median power frequencies for the vastus lateralis throughout the time trial, providing further evidence of a greater portion of type I fibres. These results are in line with the previous literature that has demonstrated a negative correlation between the proportion of type I muscle fibres and the power frequency of the muscle activation (Gerdle et al., 1991). Muscle fibre type disparity would also explain the differences in muscle activation amplitude between the sexes within the leg muscles. Females began the trial using a greater portion of their maximal muscle activation amplitude compared to males in both vastus lateralis and rectus femoris. No previous studies compared these values between the sexes during rowing. This difference suggests that to row at the high intensity required for the time trial, females must recruit a greater portion of their motor units. The differences in force production ability between the type I and type II fibres would create the need for a greater motor unit recruitment in a type I-rich muscle. Despite the slower twitch speeds of type I fibres, the overall fatigue resistance of the muscle is increased (Plotkin et al., 2021). This information has formed the basis for previous research suggesting that female muscle is more fatigue-resistant across a variety of tasks, including cycling and repeated isometric contractions (Billaut & Bishop, 2009; Hunter, 2016). However, given the greater initial muscle activation amplitude utilized by females from the beginning of the trial, it is possible that females have a smaller strength reserve. This means that as the muscle fatigues throughout the task, there are fewer unfatigued motor units available to help maintain force production, thereby leading to the overall exhaustion of the system. This phenomenon is exemplified by the differences in rectus femoris activation amplitude. Indeed, males demonstrated a relatively linear increase in activation amplitude, suggesting that as the muscle is fatiguing, the neuromuscular system is recruiting more motor units to maintain force production. In comparison, females use a greater portion of their maximal activation amplitude and may not have as many unfatigued motor units available to maintain force production, which is represented by their linear decrease in muscle activation amplitude of rectus femoris. Although type I muscle fibers may have a greater fatigue resistance during lower intensity tasks, the massive force generation requirements of rowing a 2000m time trial force the female rowers to use a large portion of their muscle's potential. Ultimately, in the long run, this could prove to be more taxing on the athletes and require more force production from the other areas of the body such as the trunk and arms especially as fatigue develops.

Exhaustion of the Arms, Shoulders, and Trunk in Females

Across the duration of the time trial, the activation amplitude of the female athletes decreased across several muscles within the arms, shoulders, and trunk. Similar to rectus femoris, females experienced a relatively linear decrease in biceps brachii, middle trapezius, thoracic and lumbar erector spinae. Decreases in amplitude have been proposed as the representation of the exhaustion of the central nervous system in the fatigue model known as central activation theory (Abbiss & Laursen, 2005; Mendez-Villanueva et al., 2007). This linear decrease suggests that muscle fatigue is constant and compounding throughout the trial, and that females are exerting effort within these muscle groups at an intensity high enough to induce central nervous system exhaustion (Abbiss & Laursen, 2005). As the trial carries on, this fatigue-induced decrease in amplitude impairs force generation capacity within these muscle groups, resulting in reduced performance capability, and increased likelihood of injury within these regions (Dugan & Frontera, 2000; Mair et al., 1996; Murgia, 2013). It should also be noted that when males demonstrate a drop in muscle activity amplitude, such as in the lumbar and thoracic erector spinae, these changes occur much later within the time trial, possibly suggesting a greater resistance to fatiguability within these muscles while rowing. These differences in fatigue may reflect a female's lower force generating capacity in the upper body and trunk. Previous studies have noted lower strength in females (Côté, 2012; Faber et al., 2006) and their reliance on upper body strength particularly during whole-body occupational tasks involving engagement of the lower limbs, trunk, and upper limbs, in a sequence similar to that of rowing (Martinez et al., 2019; Yehoyakim et al., 2016)). Despite this reliance, sex-based strength differences have been shown to be higher in the upper body compared to the lower body, with the strength differences in equally trained individuals almost entirely accounted for by differences in muscle size (Bishop et al., 1987). Thus, increases in strength, particularly via increased muscle size, could be an advantageous performance enhancing strategy for females. Since the upper limbs incur significantly fewer injuries than the legs and back in rowing among both sexes, one could think that upper body strength training might not be an injury preventative approach for females. However, it is possible that increasing upper body strength, i.e. the region of greatest strength disparity between the sexes, could potentially alleviate overload on the comparatively stronger trunk and legs of the female rower. Increased upper body muscle strength would then be available to activate and use as the other main agonists fatigue without reaching exhaustion as quickly in the accessory muscles.

