**Assessing the prevalence of injuries in competitive rowing athletes: the effects of body location, sex, and perceived fatigue**

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## ABSTRACT

The purpose of this study is to; assess the lifetime prevalence of musculoskeletal injures, based on different anatomical regions, including the perceptions of muscular fatigue as a contributing factor to these injuries in recreational rowing athletes; to assess the relative effect of muscle fatigue on musculoskeletal injury in male and female athletes, respectively; to assess the effect of sex on LBP prevalence and severity in recreational rowing athletes. With this purpose in mind a survey was conducted involving rowing athletes across all ages and sexes. In this survey information on rowing experience, injury history, prevalence of low back pain, subjective level of fatigue at the time of injury, activity at the time of most severe injury, and type of pain with most severe injury. The most severe injury incurred for participants most commonly on a rowing ergometer (n=31), followed by training on the water (sweep n=26, scull n=24), most severe injuries were described as a dull pain (n=77). The most common injury site was the back, which had a significantly higher prevalence than the upper body, lower body and other injury sites. Injury prevalence of the upper body was significantly greater than the lower body and other injury sites, and lower body injury prevalence was significantly greater than the other injury sites. Lastly, Participants perceived that they were significantly more fatigued when a back injury occurred than injuries to any other site. Additionally, Injuries to the lower extremity had a higher perception of fatigue than upper extremity and other injury sites. The current work also suggests that there are no systematic differences in the prevalence of low back pain between male and female rowing athletes, nor in the severity of duration of such pain experienced at the low back or in other more general body regions.

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# CHAPTER I: INTRODUCTION

Rowing is a popular sport around the world and continues to grow particularly in female participants at a colligate level (Keenan *et al., 2018)*. Part of this growth is due to the accessibility of rowing to those with recreational interests through the use of indoor ergometers or water-based rowing clubs. Rowing can have a wide range of benefits, both physical and mental, as it is an aerobic sport which combines aspects of both strength and endurance. Despite its benefits, rowing is not without its risks as low back pain (LBP) is the most reported musculoskeletal injury among rowing athletes (Budgett *et al.*, 1989), having been reported by 71 percent of senior British trialists (Pike, 2000). Further, amateur rowers appear to be even more susceptible to low back injuries when compared to reports from other groups of elite athletes (Finlay et al., 2020). In addition to low back injury, other common injury sites include the shoulder, knee, and wrist (Pike, 2000). For the purpose of this study, we will define injury as an acute event causing musculoskeletal damage and pain which may be caused by musculoskeletal damage however is a perceptual construct, we will refer to them collectively as musculoskeletal disorders. Previous literature has yet to investigate causes of injuries at these sites within the sport of rowing; however, previous studies have found that acute shoulder injuries are typically caused by excessive force when the arm is in either an outstretched position, or extension of an abducted arm (Crichton *et al.*, 2012). Chronic shoulder, knee and wrist injuries typically occur when an athlete is subjected to a repetitive movement done either under load, or at high velocities (Oliver *et al.*, 2019, Salati *et al.*, 2016).

## 1.1 Rowing-Related Injury Risk Factors

Lower back injuries are associated with several biomechanical risk factors, many of which are present during a typical rowing stroke. The first risk factor is repeated spine flexion under a compressive load (Callaghan & McGill, 2001; Hangai et al., 2008). Specifically, it has been noted that during a single rowing stroke the spine experiences compressive and shear forces that can exceed normal levels and can approach National Institute for Occupational Safety and Health (NIOSH) (3400 N compression) safety limits (Morris *et al.*, 2000). Considering the cumulative/repetitive nature of a rowing movement, the spine joint forces that an athlete must endure throughout a rowing event have the potential to accumulate over the course of any rowing bout, potentially resulting in injuries associated with chronic repeated loading (Potvin, 2012), again suggesting why LBP is the most reported condition among rowing athletes (Budgett *et al.*, 1989). Other MSD risk factors which are present during a typical rowing stroke include both instances of high thoracolumbar spine flexion (Hemming *et al.*, 2018) and compound postures involving a combination of spine flexion, lateral flexion, and rotation (Stevens *et al.*, 2016). Such end-range postures may place added risk on the passive tissues, such as spinal ligaments or intervertebral discs responsible for stabilizing the spine. These risks may be further exacerbated when considering the postures required in the catch-position of a sweep rowing movement (fully flexed position at the beginning of the stroke). This awkward position is composed of spine flexion, as well as lateral flexion and rotation toward the oarside which loads spinal tissues asymmetrically, potentially further increasing the risk of MSD. Although many occupations have the capacity to expose an individual to single biomechanical risk factors, due to the technique used in rowing it is possible that elite rowers may be subjected to all three risk factors (i.e., high-load, high flexion, and compound postures). These risk factors are then further modulated through manifestations of muscle fatigue, which has been shown to have negative effects on spine movement coordination and proprioception.

The high prevalence of low back MSD in rowing athletes has been linked to a variety of potential contributing factors. These risk factors include a previous history of LBP or injury (Foss *et al.*, 2012), high training volumes (Foss *et al.,* 2012), indoor ergometer training (Maselli *et al.*, 2015), age (Ng *et al.*, 2014), and athlete sex (Finlay *et al.*, 2020). Through a recent review, many of these factors have been linked to changes in rowing biomechanics (Nugent *et al.*, 2021). For example, typically rowers with LBP have greater posterior pelvic rotation at the catch, and greater hip extension at the finish, combined with far less efficient trunk muscle activity, noted through an increased muscle co-activation. Further, fatigue has been shown to result in increased lumbar flexion at the catch, which is further increased when using an indoor ergometer (Wilson *et al.*, 2013). Despite an increasing amount of research assessing risk factors, related to low back MSD either collectively, or individually, a lack of consensus exists in the relative effects of muscle fatigue, and athlete sex, including any potential association or interaction between these two factors on MSD prevalence. Further, it is unclear whether these two potentially intersecting factors may disproportionately affect musculoskeletal injuries, particularly those relating to the low back.

## 1.2 An Overview of Muscle Fatigue

Muscle fatigue is caused by one or several of the physiological processes both neural and metabolic that enable the contractile proteins (i.e., actin and myosin) present within a muscle to generate a force. Such processes include, central fatigue, and peripheral increases in ADP, accumulation of lactic acid, and depletion of glycogen. When impaired, muscles become weak, with localized muscle fatigue effecting a specific anatomical region, or set of muscles used during a given task. The isolated fatiguing effects that a specific task has on a group of muscles is called the *task dependency* of muscle fatigue and is a prominent principle in the field of ergonomics and sport biomechanics (Asmussen, 1979).

Throughout the literature there are many examples which suggest sex-specific responses to neuromuscular fatigue. In general, females are less fatigable than males for many isometric tasks and some dynamic tasks when completing matched intensity isometric muscle contractions in the upper and lower extremities (Hunter, S. K., 2014). Further, several studies have demonstrated that after long duration cycling and running females have preserved lower extremity strength relative to males (Glace *et al.*, 2013, Glace *et al.*, 1998, Temesi *et al.,* 2015). Recently many of the mechanisms behind these apparent disparities in fatiguability have been summarized (Hunter S. K., 2016). Some of the potential mechanisms behind any sex-related differences in muscle fatiguability may be related to differences in muscle fibre type, skeletal muscle metabolism, muscle perfusion, and supraspinal excitability (Enoka *et al.*, 2008). It is currently unknown; however, if muscle fatiguability may play any role in any apparent sex-related differences related to MSD prevalence potentially implicated in the sport of rowing (e.g., Ng et al., 2014). It may be possible that changes in the fatiguability of male and female rowers may directly affect the development of biomechanical risk factors (i.e., high thoracolumbar spine flexion, compound postures, etc.) associated with low back injury (Enoka *et al.,* 2008). As such the intersection between biological sex, muscle fatigue, and injury prevalence warrants further investigation.

### 1.3 Muscle Fatigue and Injury Risk

The main predictors of low back injury within the sport of rowing a previous history of LBP and training volume, particularly sessions exceeding 30 minutes on ergometers (Thornton *et al.,* 2017). Furthermore, fatigue in the trunk extensors can lead to impaired awareness of excessive spine flexion which is associated with an increased risk of injury (Thornton *et al.*, 2017), and can impair the neuromuscular stabilising control of dynamic torso movement (Granata *et al.*, 2008). As the musculature of the spine fatigues antagonistic co-contraction will begin to occur. This may restore mechanical stability to the spine; however, it can lead to an increased spinal load which can lead to an increased risk of overload injury during a repetitive movement task (Granata *et al.*, 2004). As mentioned in Section 1.1, rowing athletes commonly injure their shoulders, knees, and wrist as well (Pike, 2000), this could be due to the association between fatigue and decreased eccentric strength leading to overload which could cause tearing in the musculotendinous unit (Garrett, 1990), or damage to other passive mechanical structures located within the shoulder region.

### 1.4 Sex Differences in Injury Prevalence

In general, previous work has determined that low back injuries are disproportionately higher than other body regions in rowing athletes (Finlay *et al.*, 2020, Newlands *et al.*, 2015, Ng *et al.*, 2014, Trompeter *et al.*, 2017). Despite this, the relative distribution of low back injuries between rowers and non-rowers and between male and female athletes is not clear. Some previous researcher has noted an added risk of low back injury in rowing athletes (Trompeter *et al.*, 2017) relative to a general population, whereas others have suggested the risk to be comparable to the general population (Maselli *et al.*, 2015). Further, previous rowing injury studies have found varying results in the analyses of any specific sex effects related to low back injury prevalence. Some studies have noted low back injuries to be more common among males than females (Ng *et al.*, 2014); however, some studies have also noted no difference between males and females in terms of injury prevalence (Finlay *et al.*,2020). All current research that assesses injury prevalence and history among rowing athletes, to our knowledge, fails to account for muscle fatigue. However, the phenomenon of muscle fatigue may play a role in the development of chronic overuse injuries in males and females, especially females are generally less fatigable than males for many isometric and dynamic tasks (Hunter, S. K., 2014). This phenomenon may play into the results of previous research studies which have found males to have a higher prevalence of low back injury than their female counterparts (Ng *et al.*, 2014).

## 1.5 Summary of Previous Work

Previously, retrospective studies involving the injury history of rowing athletes have been consistent with their findings with some exceptions (Finlay *et al.,* 2020, Newlands *et al.,* 2015, Ng *et al.*, 2014, Trompeter *et al.,* 2017). Collectively, studies of rowing athletes have found injuries to the lower back to be the most common (Pike, 2000, Trompeter *et al.*, 2017). Previous work has also identified several risk factors that lead to an increased risk of low back injury these being; (1) time of year (Finlay *et al.*, 2020), (2) increased training volume (Finlay *et al.*, 2020, Foss *et al.*, 2012, Newlands *et al.*, 2015, Ng *et al.*, 2014), (3) training environment (Finlay *et al.*, 2020, Ng *et al.*, 2014), (4) sweep rowing (Ng *et al.*, 2014, Maselli *et al.*, 2015), (5) sex (Ng *et al.*, 2014, Maselli *et al.*, 2015), (6) previous history of injury (Foss *et al.*, 2012). With these risk factors there is some disagreement regarding the association of each risk factor and the development of low back injury. Previous work has identified training environment as a risk factor; however, results differ on the environment. In some cases, higher low back injury risk has been associated with water-based training (Finlay *et al.*, 2020), whereas in another cases low back injury risk has been linked with ergometer use (Ng *et al.*, 2014). Previous work has also had some disagreement as the overall prevalence of low back injury among the rowing population relative to a control population, with one study stating that rowing athletes have a higher lifetime and point prevalence than the controls (Trompeter *et al.*, 2017), whereas another study stated that rowing athletes are not more predisposed to low back injuries than the general population (Maselli *et al.*, 2015). One reason potentially explaining this discrepancy may be the difference in study design. Specifically, the study by Trompeter (2017) was a systematic review of rowing studies as well as relevant studies from other sports including the Maselli study, in contrast the Maselli (2015) study focused on a group of elite rowers from an indoor rowing championship with no apparent focus on training frequency or type.

Previous studies have also been inconclusive in the assessment of injury prevalence stratified according to biological sex. Specifically, some studies have not found any sex differences (Finlay *et al.*, 2020), whereas others have reported that males are more susceptible to low back injury (Ng *et al.*, 2014). No previous study has assessed the effects of fatigue on injury prevalence across biological sexes within the sport of rowing. Similarly, minimal research has been done on injuries to regions other than the back within the sport of rowing. Previous work assessing injury prevalence has noted that following the back, the shoulder, knee, and wrist are the most injured body regions (Pike, 2000).

## 1.6 Research Objectives

Given the summary or previous work noted above, it is clear that there are many potentially relevant risk factors linked to the development of rowing-related musculoskeletal injuries. Specifically, it is currently unknown if fatigue plays a larger role in the development of musculoskeletal injuries in varying body regions. Further it is unknown if the development of muscle fatigue affects males vs. females differently. Given this, the purpose of this study is threefold:

(1) To assess the lifetime prevalence of musculoskeletal injures, based on different anatomical regions, including the perceptions of muscular fatigue as a contributing factor to these injuries in recreational rowing athletes.

(2) To assess the relative effect of muscle fatigue on musculoskeletal injury in male and female athletes, respectively.

(3) To assess the effect of sex on LBP prevalence and severity in recreational rowing athletes.

Based on these aims, we hypothesized that:

(1) Lower back injuries will be the most common in rowing athletes, and that muscular fatigue will play the largest role in injuries affecting axial structures.
(2) That muscle fatigue will have a larger association with injury in males vs. females.
(3) The prevalence and severity of LBP will be higher in male athletes relative to female ones.

To assess these aims a retrospective survey-based study was designed and implemented allowing self-reported rowing athletes to describe their musculoskeletal injury history, across various body regions, including their perceptions of fatigue at the time of injury. In addition to this, the effects, and descriptors of LBP were obtained across biological sexes and compared with each participants self reported, most severe injury. The results of this survey were intended to improve the understanding of sex and anatomical location effects of rowing related musculoskeletal injuries, including the potential association of muscular fatigue in the development of such injuries. The results of this work will guide the development of training and racing regimes, with optimal work to rest ratios to avoid the development of any potential chronic, overuse injuries.

# CHAPTER II: LITERATURE REVIEW

## 2.1 Rowing Technique

The rowing stroke can be divided into two distinct phases: the drive phase and the recovery phase. These two phases are based around two different positions: the catch and the finish positions. The catch (Figure 1) is the most anterior position of the trunk and requires high flexion of the knee, hip, and lumbar intervertebral joints. The finish (Figure 2) is the most posterior position of the trunk and requires extension of the knee, hip, and lumbar intervertebral joints. In previous literature the catch position has been defined in three different ways: the most anterior position of a reflective kinematic marker that was placed on the athlete's wrist (Pollock *et al*, 2009), the point in time where tensile force is first applied to the handle on the ergometer (McGregor *et al*, 2004), and the instance of peak lumbar flexion (Trompeter et al., 2019). The finish was defined as a similar term as either the most posterior position of a reflective kinematic marker located on the athlete's wrist (Pollock *et al*, 2009), the point where the tensile force on the rowing handle reaches a minimum (McGregor *et al*, 2004), or the instance of peak lumbar extension (Trompeter et al., 2019). To put these positions and phases together, the drive phase is from catch to finish (where a driving force would be applied to an oar propel the boat forward), and the recovery phase is from finish to catch (where the participant is not applying force a driving force to an oar and is actively flexing their joints to get ready for the next stroke).

There are two different styles of rowing each requiring different interactions between the athlete and the oars used to propel the boat forwards. *Sculling* is a bilateral form of rowing where the athlete operates an oar on both sides of the boat and performs a more controlled motion comprised of solely flexion and extension. *Sweep* rowing is a unilateral form of rowing where the athlete uses a single oar on one side of the boat and performs primarily flexion and extension in addition to lateral flexion and spinal rotation (Parkin *et al.*, 2001). The typical rowing race is 2000 meters long and over this distance the athlete will perform 230-260 strokes (Pollock *et al.*, 2009). With each stroke a large amount of stress is applied on the body at the L4/L5 joint; approximately 2694 N of compressive force and 660 N of shear force (Morris *et al.*, 2000). With such forces it has been determined that injuries in the lumbar spine are the most prevalent reported injury in rowing athletes (Budgett *et al.*, 1989). This may be due to an increase in the angular displacement of L3 in the frontal plane increasing with fatigue (Wilson *et al.*, 2013). Despite this, the study conducted by Wilson (2013) did not take into account the type of rowing (i.e., sweep vs. scull) performed as the results found could potentially be a result of any improved unilateral muscular strength or endurance of the lumbar spine extensors in sweep-trained rowing athletes (Parkin *et al.*, 2001). To the authors knowledge, individual joint forces have yet to be investigated outside of the Morris (2000) which noted that total compressive intervertebral force generated was 8.99 N/kg with a SD of 1.12N/kg.


**Figure 1**. Athlete in catch position


**Figure 2.** Athlete in finish position

## 2.2 Musculoskeletal Demands of Rowing

Each phase of the rowing stroke has very different musculoskeletal demands. The drive phase is where the power is developed that propels the boat forward by using athlete's legs, back, and lastly arms (typically in that order). The recovery phase serves as a rest period as the athlete returns to the catch position in order for the next drive phase to begin. The drive phase can be broken down to three distinct movements; (1) knee extension; (2) hip and spine extension; (3) simultaneous shoulder extension and elbow flexion. The lower limbs provide a large portion of the power delivered to the oars, such that foot reaction forces at the feet are often used to assess an individual's leg power and athletic performance (Buckridge *et al.*, 2014). Following knee extension, the hips and spine will extend to continue the stroke to a greater length. Finally, as the athlete nears the finish position there is some agonist-antagonist coactivation of the trunk musculature, which is hypothesized to act as a breaking mechanism (Pollock *et al.*, 2009). The last body segment to be involved in the drive phase is the arms in which the shoulders must be extended, and the elbows must be flexed to reach the finish position. Once the finish is reached athletes will commence the recovery phase in which actions are taken in the exact opposite order of the drive phase. With the oar out of the water this phase imposes less resistance and therefore requires less musculoskeletal effort.

## 2.3 Rowing Motor Control and Function

### *2.3.1 Lower Body Kinematics*

The lower limbs play an important role in force development during the drive phase of the rowing stroke (Buckeridge *et al.*, 2012). The ankle, knee, and hip go through a large range of motion (ROM) to facilitate each stroke. All three joints discussed travel in primarily the sagittal plane (flexion/extension or plantarflexion/dorsiflexion) during the sport of rowing. Previous studies have used similar methodologies requiring the use of a 3D motion capture system (e.g., Flock of Birds, Ascension Technology, Burlington, VT) with markers or sensors generally placed on participants lumbar-sacral joint (L5/S1), and the anterior tibial spine (midpoint) on both legs. Using these sensors, the following landmarks were digitized bilaterally; head of the fifth metatarsal, lateral and medial malleoli, lateral and medial femoral epicondyles, anterior superior iliac spines, and posterior superior iliac spines, the hip joint center was also digitized (Buckeridge *et al.,* 2012). Using these methods it was determined that the knee ROM for elite rowing athletes on a rowing ergometer was 134.5 ± 14.1° (right)/ 135.3 ± 14.9° (left) by using the angle between a line joining the hip joint center and the proximal origin of the shank, and the hip ROM for elite rowing athletes was 97.2 ± 10.6° (right)/ 92.7 ± 9.0° (left) hip joint angles were calculated using the joint coordinate system where the hip joint coordinate frame was derived from the pelvis and thigh coordinate frames, each angle was defined by the difference between end-range postures (Buckeridge *et al.,* 2012). Another study assessed ankle ROM of elite rowing athletes by using a dual axis electrogoniometer positioned horizontally directly below the participants lateral malleolus of the right ankle, it was determined that participants had a mean ankle ROM of 2.9 ± 7.1° on a rowing ergometer, the ROM observed was determined as the difference between flexion and extension endpoints (Soper *et al.*, 2004).

### *2.3.2 Spine Kinematics*

When transitioning from the finish position to the catch position, lumbar flexion will occur during every rowing stroke. This range of lumbar flexion-extension motion does vary depending on stroke rate; at a rate of 18 strokes per minute an athlete’s range of motion is 18.9° ± 6.1°, whereas at higher stroke rates (i.e., 30 strokes per minute) the lumbar flexion-extension ROM increases to 23.6° ± 5.3° (Wilson *et al.*, 2013). Many different approaches have been taken to estimate lumbar flexion ROM throughout the scientific literature, including research studies assessing the effects of chronic LBP on spine flexion ROM (Zoubi *et al.*, 2013) during standardized flexion ROM tests or while capturing ROM during sport-specific movements. Conventionally, maximum flexion ROM can be determined using kinematic markers (i.e., rigid bodies) placed on the athlete's T12 and sacrum (i.e., S1/S2) and measuring the angular displacement that occurred between the two local coordinate systems (Laird *et al.*, 2018). With this equipment in place, the athlete can be instructed to flex their spine through their full active flexion ROM or to complete a relevant sport-specific movement. These measures allow researchers to record the amount of the angular displacement that occurred between the T12 vertebra (i.e., thorax) and the pelvis, facilitating an estimation of gross lumbar angular motion. In rowing-specific movements ROM has been recorded previously using an electrogoniometer (Wilson *et al.*, 2013). In addition, previous research has also utilized optical motion capture approach to estimate lumbar flexion ROM using surface mounted markers and custom kinematics models for post-processing (Pollock et al., 2009; Willwacher et al., 2020). For example, in a study by Pollock and colleagues (2009) lumbar joint angles were estimated in the sagittal plane by recording the positions of reflective kinematic markers placed on the skin superficial to specific bony landmarks (i.e., spinous process of C7, T4, T7, T10, L1, L3, S1, the right scapula, bilaterally at the lateral midline of iliac crest, greater trochanter, knee, ankle, wrist, elbow, and acromion process) allowing for researchers to estimate local, multi-segment spine flexion-extension kinematics.

Although rowing movements occur predominantly within the sagittal plane, lateral flexion is an important action of the lumbar spine as it is crucial to facilitate a sweep rowing motion (i.e., rowing on either the port or starboard side of the boat). There has been minimal research done assessing lumbar lateral flexion kinematics during rowing. However, there has been a study to test the validity and reliability of a lateral flexion range of motion task. For this task, the participant would stand with feet shoulder width apart and laterally flex their spine as much as possible while researchers measured the relative angular displacement of their T12 vertebrae relative to their S1. As with the estimation of lumbar flexion kinematics, this provides an estimation of gross lumbar lateral flexion ROM; a section of the spinal column where most lateral flexion occurs (Hecimovich *et al.,* 2016). In rowing frontal plane motion has previously been studied using a spectrotilt inclinometer positioned at L3 to examine frontal plane angular inclination of the trunk, this study found that lateral flexion ROM is dependant of stroke rate as at a stroke rate of 18 strokes per minute lateral flexion ROM way 4.7° whereas at 30 strokes per minute ROM was 8.7° (Wilson *et al.*, 2012), these methods could be modified to utilize reflective kinematic markers or rigid bodies (e.g. Beaudette et al., 2014, Zwambag et al., 2018).