Similarities in Shoulder Fatigue Adaptions between Males and Females

The posterior deltoid of both males and females experienced a relatively linear drop in muscle activation amplitude. The exhaustion in posterior deltoid for both sexes evoked a similar fatigue response as activation increased in latissimus dorsi towards the end of the trial. This increase in activation later in the trial is likely compensating for the loss in force production ability within posterior deltoid. In males, the activation of middle trapezius and latissimus dorsii all increased with the exhaustion of posterior deltoid, possibly as a strategy to compensate for decreased force production. Both of these muscles serve as accessory muscles to the rowing motion. In comparison, females only saw an increase in latissimus dorsii activation. The greater initial activation among females is likely preventing the same adaption pattern for muscles that could help compensate for main agonist force production loss. A greater activation of shoulder synergist muscles has already been observed among females both before and after fatigue during push-up (Anders et al., 2004) and repetitive pointing tasks (Fedorowich et al., 2013). In our study, greater activation of shoulder accessory muscles at the onset is likely preventing the compensatory increase in muscle activation upon the exhaustion of posterior deltoid. However, given the lower prevalence of upper limb injuries, what may be more important for rowers is to strongly engage the main upper limb agonists to finish the drive phase, initiated by the legs and the trunk. This may be where females are at a disadvantage, regardless of the actions of upper limb stabilizers.

Fatigue and Performance: Next Steps

Females are generally reported as having a smaller muscle cross sectional area (Miller et al., 1993), which likely is the cause of their lower force production capacity. Muscle fiber hypertrophy is evident in both type I and II fibers among internationally successful rowers (Larsson & Forsberg, 1980). To improve performance and reduce fatigue, the overall strength reserve and force production capacity of the athlete must increase. Hypertrophy of all muscles leading to the increase in muscle cross sectional area could prove extremely beneficial for female rowers. However, strength can also be gained by increased specificity in training, improved muscle recruitment dynamics such as motor unit synchrony, coordination, and better training recovery. By increasing the force production ability of muscles, females will increase their strength reserve and will not need to activate as significant a portion of their muscles, thus delaying the onset of exhaustion. Additionally, by increasing the upper body muscle strength specifically, females will remove some stress from the entire neuromuscular system and avoid the total system fatigue we observed in these athletes. Training adaption should however be made on an individual basis especially with those who are injury prone or recovering from an injury. By avoiding systemic fatigue, the athletes who are at highest injury risk (in our case, the female athletes) can also decrease the overall incidence of injury.

Limitations

The results of the current study should be interpreted taking into consideration that the participants were mostly of collegiate training level and that results could change based on increasingly elite levels of rowing training. Additionally, this study does not take into consideration the full body kinematics and what impact they could have had on the fatiguing process. Before conducting this study, the sample size needed was 32 participants. Only 16 individuals were available for recruitment. In addition, both NIRS and EMG signals can be influenced by subcutaneous adipose tissue thickness. While this study accounted for the differences in the NIRS measures, it was not accounted for this at the many different EMG sensor sites. It should also be noted that rowing on an ergometer is substantially different from on water rowing. In knowing this, the results of this study should be interpreted understanding that on-water rowing has many additional internal and external factors that would influence the rower and their ability to complete a rowing task. This could result is different adaptation for on water rowing as compared to the use of the rowing ergometer. Finally, future studies with greater sample sizes, should also investigate whole-body sex differences during long steady state rows. This rowing format better reflects what rowers complete during day-to-day rowing training sessions.

CONCLUSION

Previous studies have used measures of muscle activity and oxygenation to examine fatigue in rowing. However, there is limited research on the sex specificity of how fatigue affects the whole body among competitive rowers. To our knowledge this is the first study to address this issue. Our results determined that females display greater evidence of fatigue than males, especially in the upper body. Muscles of the upper back and arms (middle trapezius and biceps brachii) both demonstrated evidence of exhaustion in females while males did not display the same response. Most likely caused by a strength disparity between the sexes, females are required to use a greater portion of their muscles from the beginning of the trial. As a result of greater initial activation an earlier exhaustion occurs since there is less unfatigued muscle to compensate. Additionally, females demonstrated a greater total muscle oxygenation in the quadriceps (vastus lateralis). Likely a reflection of the greater proportion of type I muscle fibres comprising the female quadricep, it could also contribute to the lower force production capacity among females. The results of this study however, can only be generalized to collegiate level competitive rowers. Further research would be required to understand these same fatiguing metrics in rowers of different calibres. Our results shed new light on sex differences in high level athletes by discovering greater levels of muscle exhaustion among female rowers compared to their male counterparts. Athletes, coaches, and sports therapists may use this information to determine whether their training and rehabilitation approaches should be the same or different for male and female rowers at risk of muscle injury.

REFERENCES

Abbiss, C. R., & Laursen, P. B. (2005). Models to Explain Fatigue during Prolonged Endurance Cycling. *Sports Medicine*, *35*(10), 865-898. https://doi.org/10.2165/00007256-200535100-00004

Albert, W. J., Wrigley, A. T., McLean, R. B., & Sleivert, G. G. (2006). Sex differences in the rate of fatigue development and recovery. *Dynamic Medicine*, *5*(1), 2. https://doi.org/10.1186/1476-5918-5-2

Anders, C., Bretschneider, S., Bernsdorf, A., Erler, K., & Schneider, W. (2004). Activation of shoulder muscles in healthy men and women under isometric conditions. *Journal of Electromyography and Kinesiology*, *14*(6), 699-707.