#### *2.3.3 Upper Body Kinematics*

The upper limbs allow for the rowing athlete to reach the finish position and complete their stroke. Research on the upper limbs is very limited and typically neglects the elbow and wrist. Despite this, the ROM of the shoulder joint has been previously researched, shoulder ROM was determined by using inertial measurement units (IMU) placed on participants thoracic spine, scapula, and upper arms to track angular orientation body segments in absolute space (Yumeng *et al.,* 2020). Using this methodology, it was determined that the flexion-extension ROM of the shoulder was 96.3 ± 13.4° for males and 109.8 ± 13.4° for females, it was noted that ROM of the shoulder increased with stroke rate (Yumeng *et al.*, 2020).

## 2.4 Spine Stability Demands

Spine stability is achieved through the combination of passive elements (i.e., ligaments, intervertebral discs) and the active recruitment of the trunk muscles (Appendix A) traversing the lumbar spine (Bergmark, 1989). In particular, muscular agonist-antagonist coactivation allows for greater stability and thus a spinal column which is more robust to external perturbations (Reeves *et al.*, 2006), this is seen in rowing literature as there is a period of coactivation in the drive phase of the rowing stroke (Pollock *et al.,* 2009). Furthermore, coactivation has been shown to increase in tasks introducing asymmetrical or unstable loads (Lavender *et al.,* 1998; Beaudette et al., 2014). Given these findings it would be expected for there to be more coactivation of trunk flexors and extensors during sweep rowing, or when the motor control system is compromised (such as during fatigue). As noted previously, rowing-movements are predominantly occurring within the sagittal plane; however, in sweep-style rowing the athlete must generate lateral flexion of the lumbar spine to maneuver an oar on a single side of the boat. This motor pattern in turn could strengthen the muscles unilaterally and thus affect an athlete's optimal mechanical stability, this has been demonstrated in joints like the knee (Zhou *et al.*, 2002). In general, spine instability events must be reduced to avoid structural/mechanical injury, therefore the active, passive, and neuromuscular systems must work together to ensure spine stability is maintained for any given posture, as well as during any dynamic movement (Panjabi, 1992). Previous work has also assessed muscle activation patterns in the lower extremities which determined a similar period of coactivation (Figure 4), specially among the muscles in the upper leg (Janshen *et al.,* 2009) of note coactivation of these muscles was also seen during the recovery phase.

## 2.5 Neuromuscular Control

### *2.5.1 Neuromuscular Control: Spine*

The neuromuscular control of rowing athletes has been previously investigated with a variety of different purposes; to determine if there are asymmetric muscle activation patterns (Readi *et al.,* 2015), and to determine if there is a period of coactivation between trunk flexors and extensors (Pollock *et al.,* 2009). Exploring bilateral muscular asymmetries (e.g., of the trunk or lower extremity flexors/extensors) in rowing athletes has been a common topic among rowing literature with varying success and methods. A previous study examining limb asymmetries used force transducers installed in the foot stretchers of a rowing ergometer and assessed the forces applied to each, they found that participants continuously exerted an asymmetric force (left/right) on the foot stretchers (Fohanno *et al.,* 2015). Another study examining asymmetries of the paraspinal musculature in rowing athletes used a series of high-density EMG arrays positioned between T10 and L5, this study ultimately found that there was a difference in muscle activation between the left and right side; however, it was not statistically different (Readi *et al.,* 2015). Furthermore, the same study noted that activation of the low back muscles was six times greater during the drive phase than the recovery phase; given previous reports, this result is unsurprising (Pollock et al., 2009; Readi *et al.,* 2015). The other aspect of neuromuscular control that has been explored in rowing athletes involves coactivation of both trunk flexor and extensor groups (Figure 3). Previous reports have noted a period of coactivation which starts at 28.2% ± 2.2% post-catch to 36.8% ± 3.2% of the stroke (Pollock *et al.,* 2009). This period of coactivation likely serves as a braking mechanism to slow the rower as they near the finish position, Pollock hypothesized that it also assists with mechanical stability of the spinal column. It remains unknown if there is a similar coactivation pattern during the recovery phase of the stroke;

including if this co-activation period is present in novice athletes and/or modulated by motor control system demands such as muscle fatigue.

### *2.5.2 Neuromuscular Control Lower Extremity*

Only one study has addressed neuromuscular control of the lower extremities during rowing in sufficient detail. This study found a similar coactivation to that of the trunk musculature as the biceps femoris was active during almost the entire rowing stroke (Janshen *et al.,* 2009). The only other agonist muscle assessed in the study was the tibialis anterior, which was only active at the start of the recovery phase. The remaining examined muscle groups were the gastrocnemius, rectus femoris, vastus lateralis, and vastus medialis, all these muscles (Appendix A) were active when expected during the drive phase as they were all active during the first half of the drive phase (Janshen *et al.,* 2009) (Figure 4).

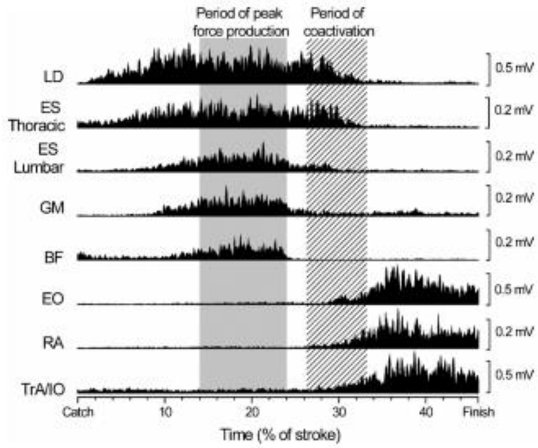


**Figure 3.** Muscular co-activation period in a rowing stroke, displays EMG activity of latissimus dorsi (LD), thoracic and lumbar erector spinae (ES), gluteus medius (GM), biceps femoris (BF), external oblique (EO), rectus abdominus (RA), and transverse abdominus/internal oblique (TrA/IO). Extracted from: 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), 628–636.

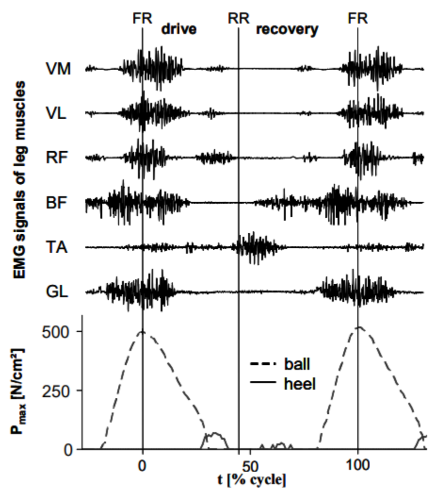


**Figure 4.** EMG activity of the vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius (GL) during a rowing stroke. Extracted from: Janshen, Lars, et al. Muscular Coordination of the Lower Extremities of Oarsmen During Ergometer Rowing. *Journal of Applied Biomechanics*, vol. 25, no. 2, 2009, pp. 156–64.

## 2.6 A Comprehensive Review of Muscle Fatigue

### *2.6.1 Neuromuscular Factors Affecting Muscle Contraction & Fatigue*

#### *2.6.1.1 Neural Contributions*

Neuromuscular fatigue can be defined as any exercise induced decrease in a muscle's ability to develop force or power (Boyas *et al.*, 2011). Typically, a muscle can increase contractile force using two neural mechanisms. These mechanisms include the (1) recruitment of new motor neuron pools (i.e., spatial summation), and (2) increased firing rate of motor neuron pools which have already been recruited (i.e., temporal summation). During submaximal contractions, typically slow-twitch, low-force, fatigue resistant (i.e., slow oxidative) muscle fibres are recruited first and subsequently rate coded to increase force production. Given *Henneman's Size Principle*, as force demands increase, fast-twitch, high-force, fatigable (i.e., fast glycolytic) muscle fibres are recruited, and subsequently rate coded to continue adjusting for increasing force demands. As noted above, in a fatigued state, the force production capacity of each individual muscle fibre is reduced. Given this, submaximal contractions (at a matched force), in a fatigued state have the capacity to elicit a higher demand on the neuromuscular system resulting in a disproportionately high amount of motor unit recruitment and rate coding to offset any external force/torque demands.

Despite these changes noted above some neuromuscular adaptation mechanisms have been proposed which can limit muscle activity before it can pose a potential risk to the body through any downstream effects related to muscle fatigue. One specific hypothesis is that of *muscle wisdom* which refers to the decrease in motor unit discharge rate and a slowing of the muscle contraction speed during fatigue (Garland *et al.*, 2002). Such changes constitute a defense mechanism for limiting fatigue by decreasing the drop in membrane excitation and leading to a decreased $Ca^{2+}$ release (Boyas *et al.,* 2011). Furthermore, it has been suggested that a fatiguing muscle can limit central excitation by using peripheral afferents in order to provide feedback on the decrease in force by the active myofibrils (Boyas *et al.,* 2011). With the *muscle wisdom* hypothesis, it is plausible that it may be more appropriate when applied to scenarios involving maximal muscle contractions and less applicable to sub-maximal efforts as it is task and muscle dependant (Garland *et al.,* 2002). More recently a *central governor model* has also been discussed in which the brain regulates muscle performance by controlling motor unit recruitment (Noakes *et al.,* 2001). This model would be dependant on the mechanoreceptors and sensory afferents that provide feedback to the central nervous system, with the end goal of limiting muscular stress to reduce risk of injury (Noakes *et al.,* 2001). This model has been widely criticized due to its limitations and the results being contraindicatory. Furthermore, it is noted that this model can't be applied to all tasks as there are more factors than just motor unit recruitment that influence muscle performance (Boyas *et al.,* 2011).

#### *2.6.1.2 Metabolic Contributions*

In general, the contraction-relaxation process can be described in three major steps. First the splitting of ATP occurs on the myosin head by myosin ATPase, this provides the needed energy for the power stroke of the cross bridge to occur. Following this, a fresh ATP molecule binds to the myosin head, which allows the head to detach from the actin filament allowing the cycle to be repeated. Lastly, active transport of $Ca^{2+}$ back into the sarcoplasmic reticulum occurs during the relaxation phase, this depends on the energy derived from the breakdown of ATP (Sherwood *et al.,* 2013). With this process there are many potential stages susceptible to change during neuromuscular fatigue (Figure 5). First, a local increase in ADP and inorganic phosphate from ATP breakdown may interfere with crossbridge cycling and possibly block $Ca^{2+}$ release and uptake (Sherwood *et al.,* 2013). Next, an accumulation of lactic acid may inhibit key enzymes in the energy producing pathways and/or excitation-contraction coupling process (Sherwood *et al.,* 2013). Further, the accumulation of extracellular potassium that occurs when the $Na^+$ - $K^+$ pump cannot actively transport $K^+$ back into the muscle cells as rapidly as this ion leaves during the falling phase of repeated action potentials, causes a local reduction in membrane potential (Sherwood *et al.*, 2013). Lastly, depletion of glycogen energy reserves may lead to muscle fatigue in extended exercise (Sherwood *et al.,* 2013).