Ansdell, P., Škarabot, J., Atkinson, E., Corden, S., Tygart, A., Hicks, K. M., Thomas, K., Hunter, S. K., Howatson, G., & Goodall, S. (2020). Sex differences in fatigability following exercise normalised to the power–duration relationship. *The Journal of physiology*, *598*(24), 5717-5737.

Arne, G., Stephen, S., & Eike, E. (2009). Training Methods and Intensity Distribution of Young World-Class Rowers. *International Journal of Sports Physiology and Performance*, *4*(4), 448-460. https://doi.org/10.1123/ijspp.4.4.448

Avin, K. G., Naughton, M. R., Ford, B. W., Moore, H. E., Monitto-Webber, M. N., Stark, A. M., Gentile, A. J., & Law, L. A. (2010). Sex differences in fatigue resistance are muscle group dependent. *Medicine and science in sports and exercise*, *42*(10), 1943-1950. https://doi.org/10.1249/MSS.0b013e3181d8f8fa

Ballinger, G. A. (2004). Using generalized estimating equations for longitudinal data analysis. *Organizational research methods*, *7*(2), 127-150.

Barbero, M., Merletti, R., & Rainoldi, A. (2012). *Atlas of muscle innervation zones: understanding surface electromyography and its applications*. Springer Science & Business Media.

Billaut, F., & Bishop, D. (2009). Muscle Fatigue in Males and Females during Multiple-Sprint Exercise. *Sports Medicine*, *39*(4), 257-278. https://doi.org/10.2165/00007256-200939040-00001

Billaut, F., & Bishop, D. J. (2012). Mechanical work accounts for sex differences in fatigue during repeated sprints. *European Journal of Applied Physiology*, *112*(4), 1429-1436. https://doi.org/10.1007/s00421-011-2110-1

Bishop, P., Cureton, K., & Collins, M. (1987). Sex difference in muscular strength in equally-trained men and women. *Ergonomics*, *30*(4), 675-687. https://doi.org/10.1080/00140138708969760

Boushel, R., & Piantadosi, C. (2000). Near-infrared spectroscopy for monitoring muscle oxygenation. *Acta Physiologica Scandinavica*, *168*(4), 615-622.

Bowen, T. S., Rossiter, H. B., Benson, A. P., Amano, T., Kondo, N., Kowalchuk, J. M., & Koga, S. (2013). Slowed oxygen uptake kinetics in hypoxia correlate with the transient peak and reduced spatial distribution of absolute skeletal muscle deoxygenation [https://doi.org/10.1113/expphysiol.2013.073270]. *Experimental Physiology*, *98*(11), 1585-1596. https://doi.org/https://doi.org/10.1113/expphysiol.2013.073270

Burgess, K. E., Graham-Smith, P., & Pearson, S. J. (2009). Effect of acute tensile loading on gender-specific tendon structural and mechanical properties. *Journal of orthopaedic research*, *27*(4), 510-516.

Caldwell, J. S., McNair, P. J., & Williams, M. (2003). The effects of repetitive motion on lumbar flexion and erector spinae muscle activity in rowers. *Clinical Biomechanics*, *18*(8), 704-711. https://doi.org/https://doi.org/10.1016/S0268-0033(03)00117-7

Cifrek, M., Medved, V., Tonković, S., & Ostojić, S. (2009). Surface EMG based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics*, *24*(4), 327-340. https://doi.org/https://doi.org/10.1016/j.clinbiomech.2009.01.010

Côté, J. N. (2012). A critical review on physical factors and functional characteristics that may explain a sex/gender difference in work-related neck/shoulder disorders. *Ergonomics*, *55*(2), 173-182.

Côté, J. N. (2014). Adaptations to Neck/Shoulder Fatigue and Injuries. In M. F. Levin, *Progress in Motor Control* New York, NY.

Cowley, E. S., Olenick, A. A., McNulty, K. L., & Ross, E. Z. (2021). “Invisible sportswomen”: the sex data gap in sport and exercise science research. *Women in Sport and Physical Activity Journal*, *29*(2), 146-151.

Dawson, R. G., Lockwood, R. J., Wilson, J. D., & Freeman, G. (1998). The rowing cycle: Sources of variance and invariance in erogometer and on-the-water performance. *Journal of Motor Behavior*, *30*(1), 33-43.