Some of the changes noted above can be detected using experimental methods such as surface electromyography (sEMG). Specifically, an acquired submaximal sEMG signal can be processed to yield is constitutive frequency spectra, using a Fourier Transform (Willwacher *et al.,* 2020). Generally, the frequency content present in a fatigued muscle is shifted to lower frequency domains (in comparison to an unfatigued muscle) despite contracting to a matched force output. These changes can be explained in part due to the changes in conduction velocity of the muscle sarcolemma which can be affected by intramuscular metabolites, and membrane imbalances in free sodium and potassium ions.

#### *2.6.1.3 Effect of Muscle Fibre Type*

Each muscle fiber is part of a highly organized motor unit which is comprised of a motor neuron which is located in the ventral horn of the spinal cord, its axon, and of course the muscle fibers that are innervated by an electrical stimulus (Abd-Elfattah *et al.,* 2015). With muscle fibres there is several types each vary in fatiguability and force output. These fibre types are, type I, type, IIa, and type IIx/IIb (Abd-Elfattah *et al.,* 2015). Type I fibres are also known as slow-twitch muscle fibers as they contract and relax more slowly relative to type II fibres, type I fibres are innervated by $\alpha_2$ motor units, which are smaller than that of $\alpha_1$ this is important as a smaller motor unit will have a decreased activation threshold. As a result of the type I fibres are activated at lower intensities and contract approximately 10 times slower than type II, use of type I fibres does not lead to fatigue as quickly as type II (Sherwood *et al.*, 2013). Additionally, there are multiple metabolic properties of muscle fibre types, these being oxidative and glycolytic, with this, all muscle fibre types can produce energy both anaerobically and aerobically; however, typically one pathway will be dominant over the other. Type I fibres are referred to as slow-oxidative due to the fact that they derive their energy primarily through aerobic pathways; whereas type II are either fast oxidative glycolytic, type IIa (aerobic and anaerobic) or fast glycolytic, type IIb/IIx (primarily anaerobic) depending on the enzymes used in their metabolic process (Sherwood *et al.*, 2013). In general, Type I muscle fibers are recruited first (Section 2.6.1.1) and are most robust to the effects of neuromuscular fatigue, whereas Type II muscle fibers are recruited last and are the most affected by neuromuscular fatigue.

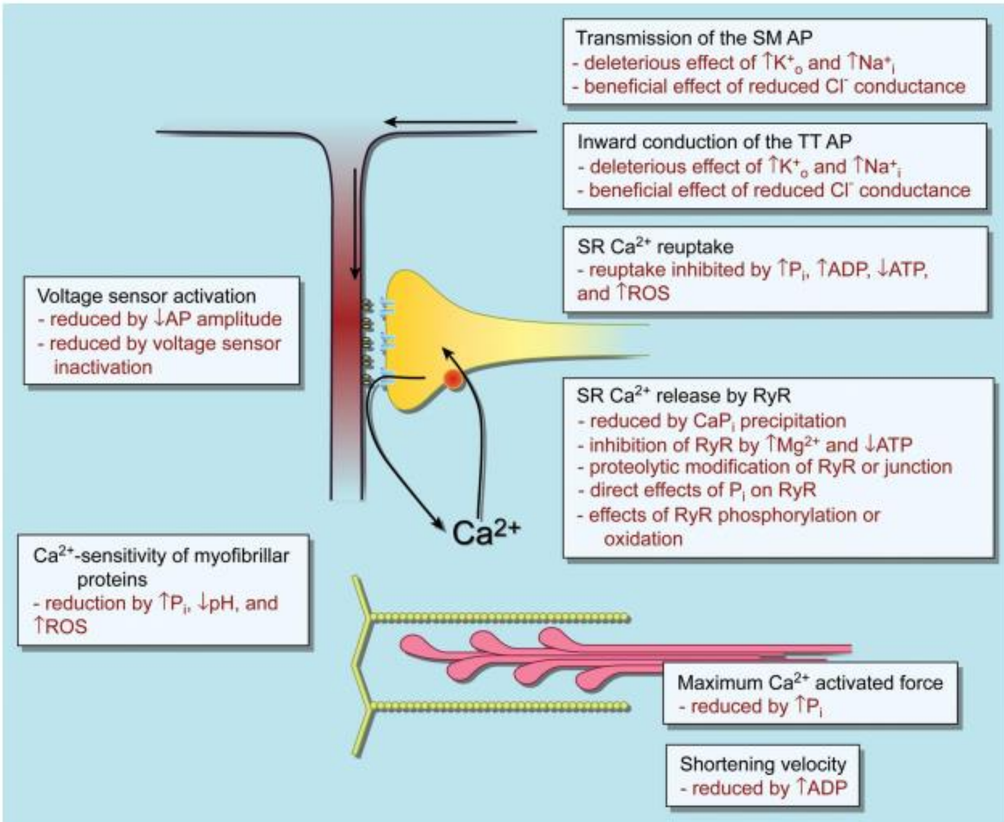


**Figure 5.** Schematic diagram illustrating the major mechanisms that contribute to muscle fatigue. Heading in each box identifies subcellular function, and the subsequent list indicates cellular changes occurring during fatigue that influence the subcellular fuction. Extracted from: Allen, D. G., et al. Skeletal Muscle Fatigue: Cellular Mechanisms." *Physiological Reviews*, vol. 88, no. 1, American Physiological Society, 2008, pp. 287–332.

### *2.6.2 Gross Changes in Neuromuscular Control and Performance*

#### *2.6.2.1 Maximal Force Output*

Fatigue decreases the amount of force a muscle can generate. Previous work has corroborated this using a variety of different methods. Some examples have been summarized below. First, a study by Babault *et al.*, in 2006 found that there was a decrease in MVC torque after three sets of maximal shortening contractions and three matched maximal isometric contractions with the knee extensor muscle group (Figure 6A). The same study found that there was a corresponding decrease in voluntary activation during the MVC (Figure 6B) (Babault *et al.*, 2006). Additionally in a study by Hunter *et al.*, 2005, participants were asked to perform an MVC every 3.5 seconds, 30 times with this study it was found that young adults experienced a 27.1% decrease in MVC force (Figure 7).

#### *2.6.2.2 Rate of Force Development*

In addition to the examination of peak muscle force (torque) another indicator of muscle fatigue is the rate of force development (RFD). In general, the RFD is an emerging outcome for the assessment of neuromuscular function, and represents a valid alternative, or complimentary metric to the evaluation of pure maximal strength. Through a recent review, reductions in RFD following fatiguing contractions (-19-25%) were comparable to decrements in peak muscle force (torque) (-19%) (D'Emanuel *et al.*, 2021). This suggests that RFD may be an equally, or more sensitive metric to quantify neuromuscular fatigue when compared to maximal force or torque.

### *2.6.3 Task Dependency in the Development of Muscle Fatigue*

The principle of task dependency of muscle fatigue tells us that participants will fatigue differently depending on the task performed (Asmussen, 1979), whether it's a simple isometric contraction or a more dynamic task (Hunter S. K., 2014). Further, given the varying muscle architectures, muscle fibre types, perfusion rates, etc. many different muscles have the capacity to fatigue at different rates and magnitudes, even across a single task (Enoka, 1995). Given this, the best approach is to understand localized fatigue effects, across different anatomical regions (i.e., muscle groups) for a given task of interest (i.e., a rowing stroke).

### *2.6.4 Demographic Differences in the Manifestations of Muscle Fatigue*

In addition to the task dependency effects previously noted, there are some basic demographic factors that have an effect on an individual's fatigability, including (1) age, and (2) sex. Previous work by Baudry *et al.*, (2007) determined that older people fatigue quicker when measuring the decline in torque of men and women in both a young (mean ± SD; 30.5 ± 2.5 years) and old (77.2 ± 1.4 years) age groups when performing maximal dorsiflexion and plantarflexion exercises. In this study participants performed 5 sets of a 30 maximal voluntary contractions, with each contraction being every 3.5 seconds. Specifically, each contraction required the participant to move their ankle 30 degrees at a rate of 50 degrees per second as controlled by a motor. In this study the young adults were stronger than the older group as indicated by the young group having a higher peak torque during a maximal isometric contraction (38.3 ± 3.1 Nm), compared to the old group (28.6 ± 1.3 Nm). Throughout the study peak torque for the young group decreased by 27.1% compared to the old group who experienced a 42.1% decrease in final peak torque (Baudry *et al.*, 2005) (Figure 7).

In addition to these age-related effects, many studies have also uncovered sex-effects related to neuromuscular fatigue. In general, most studies have found that females are less fatigable than males for many isometric tasks and some dynamic tasks when completing matched intensity isometric muscle contractions in the upper and lower extremities (Hunter, S. K., 2014). Further, several studies have demonstrated that after long duration cycling and running females have preserved lower extremity strength relative to males (Glace *et al.*, 2013, Glace *et al.*, 1998, Temesi *et al.*, 2015). Recently many of the mechanisms behind these apparent disparities in fatiguability have been summarized (Hunter S. K., 2016). Some of the potential mechanisms behind any sex-related differences in muscle fatiguability may be related to differences in muscle fibre type, skeletal muscle metabolism, muscle perfusion, and supraspinal excitability (Enoka *et al.*, 2008). It is currently unknown; however, if muscle fatiguability may play any role in any apparent sex-related differences related to musculoskeletal injury prevalence. It may be possible that changes in the fatiguability of males and female rowers may directly affect the development of biomechanical risk factors (i.e., high thoracolumbar spine flexion, compound postures, etc.) associated with low back injury (Enoka *et al.*, 2008).

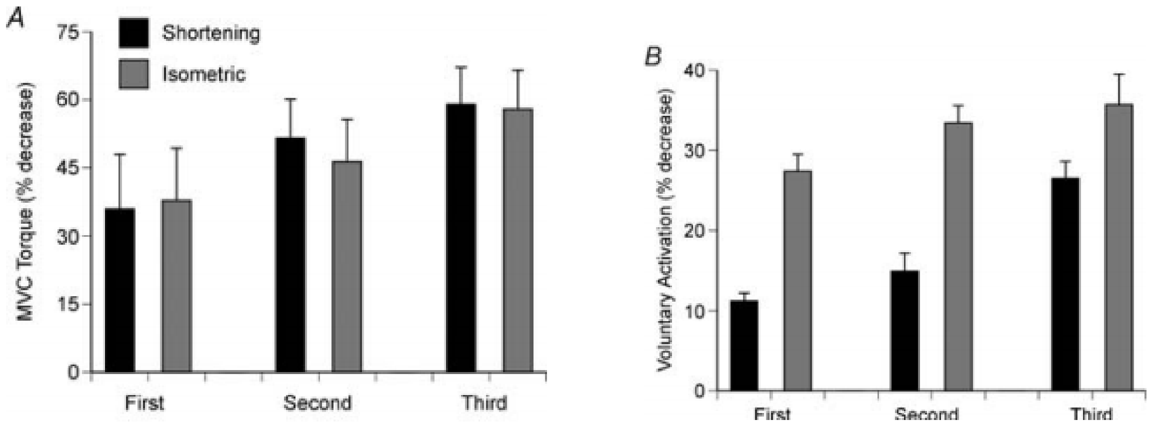


**Figure 6.** A. MVC torque decrease after 3 sets of maximal shortening contractions. B. Corresponding decreases in voluntary activation. Extracted from: Babault, Nicolas, et al. Neuromuscular Fatigue Development During Maximal Concentric and Isometric Knee Extensions. *Journal of Applied Physiology*, vol. 100, no. 3, American Physiological Society, 2006, pp. 780–85.

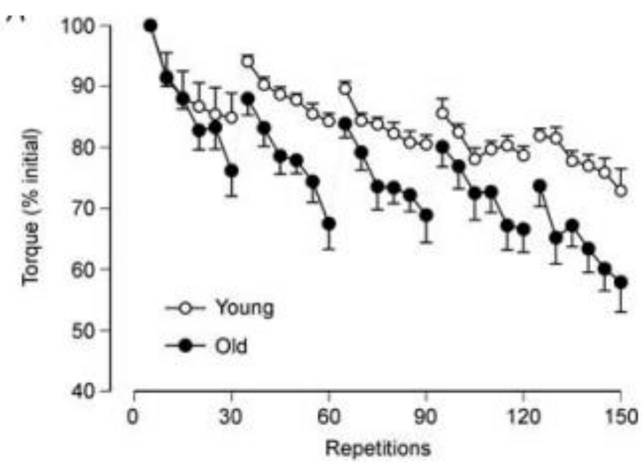


**Figure 7.** Fatiguability of dorsiflexors compared between young and old participant groups. Extracted from: Baudry, S., et al. Age-Related Changes in Fatigability During Concentric and Eccentric Contractions. *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 8, no. sup1, Taylor & Francis Group, 2005, pp. 21–22.

## 2.7 Effect of Fatigue on Rowing Kinematics and Neuromuscular Control

### *2.7.1 Range of motion and Fatigue*

A standard race in rowing is 2000 meters long and takes approximately six-minutes at an international level (Mahler *et al.,* 1984). With the race taking that long fatigue can become an issue resulting in lowered muscle strength and encumbered coordination patterns (Turpin *et al.,* 2011). Previous studies that examined a participant's ROM in flexion and extension during 2000-meter rowing trials, found that lumbar flexion range of motion (% maximum ROM) increased as the 2000-meter trial progressed (Caldwell *et al.,* 2003) (Figure 8). The findings of the study suggest that this change could be due to the increased muscle activation resulting in the muscle "warming up" (Figure 9). The methods that could be used to measure range of motion before and after the task would be the same as mentioned in the previous two sections (Laird *et al.,* 2018; Hecimovich *et al.,* 2016). More recently a study using three-dimensional kinematics analyzed how the sagittal curvature of the spine changes throughout a 2000-meter rowing trial involving cross-fit athletes (Willwacher *et al.,* 2020). They found that the curvature of the spine increased significantly at vertebrae T6 through T11, with the single largest change at T8/T9, these changes increased as the participants became more fatigued (Figure 10). Interestingly, Willwacher and colleagues (2020) also noted some participant-specific variability in the response to the fatiguing rowing bout (Figure 11), potentially linked to the baseline kinematics of each rowing athlete. There has yet to be a study to assess the effect of fatigue on ROM of the upper or lower extremities within the sport of rowing. Previous work outside of a sport context has found that as the upper limb fatigues ROM of the limb decreased and participants began to compensate the repetitive movement by using their trunk (Bouffard *et al.,* 2018).

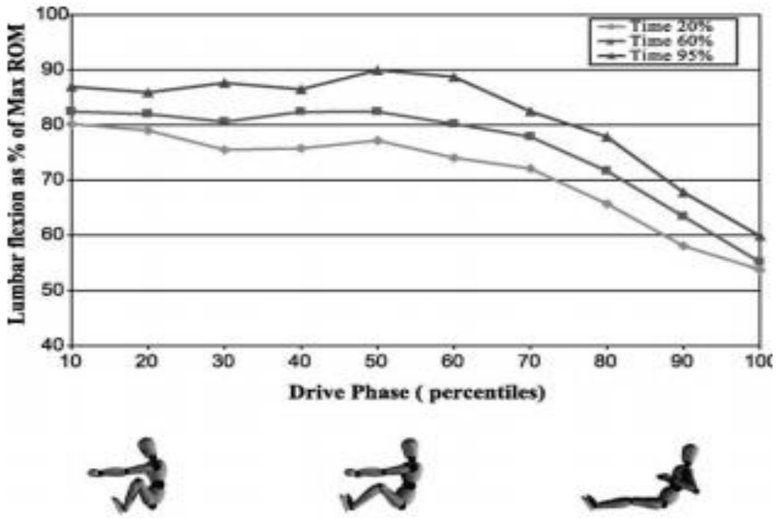


**Figure 8**. Range of motion of the lumbar spine over the course of a rowing trial. Extracted from: Caldwell, J. S., McNair, P. J., & Williams, M. (2003). The effects of repetitive motion on lumbar flexion and erector spinae muscle activity in rowers. *Clinical Biomechanics*, 18(8), 704–711.

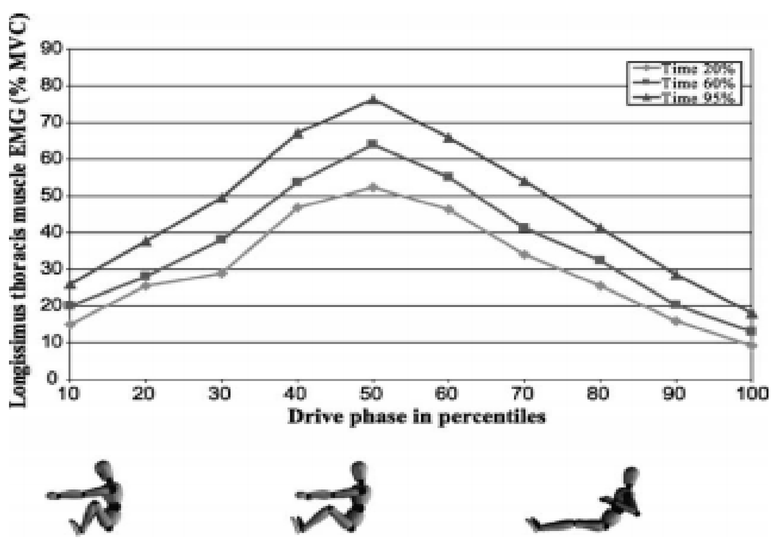


**Figure 9**. EMG activity over the course of a rowing trial in longissimus thoracis. Extracted from: Caldwell, J. S., McNair, P. J., & Williams, M. (2003). The effects of repetitive motion on lumbar flexion and erector spinae muscle activity in rowers. *Clinical Biomechanics*, 18(8), 704–711.

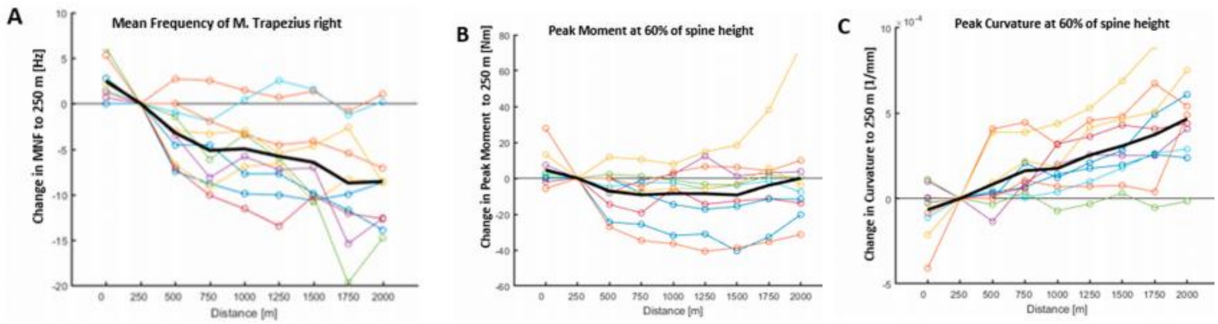


**Figure 10.** EMG and kinematic data throughout the duration of a fatiguing rowing bout. A: MPF of M. trapezius right. B: Peak Moment at 60% spine height. C: Peak Curvature at 60% spine height. Extracted from: Willwacher, Steffen, et al. Dorsal Muscle Fatigue Increases Thoracic Spine Curvature in All-Out Recreational Ergometer Rowing. *European Journal of Sport Science*, vol. 21, no. 2, Routledge, 2021, pp. 176–82.

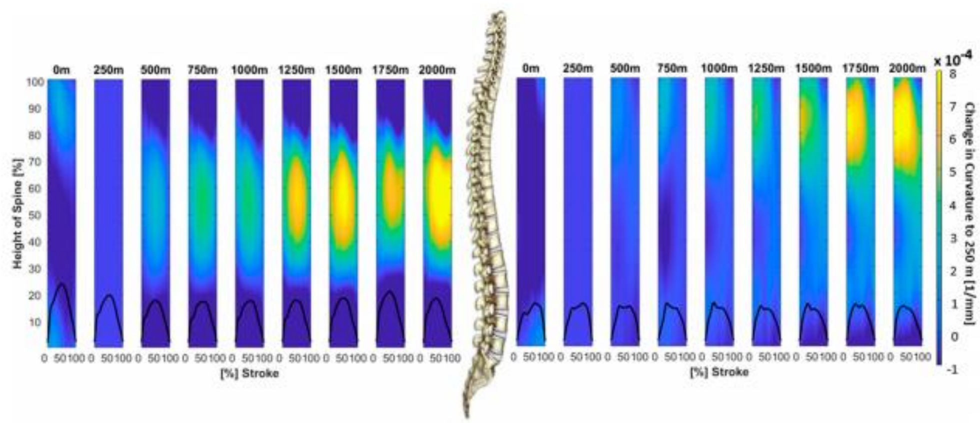


**Figure 11.** Spine curvature of two different people over the course of a 2000 m rowing trial. Extracted from: Willwacher, Steffen, et al. Dorsal Muscle Fatigue Increases Thoracic Spine Curvature in All-Out Recreational Ergometer Rowing. *European Journal of Sport Science*, vol. 21, no. 2, Routledge, 2021, pp. 176–82.

### *2.7.2 Strength based indicators of Fatigue*

As we know from many studies, fatigue influences the force generating capacity of a muscle (Enoka *et al.*, 2008). Studies have also found that younger adults recover faster than older adults and that males recover faster than females (Solianik *et al.*, 2016). Based on these studies, we can assume that over the course of a rowing trial fatigue will occur and we can expect to see a decline in maximum spine flexor/extensor strength (Caldwell *et al.*, 2003). In general, there are two ways of being able to measure muscular fatigue. The first is by having the athlete perform maximal strength assessments pre- and post-testing and the second requires the monitoring of force generation capacity throughout a specific isometric or dynamic task. Using both approaches a decline in force generation capacity would be indicative of fatigue. Previous studies investigating rowing movement have found that muscle strength is reduced following a fatiguing rowing bout (Willwacher et al., 2020). Further when monitoring pulling force throughout a simulated racing movement, a general decrease in force has been observed with fatigue (Willwacher et al., 2020).