Dugan, S. A., & Frontera, W. R. (2000). Muscle Fatigue and Muscle Injury. *Physical Medicine and Rehabilitation Clinics of North America*, *11*(2), 385-403. https://doi.org/https://doi.org/10.1016/S1047-9651(18)30135-9

Edwards, W. B. (2018). Modeling overuse injuries in sport as a mechanical fatigue phenomenon. *Exercise and sport sciences reviews*, *46*(4), 224-231.

Enoka, R. M., & Duchateau, J. (2016). Translating Fatigue to Human Performance. *Medicine and science in sports and exercise*, *48*(11), 2228-2238. https://doi.org/10.1249/MSS.0000000000000929

Faber, A., Hansen, K., & Christensen, H. (2006). Muscle strength and aerobic capacity in a representative sample of employees with and without repetitive monotonous work. *International Archives of Occupational and Environmental Health*, *79*(1), 33-41. https://doi.org/10.1007/s00420-005-0025-z

Fedorowich, L., Emery, K., Gervasi, B., & Côté, J. N. (2013). Gender differences in neck/shoulder muscular patterns in response to repetitive motion induced fatigue. *Journal of Electromyography and Kinesiology*, *23*(5), 1183-1189. https://doi.org/https://doi.org/10.1016/j.jelekin.2013.06.005

Fournier, G., Bernard, C., Cievet-Bonfils, M., Kenney, R., Pingon, M., Sappey-Marinier, E., Chazaud, B., Gondin, J., & Servien, E. (2022). Sex differences in semitendinosus muscle fiber-type composition [https://doi.org/10.1111/sms.14127]. *Scandinavian Journal of Medicine & Science in Sports*, *32*(4), 720-727. https://doi.org/https://doi.org/10.1111/sms.14127

Gerdle, B., Henriksson-LarsÉN, K., Lorentzon, R., & Wretling, M. L. (1991). Dependence of the mean power frequency of the electromyogram on muscle force and fibre type

[https://doi.org/10.1111/j.1748-1716.1991.tb09180.x]. *Acta Physiologica Scandinavica*, *142*(4), 457-465. https://doi.org/https://doi.org/10.1111/j.1748-1716.1991.tb09180.x
Hagerman, F. C. (1984). Applied physiology of rowing. *Sports medicine*, *1*(4), 303-326.
Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol*, *10*(5), 361-374. https://doi.org/10.1016/s1050-6411(00)00027-4
Hosea, T. M., & Hannafin, J. A. (2012). Rowing injuries. *Sports health*, *4*(3), 236-245.
Howell, D. W. (1984). Musculoskeletal profile and incidence of musculoskeletal injuries in lightweight women rowers. *The American Journal of Sports Medicine*, *12*(4), 278-282. https://doi.org/10.1177/036354658401200407
Hunter, S. K. (2016). Sex differences in fatigability of dynamic contractions [https://doi.org/10.1113/EP085370]. *Experimental Physiology*, *101*(2), 250-255. https://doi.org/https://doi.org/10.1113/EP085370
Hunter, S. K., Critchlow, A., Shin, I.-S., & Enoka, R. M. (2004). Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength. *Journal of Applied Physiology*, *96*(1), 195-202. https://doi.org/10.1152/japplphysiol.00893.2003
Husmann, F., Gube, M., Felser, S., Weippert, M., Mau-Moeller, A., Bruhn, S., & Behrens, M. (2017). Central Factors Contribute to Knee Extensor Strength Loss after 2000-m Rowing in Elite Male and Female Rowers. *Medicine & Science in Sports & Exercise*, *49*(3), 440-449.
Kleshnev, V. (2002). Power in rowing. *International research in sports biomechanics*, 224-230.
Klusiewicz, A., Rębiś, K., Ozimek, M., & Czaplicki, A. (2021). The use of muscle near-infrared spectroscopy (NIRS) to assess the aerobic training loads of world-class rowers. *Biology of Sport*, *38*(4), 713-719. https://doi.org/10.5114/biolsport.2021.103571
Larsson, L., & Forsberg, A. (1980). Morphological muscle characteristics in rowers. *Canadian journal of applied sport sciences. Journal canadien des sciences appliquees au sport*, *5*(4), 239-244. http://europepmc.org/abstract/MED/7449040
Li, Y., Koldenhoven, R. M., Jiwan, N. C., Zhan, J., & Liu, T. (2020). Trunk and shoulder kinematics of rowing displayed by Olympic athletes. *Sports Biomechanics*, 1-13. https://doi.org/10.1080/14763141.2020.1781238
Mair, S. D., Seaber, A. V., Glisson, R. R., & Garrett Jr, W. E. (1996). The role of fatigue in susceptibility to acute muscle strain injury. *The American Journal of Sports Medicine*, *24*(2), 137-143.
Martinez, R., Bouffard, J., Michaud, B., Plamondon, A., Côté, J. N., & Begon, M. (2019). Sex differences in upper limb 3D joint contributions during a lifting task. *Ergonomics*, *62*(5), 682-693.
McKay, A. K. A., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J., & Burke, L. M. (2022). Defining Training and Performance Caliber: A Participant Classification Framework. *Int J Sports Physiol Perform*, *17*(2), 317-331. https://doi.org/10.1123/ijspp.2021-0451
Mendez-Villanueva, A., Hamer, P., & Bishop, D. (2007). Fatigue responses during repeated sprints matched for initial mechanical output. *Medicine & Science in Sports & Exercise*, *39*(12), 2219-2225.