### *2.7.3 Electromyographic Indicators of Fatigue*

Several studies have investigated fatigue in rowing using EMG. However, results have varied between these studies. When using an EMG approach to detect muscle fatigue, indicators associated with fatigue include an increased EMG amplitude, and a decreased EMG mean power frequency (MPF) (Caldwell *et al*, 2003). Previously a study be Caldwell and colleagues (2003) found that mean activation magnitude (% Maximum Voluntary Contraction; MVC) of the back extensors increased throughout a rowing trial (Figure 9), this was further expressed as Caldwell found a significant decrease in MPF of the examined muscle groups in post-test isometric testing. In general, the most common objective measure of muscle fatigue in rowing related research studies is the MPF measure (Willwacher *et al.,* 2020, Pollock *et al.,* 2012). The Willwacher et al., (2020) study used a Fast Fourier Transform on the dynamic EMG data during a rowing trial to estimate the MPF; however, the authors made a point that the use of a wavelet-transform might have been more appropriate for the quantification of dynamic EMG waveforms.

### *2.7.4 Subjective Indicators of Fatigue*

There are several subjective scales that have been used in previous research, these are (1) Likert Scales, (2) visual analogue scales, and (3) Borg scales. All three of these subjective scales accomplish the same thing just with varying specificity. These subjective measures of fatigue have been assessed previously based on their reproducibility and their sensitivity to change in a 1999 study by Grant and colleagues. In this study participants completed a series of four submaximal tests in which participants ran at for 2 minutes at 60% of their VO2 max, and 6 minutes at 70% of their VO2 max. Subjective measures of fatigue were recorded at 90 seconds, 330 seconds, and 435 seconds of the trial. In this they found that visual analogue scales and Borg scales to be the most reproducible (Grant *et al.,* 1999).

## 2.8 Rowing related injuries

### *2.8.1 Rowing related injuries: Back*

Previous literature has come to a unanimous conclusion that injuries to the back are the most common in rowing athletes (Pike, 2000, Ng *et al.,* 2014, Trompeter *et al.,* 2017). Furthermore, it has been found that males have a higher point prevalence than females during indoor rowing (Ng *et al.,* 2014). Suspected causes of elevated low back injury risk include; (1) training load (Finlay *et al.,* 2020, Foss *et al.,* 2012, Newlands *et al.,* 2015); (2) rowing typology (Maselli *et al.,* 2015); (3) training environment (Finlay *et al.,* 2012). Multiple studies have made the conclusion that there is a relationship between having an increased training volume and the increased prevalence of LBP (Finlay *et al.,* 2020, Foss *et al.*, 2012, Newlands *et al.,* 2015). Rowing typology is something that has been discussed rarely as only one study has made conclusions about sweep rowing having an increased risk for LBP (Maselli *et al.,* 2015). Lastly, the same study that found the correlation between training volume and LBP also discusses that training on the water puts novice athletes at a greater risk for LBP. Furthermore, when compared to the general population rowing athletes experience a higher lifetime prevalence (63-94%) and point prevalence (25-65%) of LBP (Trompeter *et al.*, 2017). Lastly, there is the potential for rowing athletes to be at an elevated risk for disc related injury due to the high spine flexion needed in the sport and the early morning training periods due to the increased disc hydration as a result of the decreased spinal load stemming from diurnal variation in spinal loading (Belavy *et al.*, 2015).

### *2.8.2 Rowing related injuries: Other*

In contrast to the low back, other body regions have been comparatively under-researched in rowing athletes. After the low back, the next most common injury sites are the knee, shoulder, and followed closely by the wrist (Finlay *et al.,* 2020, Pike, 2000). Causes of injuries to these sites have yet to be identified with in rowing literature; however, previous studies have found that acute shoulder injuries are typically caused by excessive force when the arm is in either a outstretched position, or extension of an abducted arm (Crichton *et al.*, 2012). Chronic shoulder, knee and wrist injuries typically occur when an athlete is subjected to a repetitive movement done either under load, or at high velocities (Oliver *et al.*, 2019, Salati *et al.,* 2016).

## 2.9 Notable Sex-Related Differences

Within the sport of rowing there are four main areas where sex related differences may or may not exist: (1) Musculoskeletal anatomy, (2) rowing technique, (3) muscle fatiguability, and (4) injury prevalence.

### *2.9.1 Musculoskeletal Anatomy*

There are several differences in the musculoskeletal anatomy between males and females. Some of these differences in the skeletal anatomy include a greater interacetabular distance, and a greater hip width normalized to femur length in women compare to men. As well as women having a greater genu recurvatum, more lateral patellar alignment, greater tibial torsion, and more bunions and deformities of the lesser toes. Women also have a larger Q-angle than men which is a function of the structural and alignment characteristics of the pelvis width, patella position, and tibial torsion (Sizer *et al.*, 2008).

### *2.9.2 Rowing Technique*

To the authors knowledge there are no reported differences in rowing technique between male and female rowing athletes. Despite this, given the general changes in musculoskeletal anatomy noted above, it is possible that female athletes interact with their rowing equipment in a different manner than males. Specifically, females having a shorter stroke length due to having shorter limbs and being shorter on average. The possibility of a relatively larger portion of the overall force being derived from the legs. Lastly, females having a catch position with the hips and knees further forward due to differences in flexibility.

### *2.9.3 Muscle Fatigability*

As previously noted (Section 2.6.4), females do not fatigue as quickly as males these sex-related differences in muscle fatiguability may be related to differences in muscle fibre type, skeletal muscle metabolism, muscle perfusion, and supraspinal excitability (Enoka *et al.,* 2008).

### *2.9.4 Injury Prevalence*

Some rowing related studies have reported that males are more susceptible to LBP within the sport of rowing (Ng *et al.*, 2014). Additionally, due to the fact that female's have a larger Q angle this may contribute to them being more prone to knee and foot pathologies although this is rather questionable in nature (Sizer *et al.,* 2008). As stated above, males have a higher point prevalence of LBP being caused during indoor rowing (Ng *et al.,* 2014). This may be due to forcing the body to perform at a level it's no used to try and do better than your peers, or just the male body might not adapt as well as the female body to rowing on an ergometer.

## 2.10 Addressing Current Gaps in Literature

Previous literature examining the prevalence of LBP among rowing athletes has identified LBP as the most common injury or ailment (Finlay *et al.,* 2020, Pike, 2000). Previous studies have also found that among adolescents and indoor rowing athletes that males have a higher prevalence than females (Ng *et al.,* 2014). Furthermore, previous studies often neglect an in depth look at other factors such as age, height, weight, rowing experience, and fatigue at the time of injury that may also influence the prevalence of LBP among the population. Lastly, previous studies have neglected to take fatigue into account when examining the prevalence of acute injury among rowing athletes (Finlay *et al.,* 2020, Newlands *et al.,* 2015, Ng *et al.,* 2014, Pike, 2000). Given the previous work summarized above, it is clear that there are potential sex-related factors affecting the prevalence of LBP in rowing athletes, as well as the relative muscular fatiguability in males vs. females. However, it is currently unknown if fatigue plays a larger role in the MSD of varying body regions in rowing athletes. Further, it is unclear if any effects associated with fatigue differentially affect male vs. female athletes. Given this, there is a clear need for research in the following areas:

(1) An assessment of the effect of sex on the prevalence of LBP among a wide cohort of elite and recreational rowers has yet to be conducted.
(2) A deeper understanding of the other factors that could influence the prevalence of LBP, including neuromuscular fatigue.
(3) Examine the effect of fatigue on acute injury by injury site.

### *2.10.1 Research Aims and Hypotheses*

Given these apparent research gaps, the primary aim of the current work was to assess the lifetime prevalence of musculoskeletal injures, based on different anatomical regions, including the perceptions of muscular fatigue as a contributing factor to these injuries in recreational rowing athletes. Secondary aims of the current work included the assessment of sex-specific effects in self-reported rowing-related injuries, as well as assessing the effect of sex on LBP prevalence. Given these aims it was hypothesized that lower back injuries would be the most common musculoskeletal injury in the athletes sampled, and that muscular fatigue would have a disproportionate effect for injuries affecting axial anatomical structures. Further, it was hypothesized that muscle fatigue would have a larger association with injury in male vs female athletes, given the general fatigue resistance of female cohorts (Enoka *et al.*, 2008). Finally, it was hypothesized that the prevalence and severity of LBP would be higher in male athletes relative to female athletes.

# CHAPTER III: METHODOLOGY

## 3.1 Participants

The participants included in this study included those who were between the ages of 17 and 65, who self identified as a rowing athlete. Participants fulfilling this inclusion criteria were recruited from post secondary institutions and community rowing clubs from across Canada. All participants were recruited via social media, word of mouth, or directly via email to coaches of rowing clubs across Canada. Exclusion criteria included: (1) participants with ages <17 or >65 years; (2) and participants who did not self-identify as at least a recreational rower (i.e., participants must have been an occasional rowing athlete for at least 1 year of training and/or competition). If a participant did not self identify as a rowing athlete or did not complete a single question of the survey, they were excluded from the current study. The approach to sampling taken here was used to obtain a representative sample of rowing athletes of a variety of experience levels, ages, and sexes; however, given the approach to sampling, and the fact that participants were aware of theme of the survey, it is possible that some responder bias may exist.

## 3.2 Experimental Protocol

The proposed experimental protocol was reviewed, and approved, by the Brock Health Sciences Research Ethics Board (REB 19-310). A REB clearance certificate is included in Appendix B. An informed consent form (Appendix D) was included with the online survey for a participant to address prior to comencing the online survey. Participants in this study completed a single 44-question digital questionnaire (Appendix C), administered using Qualtrics online survey software (Qualtrics International) between the periods of July 2020-June 2021. The questionnaire (which is available in the supplementary material) utilized for the current study is an adapted version of those used previously (Pike, 2000) and consisted of four sections. *Section*

*A* was used to gather participant demographic information (Table 1) related to self-reported sex, age, height, and mass. *Section B* was used to survey the rowing related training history including each participant's predominant rowing type (i.e., sweep, scull), years of experience, and training preferences. *Section C* was used to survey the general *injury* history of each participant, including the number, location, and severity of different musculoskeletal injuries, and the perceived fatigue during the onset of injury. *Section D* was used to survey the rowing-related *pain* history of each participant, including the duration, severity, and location of any pain/discomfort. A visual depiction of the structure of the survey is presented in Figure 12.

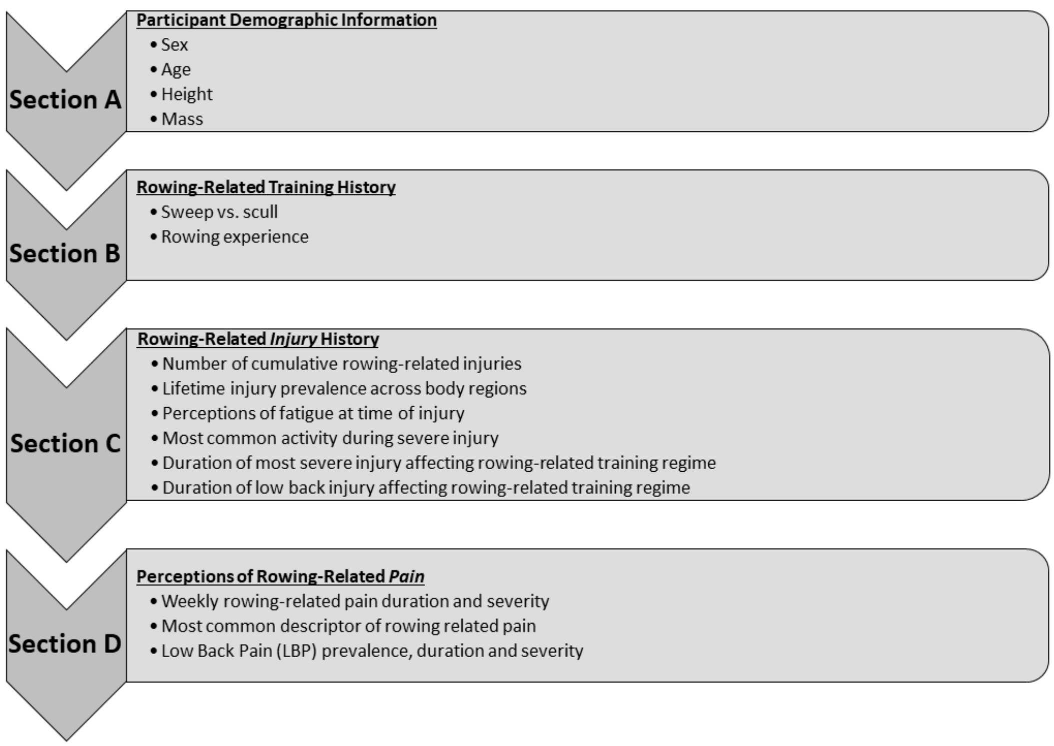


**Figure 12**. Depiction of the structure of the online survey.

The primary and secondary aims of the study were investigated using *Sections C and D* of the online survey, respectively. Within *Section C*, participants were required to reflect on their rowing-related injury history, with an injury being defined as a hurt or damaged body part, isolated to a specific region. This section required that participants report their cumulative number of rowing related injuries, including if they had experienced a rowing-related injury to one of 16 specific body regions (back, neck, shoulders, wrist/forearm, hands, other arm injury, groin, shins, knees, thighs, ankle, other leg injury, head, abdominals, and other). Further, participants were required to reflect on how fatigued they felt at the time of injury for each given body region. In addition to these questions, participants were asked to note the most common rowing-related activity they were completing at the time of injury, and how their injuries affected their rowing-related training regime. Within Section D, participants were required to reflect on their rowing-related pain experiences. In this context, pain was defined as discomfort which may (or may not) be attributable to a specific injury. Participants were required to report their approximate weekly rowing-related pain duration and severity (in general and localized to the low back). In addition to this, participants were asked to describe their pain experiences from a list of five specific descriptors (sharp, dull, burning, tingling, other). During the development of the survey pilot testing was conducted involving 10 rowers who have rowed for less than 1 year, Feedback from these individuals was used to break the survey down into blocks (Figure 12), and to adjust the potential response fields for certain questions. The initial version of the survey was also based off of a pre-existing survey used in a previously published thesis (Pike, 2000).

### 3.3 Data Extraction

Coded nominal and ordinal data were extracted from Qualtrics and input into Microsoft Excel for further visualization and organization. Specifically, to facilitate the analyses of body location, on injury incidence and fatigue (at time of injury), body region data were reduced from 16 groups (with injuries ranging from 2 to 30 in each group, to gross Axial, Upper Extremity (UE), Lower Extremity (LE) and other groups (all $n > 40$). To accomplish this and averages were computed for fatigue and injury prevalence scores, within each of the four condensed body regions, prior to any further analysis.

### 3.4 Outcome Measures

To structure the analysis injury data was simplified into broader groups (axial, upper extremity, lower extremity, and other), data were then grouped based on those (1) related to lifetime injury prevalence and the perceptions of fatigue at the time of injury and (2) those related to pain reports related to the low back, or other more serious injuries. Outcome measures for the first analysis included (a) the prevalence of acute injury across different body regions (yes or no) and (b) the subjective level of fatigue (1-5) at the time of injury. Outcome measures for the second analysis included (a) the perception of pain on a weekly basis (yes or no), (b) the severity and duration of pain on a weekly basis (1-5), (c) the most common activity during severe injury (sweep (racing), sweep (training), scull (racing), scull (training), ergometer, running, circuits, weights, cycling, aerobics, and other), (d) the duration of rowing-related inactivity caused by musculoskeletal injuries (spanning injuries < 1 week and those >1 year), and (e) the most common descriptor of pain (sharp, dull, burning, tingling, none, and other). Independent variables for all outcome measures will include participant sex, and/or the location of any given injury.

### 3.5 Statistical Analysis

Statistical analyses were performed using SPSS V27 (SPSS Inc., Chicago, USA). Given the mixed structure of the data obtained from the current survey, Mann-Whitney U tests were used for comparison between continuous variables with $X^2$ tests being used for categorical variables (e.g., Ng et al., 2014, Smoljanovic et al., 2015, Trompeter et al., 2019). For all analyses, an alpha level of 0.05 was used to represent statistically significant differences between all classes of independent variables (i.e., anatomical location, participant sex) included in the current study.

### *3.5.1 Effect of Sex on Participant Demographics*

Means and proportions (of either the total, or sex-grouped sample) were used to represent participants' height, mass, age, rowing experience and number of rowing-related musculoskeletal injuries. $X^2$ tests were used to determine between sex differences in participant demographic variables between sexes. For this analysis the independent variable included participant sex, and the dependant variables included participant height, mass, age, rowing experience and number of rowing related injuries.

### *3.5.2 Effect of Sex and Body Location on Lifetime Injury Prevalence and Perceptions of Fatigue at Time of Injury*

All lifetime musculoskeletal injury prevalence data are presented as proportions of the entire sample (138 participants). Fatigue ratings are presented as means and standard errors. A series of independent-samples non-parametric Mann-Whitney U test was implemented on the dataset to determine if either sex or injury location (i.e., axial, upper extremity, lower extremity or other) had a significant effect on the level of fatigue at the time of injury. For this the independent variables were (1) sex, and (2) injury location. The dependent variable for this analysis was the level of fatigue at time of injury (1-5) or the lifetime prevalence of injury.

### *3.5.3 Effect of Sex on Pain Reports, including those Related to the Low Back*

Reports of pain prevalence, severity and duration are presented as means and standard errors. For these data a non-parametric independent-samples Mann-Whitney U test was performed to determine if any sex differences existed in the report of pain prevalence, intensity or duration existed with respect so self-reported most severe injuries or those related to the low back. Given this, the independent variable for this analysis was the participant sex. Dependent variables for this analysis included (1) weekly pain, (2) weekly severity, (3) weekly LBP, (4) LBP severity and LBP prevalence.

# CHAPTER IV: RESULTS

## 4.1 Participant Demographics

The online survey was available for a period of one calendar year spanning the beginning of July 2020 and the end of June 2021. In total, 138 participants completed the digital survey of which 76 were female and 62 were male. All participant demographic variables (including rowing experience and number of rowing injuries), stratified across sex, have been depicted in Table 1. Most survey respondents, across both sexes, indicated an age of 18-24 years, height of 1.66 – 1.68 m, mass of 71-80 kg, rowing experience of 2-5 years, and 1-3 rowing-related musculoskeletal injuries. Statistical analyses indicated significant differences in height and mass between males and females. Specifically, male participants were observed to be significantly taller ($p < 0.0001$) and heavier ($p < 0.0001$) on average. No statistically significant differences in age ($p = 0.744$), rowing experience ($p = 0.188$), or rowing-related musculoskeletal injuries ($p = 0.852$) were observed between male and female participants.

**Table 1.** Survey Sample Demographics. Statistical comparisons indicate the assessment of a sex effect.

| Item | Sub Item | ALL (% $n_{tot}$) | Male (% $n_{male}$) | Female (% $n_{female}$) | p -value |
|---|---|---|---|---|---|
| **n** | - | 138 | 62 | 76 | - |
| **Age** | ***< 18 y*** | 3 (2.2) | 2 (3.2) | 1 (1.3) | 0.744 |
| | ***18-24 y*** | 75 (54.3) | 36 (58.1) | 39 (51.3) | |
| | ***25-29 y*** | 11 (8.0) | 5 (8.1) | 6 (7.9) | |
| | ***30-35 y*** | 10 (7.2) | 2 (3.2) | 8 (10.5) | |
| | ***36-42 y*** | 8 (5.8) | 2 (3.2) | 6 (7.9) | |
| | ***43-49 y*** | 7 (5.1) | 3 (4.8) | 4 (5.3) | |
| | ***50-54 y*** | 8 (5.8) | 3 (4.8) | 5 (6.6) | |
| | ***55-59 y*** | 8 (5.8) | 4 (6.5) | 4 (5.3) | |
| | ***60-64 y*** | 5 (3.6) | 3 (4.8) | 2 (2.6) | |
| | ***65-69 y*** | 3 (2.2) | 2 (3.2) | 1 (1.3) | |
| | ***> 70 y*** | 0 (0.0) | 0 (0.0) | 0 (0.0) | |
| **Height** | ***< 1.5 m*** | 0 (0.0) | 0 (0.0) | 0 (0.0) | $p < 0.0001$ |
| | ***1.5-1.65 m*** | 14 (10.1) | 0 (0.0) | 14 (18.4) | |
| | ***1.66-1.8 m*** | 61 (44.2) | 15 (24.2) | 46 (60.5) | |
| | ***1.81-1.95 m*** | 60 (43.5) | 44 (71.0) | 16 (21.1) | |
| | ***1.96-2.1 m*** | 2 (1.4) | 2 (3.2) | 0 (0.0) | |
| | ***> 2.11 m*** | 1 (0.7) | 1 (1.6) | 0 (0.0) | |
| **Mass** | ***< 50 kg*** | 0 (0.0) | 0 (0.0) | 0 (0.0) | $p < 0.0001$ |
| | ***51-60 kg*** | 16 (11.6) | 1 (1.6) | 15 (19.7) | |
| | ***61-70 kg*** | 37 (26.8) | 5 (8.1) | 32 (42.1) | |
| | ***71-80 kg*** | 48 (34.8) | 31 (50.0) | 17 (22.4) | |
| | ***81-90 kg*** | 24 (17.4) | 15 (24.2) | 9 (18.8) | |
| | ***91-100 kg*** | 7 (5.1) | 4 (6.5) | 3 (3.9) | |
| | ***> 100 kg*** | 6 (4.3) | 6 (9.7) | 0 (0.0) | |
| **Rowing Experience** | ***< 1 y*** | 10 (7.2) | 5 (8.1) | 5 (6.6) | 0.188 |
| | ***1-2 y*** | 25 (18.1) | 13 (21.0) | 12 (15.8) | |
| | ***3-5 y*** | 102 (73.9) | 43 (69.4) | 59 (77.6) | |
| | ***6-10 y*** | 1 (0.7) | 1 (1.6) | 0 (0.0) | |
| | ***>10 y*** | 0 (0.0) | 0 (0.0) | 0 (0.0) | |
| **Rowing Injuries** | ***0*** | 11 (8.0) | 5 (8.1) | 6 (7.9) | 0.852 |
| | ***1-3*** | 98 (71.0) | 43 (69.4) | 55 (72.4) | |
| | ***4-7*** | 20 (14.5) | 10 (16.1) | 10 (13.2) | |
| | ***8-11*** | 4 (2.9) | 1 (1.6) | 3 (3.9) | |
| | ***>11*** | 5 (3.6) | 3 (4.8) | 2 (2.6) | |

**Note: $n_{tot}$ corresponds to the total number of respondents ($n_{tot}$ = 138), $n_{female}$ corresponds to the total number of female respondents ($n_{female}$ = 76), and $n_{male}$ corresponds to the total number of male respondents ($n_{male}$ = 62).*

### 4.2 Effect of Sex and Body Location on Lifetime Injury Prevalence and Perceptions of Fatigue at Time of Injury

The 16-item lifetime injury prevalence data, stratified across participant sex, are depicted in Figure 13. The lifetime injury prevalence was highest for the back (84.1%), shoulder (44.2%), wrist (36.2%), knees (24.6%), and neck (22.4%). The lifetime prevalence of all other anatomical regions was <20%. Upon subjective appraisal, no clear visual difference was detected when comparing male and female respondents in the lifetime injury prevalence of any specific (i.e., 16-item) anatomical region.