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. https://doi.org/10.1007/BF00235103

Minoshima, Y., Nishimura, Y., Tsuboi, H., Sato, H., Ogawa, T., Kamijo, Y.-i., Umezu, Y., & Tajima, F. (2022). Differences in Muscle Fatigability of Vastus Medialis between Sexes Using Surface Electromyographic Power Spectral Analysis in Healthy Adults. *Progress in Rehabilitation Medicine*, *7*, 20220051.

Morris, F., Smith, R., Payne, W., Galloway, M., & Wark, J. (2000). Compressive and Shear Force Generated in the Lumbar Spine of Female Rowers. *International journal of sports medicine*, *21*(07), 518-523.

Murgia, C. (2013). Overuse, tissue fatigue, and injuries. *Journal of Dance Medicine & Science*, *17*(3), 92-100.

Newlands, C., Reid, D., & Parmar, P. (2015). The prevalence, incidence and severity of low back pain among international-level rowers. *British Journal of Sports Medicine*, *49*(14), 951-956.

Ng, L., Campbell, A., O'Sullivan, P., & Burnett, A. (2013). Gender Differences in Trunk and Pelvic Kinematics During Prolonged Ergometer Rowing in Adolescents. *Journal of Applied Biomechanics*, *29*(2), 180-187.

Niemeijer, V. M., Jansen, J. P., van Dijk, T., 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.

Nuzzo, J. L. (2023). Sex differences in skeletal muscle fiber types: A meta-analysis. *Clin Anat*. https://doi.org/10.1002/ca.24091

Peharec, S., Jerković, R., Bačić, P., Azman, J., & Bobinac, D. (2007). Kinematic measurement of the lumbar spine and pelvis in the normal population. *Collegium antropologicum*, *31*(4), 1039-1042.

Plotkin, D. L., Roberts, M. D., Haun, C. T., & Schoenfeld, B. J. (2021). Muscle fiber type transitions with exercise training: Shifting perspectives. *Sports*, *9*(9), 127.

Pollock, C. L., Jenkyn, T. R., Jones, I. C., Ivanova, T. D., & Garland, S. J. (2009). Electromyography and Kinematics of the Trunk during Rowing in Elite Female Rowers. *Medicine & Science in Sports & Exercise*, *41*(3). https://journals.lww.com/acsm-msse/Fulltext/2009/03000/Electromyography_and_Kinematics_of_the_Trunk.18.aspx

Reid, D. A., & McNair, P. J. (2000). Factors contributing to low back pain in rowers. *British Journal of Sports Medicine*, *34*(5), 321. https://doi.org/10.1136/bjsm.34.5.321

Rodriguez, R., Townsend, N., Aughey, R., & Billaut, F. (2018). Influence of averaging method on muscle deoxygenation interpretation during repeated-sprint exercise. *Scandinavian Journal of Medicine & Science in Sports*, *28*(11), 2263-2271.

Roepstorff, C., Thiele, M., Hillig, T., Pilegaard, H., Richter, E. A., Wojtaszewski, J. F. P., & Kiens, B. (2006). Higher skeletal muscle α2AMPK activation and lower energy charge and fat oxidation in men than in women during submaximal exercise [https://doi.org/10.1113/jphysiol.2006.108720]. *The Journal of physiology*, *574*(1), 125-138. https://doi.org/https://doi.org/10.1113/jphysiol.2006.108720

Russ, D. W., Lanza, I. R., Rothman, D., & Kent-Braun, J. A. (2005). Sex differences in glycolysis during brief, intense isometric contractions [https://doi.org/10.1002/mus.20396]. *Muscle & Nerve*, *32*(5), 647-655. https://doi.org/https://doi.org/10.1002/mus.20396

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), E567-E572.

Smith, E. S., McKay, A. K. A., Ackerman, K. E., Harris, R., Elliott-Sale, K. J., Stellingwerff, T., & Burke, L. M. (2022). Methodology Review: A Protocol to Audit the Representation of Female Athletes in Sports Science and Sports Medicine Research. *International Journal of Sport Nutrition and Exercise Metabolism*, *32*(2), 114-127. https://doi.org/10.1123/ijsnem.2021-0257

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.

Smith, T. B., & Hopkins, W. G. (2012). Measures of Rowing Performance. *Sports Medicine*, *42*(4), 343-358. https://doi.org/10.2165/11597230-000000000-00000

Smoljanovic, T., Bojanic, I., Hannafin, J. A., Hren, D., Delimar, D., & Pecina, M. (2009). Traumatic and Overuse Injuries Among International Elite Junior Rowers. *The American Journal of Sports Medicine*, *37*(6), 1193-1199. https://doi.org/10.1177/0363546508331205

Srinivasan, D., Sinden, K. E., Mathiassen, S. E., & Côté, J. N. (2016). Gender differences in fatigability and muscle activity responses to a short-cycle repetitive task. *European Journal of Applied Physiology*, *116*(11), 2357-2365. https://doi.org/10.1007/s00421-016-3487-7

Steinacker, J. M. (1993). Physiological aspects of training in rowing. *International journal of sports medicine*, *14*, S3-S3.

Sub Kwon, Y., & Kravitz, L. (2006). How do muscles grow? *IDEA Fitness Journal*, *3*(2), 21-25.

Tachibana, K., Yashiro, K., Miyazaki, J., Ikegami, Y., & Higuchi, M. (2007). Muscle cross-sectional areas and performance power of limbs and trunk in the rowing motion. *Sports Biomechanics*, *6*(1), 44-58.

Teitz, C. C., O'Kane, J., Lind, B. K., & Hannafin, J. A. (2002). Back pain in intercollegiate rowers. *The American Journal of Sports Medicine*, *30*(5), 674-679.

Thomas, S., Reading, J., & Shephard, R. J. (1992). Revision of the physical activity readiness questionnaire (PAR-Q). *Canadian journal of sport sciences*.

Verrall, G., & Darcey, A. (2014). Lower back injuries in rowing national level compared to international level rowers. *Asian J Sports Med*, *5*(4), e24293. https://doi.org/10.5812/asjsm.24293

Vøllestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods*, *74*(2), 219-227. https://doi.org/https://doi.org/10.1016/S0165-0270(97)02251-6

Westerbacka, J., Cornér, A., Tiikkainen, M., Tamminen, M., Vehkavaara, S., Häkkinen, A. M., Fredriksson, J., & Yki-Järvinen, H. (2004). Women and men have similar amounts of liver and intra-abdominal fat, despite more subcutaneous fat in women: implications for sex differences in markers of cardiovascular risk. *Diabetologia*, *47*(8), 1360-1369. https://doi.org/10.1007/s00125-004-1460-1

Willwacher, S., Koopmann, T., Dill, S., Kurz, M., & Brüggemann, G.-P. (2021). Dorsal muscle fatigue increases thoracic spine curvature in all-out recreational ergometer rowing. *European Journal of Sport Science*, *21*(2), 176-182. https://doi-org.proxy3.library.mcgill.ca/10.1080/17461391.2020.1737242

Yang, J., Tibbetts, A. S., Covassin, T., Cheng, G., Nayar, S., & Heiden, E. (2012). Epidemiology of overuse and acute injuries among competitive collegiate athletes. *Journal of athletic training*, *47*(2), 198-204.

Yehoyakim, M., Bellefeuille, S., Côté, J. N., & Plamondon, A. (2016). Relationship between leg and back strength with inter-joint coordination of females during lifting. *International Journal of Industrial Ergonomics*, *56*, 32-40. https://doi.org/https://doi.org/10.1016/j.ergon.2016.08.013

Yoshiga, C., & Higuchi, M. (2003). Rowing performance of female and male rowers. *Scandinavian Journal of Medicine & Science in Sports*, *13*(5), 317-321.

Yoshiga, C. C., & Higuchi, M. (2003). Oxygen uptake and ventilation during rowing and running in females and males. *Scandinavian Journal of Medicine & Science in Sports*, *13*(6), 359-363. https://doi.org/https://doi.org/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. https://doi.org/10.1117/1.3309741

SUPPLEMENTAL MATERIALS

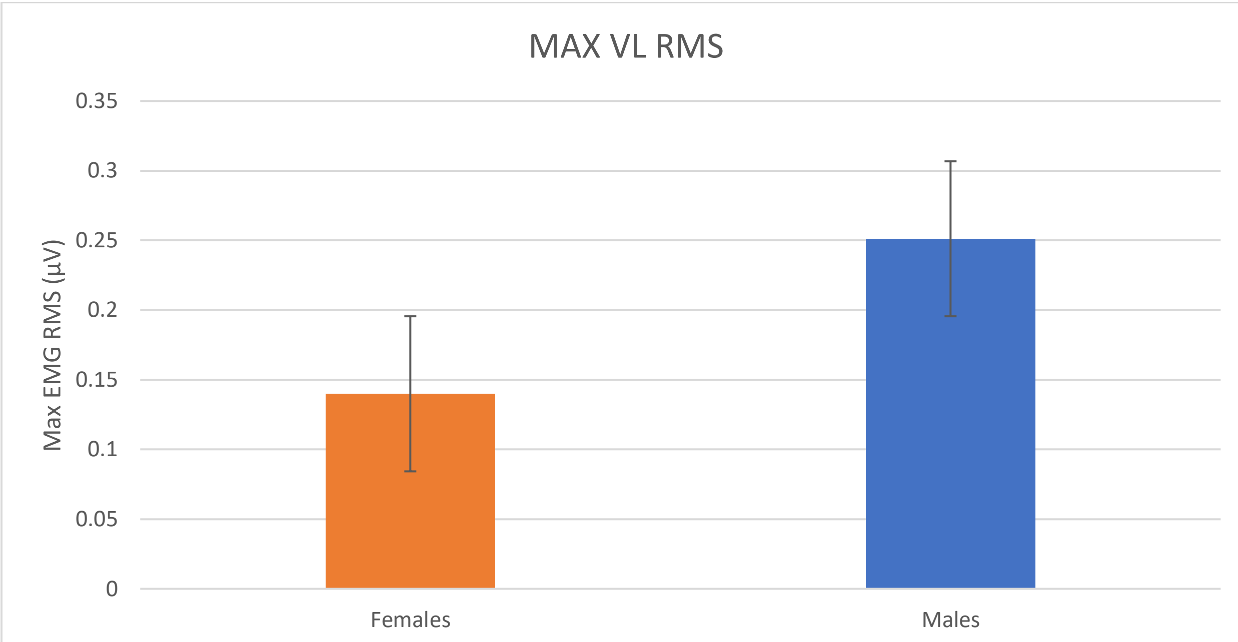

Figure 7. Maximum RMS value for VL

APPENDICES

Appendix 1: Consent Form

McGill | Faculty of Education | Department of Kinesiology and Physical Education

Consent form

Version Date: 08-19-22 REB File #:

Participant Informed Consent form

Researcher

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Supervisor

Julie Côté, Ph.D., Associate Professor, Department of Kinesiology and Physical Education, McGill University, Julie.cote2@mcgill.ca (514) 398-4184 ext. 0539,

Title of project

Sex differences in Muscle Fatigue Among Collegiate Rowers During a 2000m Race Simulation

Sponsor

Equipment and supplies for this project are funded by NSERC (RGPIN-2022-04757) and CFI (36715) research grants.

Preamble/Introduction

You are invited to participate in a study on the sex-specific effects of a 2000m rowing race simulation on the physical, physiological, and biomechanical outcomes of collegiate level rowing athletes. Before agreeing to participate in this project, please take the time to consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks and drawbacks, as well as the persons to contact, if necessary.

We invite you to ask any questions that you deem useful to the researchers and other members of the staff assigned to the study. You can ask them to explain anything that is not clear to you.

Project description, objectives, and planned dissemination

The objectives of this research are to uncover the sex-specific effects of a 2000m race simulation on muscle activity and blood oxygenation. Thirty-two (32) collegiate level rowers will be recruited to perform the 2000m race simulation, in our laboratory. The long-term objective of this project is to better understand the effects of high-intensity rowing on athletes, and the physiological mechanisms that lead to injury in the rowing population. This information will serve to improve potential training strategies and prevent future injuries among athletes. Results from this project will be disseminated in the forms of a M.Sc. Thesis, conference presentations, and a peer-reviewed manuscript.

Nature and duration of your participation

This research project aims at understanding how a 2000m rowing race simulation influences muscle activity and blood oxygenation. The study takes place at McGill University, Currie Gymnasium room 326 in Montreal. You are asked to participate in one experimental session that will last approximately two hours. The session involves six phases: Phase 1: Preparation 1 (30 minutes), Phase 2: pre-fatigue test (20 minutes), Phase 3: Preparation 2 (15 minutes), Phase 4: Warm-up (20 Minutes), Phase 5: Race simulation (8 minutes), Phase 6: Recovery (10 minutes).

During Phase 1, you will be asked to fill out questionnaires. The locations of surface electrodes and blood oxygenation sensor will be marked on your skin using a make-up pen. Ultrasound will be used to measure tissue thickness on your leg. Then, electrodes will be applied on the skin over your right side to measure muscle activity. None of these procedures are invasive. You will be asked to sit, stand, or lie down during the placement of these devices.

During Phase 2, you will be asked to complete baseline reference efforts.

During Phase 3, a blood oxygenation sensor will be placed on your leg on your left side. You will then be instructed to rest and relax for 30 seconds to record baseline values. This procedure is not invasive. You will be asked to sit down for the placement and relaxation period.

During Phase 4, you will complete a 20-minute low intensity warm-up on the rowing ergometer. Kinematic sensors will also be placed over your skin.

During Phase 5, you will be asked to complete a 2000m race simulation on the rowing ergometer.

During Phase 6, you will relax and recover from the rowing task. You will be offered stretches to help relieve any discomfort.

Voluntary participation

Participation in this research study is fully voluntary. You have the right to decline to answer any questions and the right to withdraw from the study at any time during the study, after which the data will be de-identified. If you withdraw from the study, all documents of your participation will be destroyed so long as you withdraw prior to publication. Once this study is published McGill will retain this information for 7 years, as per university policy, though it will be withdrawn from any further use.

Potential benefits associated with your participation

There are no benefits from participating in this study. However, you will contribute to the advancement of knowledge on the sport of rowing, the biomechanics and fatigue adaptation methods of its athletes and musculoskeletal injury.

Compensation

You will receive no monetary compensation for your time during this study. However, you will receive your performance results from your 2000m ergometer trial.

Potential risks associated with your participation

None of the techniques used are invasive.

In case of adverse events, emergency protocols are in place to contact emergency personnel (911, McGill security, Sports Medicine and Winsor Clinics).

Personal inconvenience

The duration of each experimental session (approximately 1.5-2 hours) may represent an inconvenience for you. Some small regions (12, 3x3 cm each) of the skin over your back, thigh, shoulder, and arm muscles must be shaven before placing the electrodes. This might be an inconvenience for you. Although it is hypo-allergenic, the adhesive tape used to fix the electrodes on your skin may occasionally produce some slight skin irritation. Should this happen, a hypo-allergic lotion will be applied on your skin to relieve skin irritation. You will experience fatigue during this protocol which may cause tenderness, stiffness, and/or pain during and/or following the session. These symptoms should dissipate with 48 hours following the completion of the protocol.

Confidentiality

All your data will be securely stored in password protected files on a password protected computer. Your identifiable information will be kept separate in a locked filing cabinet in the Supervisor's office or lab. Only the people involved in the project will have access to this information. If the results of this research project are presented or published, nothing will allow your identification. After this five-year period, identifiable data will be destroyed. The de-identifiable data will be kept for a total of five years following publication, according to University Policy.

The researchers may wish to photograph you during the study with a digital camera. All photographs are de-identified and may be used in presentations and publications. Consenting to camera photography is optional for this study. Images will not contain facial features, or other potentially identifiable features such as tattoos, scars, piercings.

Yes: ___ *No:* _____ You consent to camera photography.

Questions concerning the study

The researchers present during the testing should answer your questions in a satisfactory manner. You can ask questions at any time.

Contact persons

If you need to ask questions about the project, signal an adverse effect and/or an incident, you can contact at any time Julie Côté, Ph.D., or Luke Spagnuolo, B.Sc., at the numbers indicated on the 1st page.

If you have any questions or concerns regarding your rights or welfare as a participant in this research study, you can contact the McGill Ethics Officer at 514-398-6831 or georgia.kalavritinos@mcgill.ca.

Please sign below if you have read the above information and consent to participate in this study. Agreeing to participate in this study does not waive any of your rights or release the researchers from their responsibilities. A copy of this consent form will be given to you and the researcher will keep a copy.

Participant's Name: (please print) ______

Participant's Signature: ______________________Date: ______________

New Version Date : Tuesday August 16th 2022

Appendix 2: Recruitment Flyer

McGill | Faculty of Education | Department of Kinesiology and Physical Education

Version #: (08-19-22)

Do you want to experience what research in Kinesiology and Exercise physiology is all about?
Are you interested in contributing to science of Rowing?
You have the opportunity to take part in a study that could help prevent musculoskeletal injuries in Rowing Athletes.

WE NEED YOU!

Criteria:

- You are a collegiate level rower with competitive rowing experience and who trains regularly
- You should be between 18 and 30 years of age and in general good health, with no known injuries (e.g. rotator cuff tendonitis) or medical conditions (e.g. arthritis) preventing you from exercising

Objectives:

- Determine the effects of a rowing task on muscle fatigue and blood oxygenation.
- Evaluate the effects of this rowing task on males and females

Procedures:

- Several instruments (kinematic markers, muscle activity sensors and blood oxygenation sensors) are used to non-invasively measure posture, muscle activity and blood oxygenation during a rowing task

Exclusion Criteria:

- No Caffeine ≤ 12 hours prior to the laboratory visit
- No alcohol ≤ 24 hours prior to the laboratory visit
- Must not be injured or unable to complete the race simulation at a maximal level

Duration:

- You must be able to attend one experimental session of approximately 2 hours in duration

Location:

- Currie Gym, McGill University, 475 Pine Avenue West, Montreal, QC.

For more information, please contact:

Luke Spagnuolo (paul.spagnuolo@mail.mcgill.ca) Supervisor: Dr. Julie Côté (julie.cote2@mcgill.ca)