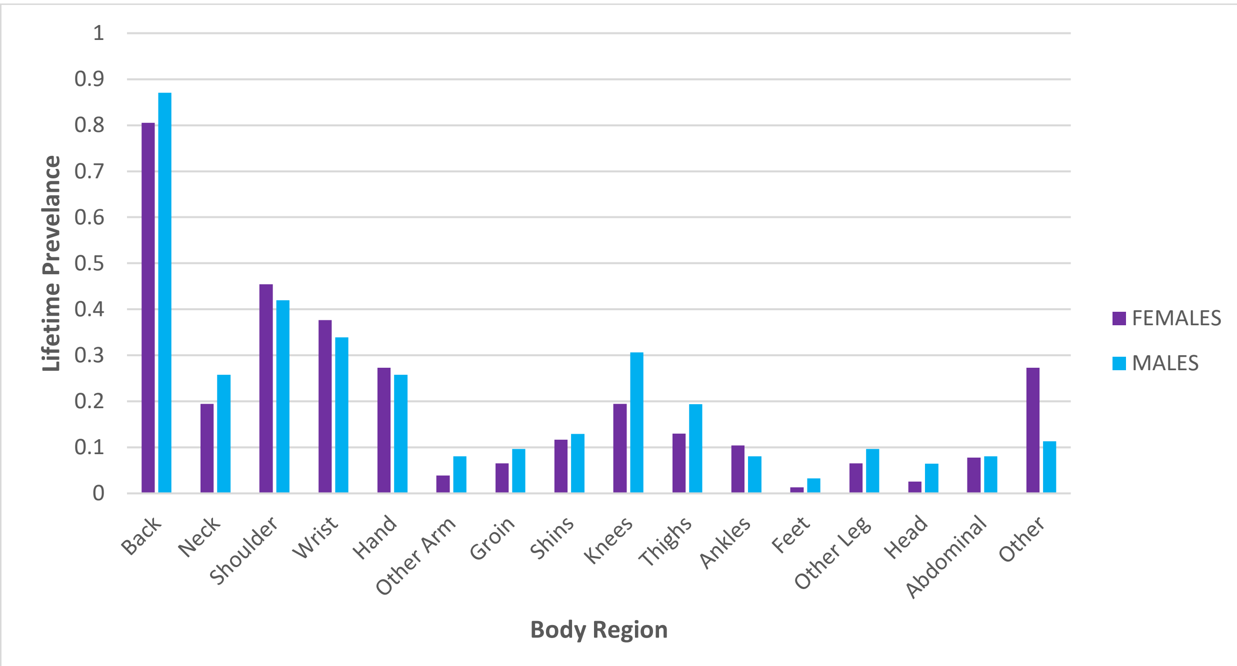


**Figure 13.** Lifetime prevalence of injuries to each body part that was surveyed for both males and females.

The 16-item fatigue effect on musculoskeletal injury data, stratified across participant sex, are depicted in Figure 14. Although the possible range of fatiguability spanned zero (no fatigue) to five (most fatigue imaginable), the majority of mean responses fell within the range of one to four. No apparent systematic differences existed between specific body regions; however, for some regions (i.e., neck, shoulder, wrist, arm, groin, thigh, feet, and head) males reported a higher level of fatiguability at the time of musculoskeletal injury, on average, than female respondents.

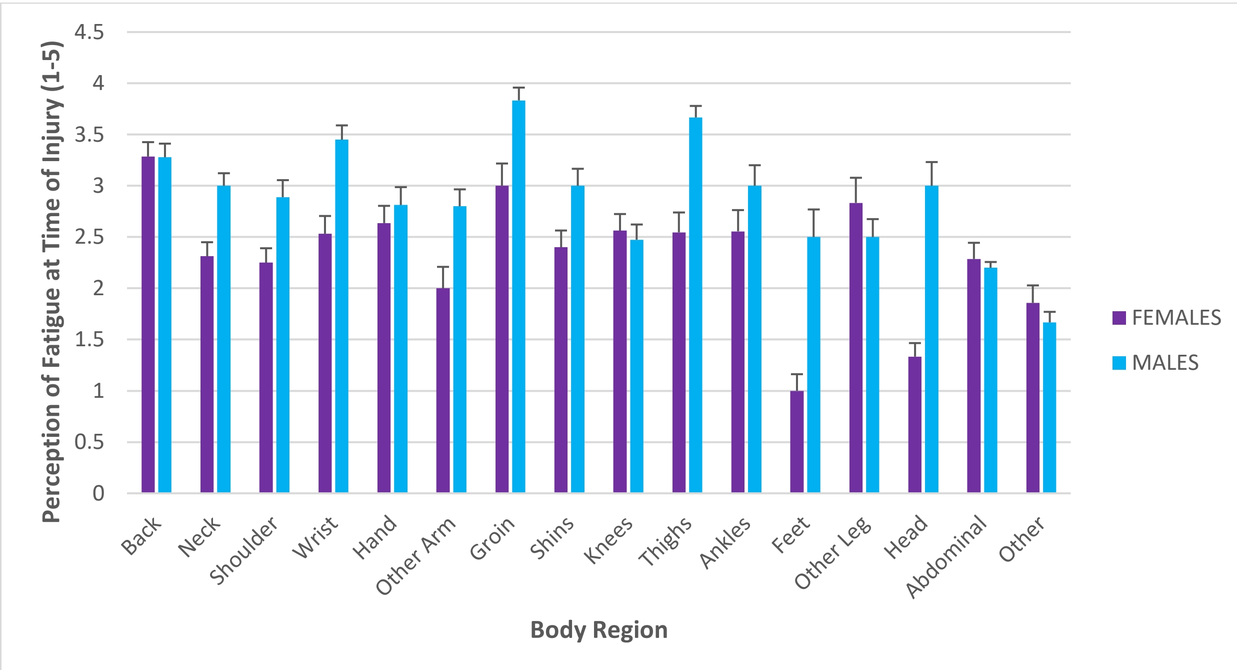


**Figure 14.** Mean (+ SEM) subjective perceived level of fatigue at the time of injury to each body location for both males and females.

Prior to statistical analyses, 16-item anatomical data were reduced to four general body regions (i.e., back/neck, upper extremity, lower extremity, and other) to ensure balance in sample size and variance between anatomical regions. The lifetime prevalence of musculoskeletal injury, reduced into these four general body regions is depicted in Figure 15. There was significant difference is in lifetime injury prevalence between injuries to the back/neck, upper extremity, lower extremity, and other body regions. Specifically, the lifetime prevalence of back/neck injuries was significantly greater than all other regions (upper extremity p = 0.006, lower extremity p < 0.001, other p < 0.001). Further, upper extremity lifetime injury prevalence rate was significantly greater than both lower extremity (p < 0.001) and other (p < 0.001). Lastly the lifetime prevalence of lower extremity injuries was significantly greater than injuries to sites within the other group (p = 0.009) (Figure 15).

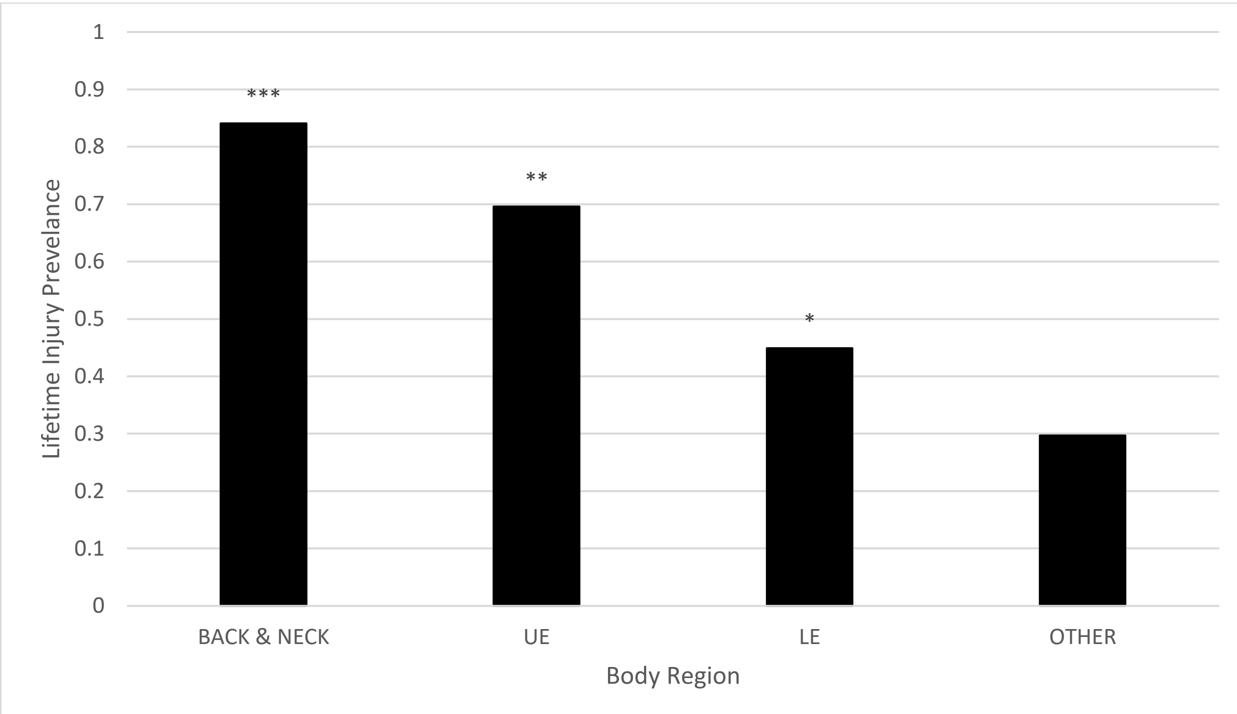


**Figure 15.** Lifetime prevalence of injury, separated across general body regions (n = 138).

In addition to the lifetime injury prevalence data, the 16-item anatomical data were reduced to four general body regions (i.e., back/neck, upper extremity, lower extremity, and other) for the subjective fatigue ratings, again to ensure balance in sample size and variance between anatomical regions. The perceptions of fatigue at the time of musculoskeletal injury, reduced into these four general body regions is depicted in Figure 16. There was a significant location effect for the level of fatigue at the time of injury (p < 0.001); however, there was not a significant effect sex effect (p = 0.054). Although insignificant, the trending sex effect appears to be driven predominantly between differences in fatiguability in the upper extremities between males (mean fatigue 2.86/5) and females (mean fatigue 2.32/5) at the time of musculoskeletal injury. Further analysis determined that the level of fatigue during an axial injury was significantly greater than all of upper extremity ($p < 0.001$), lower extremity ($p = 0.006$), and other ($p < 0.001$). Further, lower extremity fatigue at the time of musculoskeletal injury was significantly greater than both upper extremity ($p = 0.031$) and other ($p = 0.012$) regions. There was no statistical difference in the level of fatigue between upper extremity, and other injury sites ($p = 0.475$) (Figure 16).

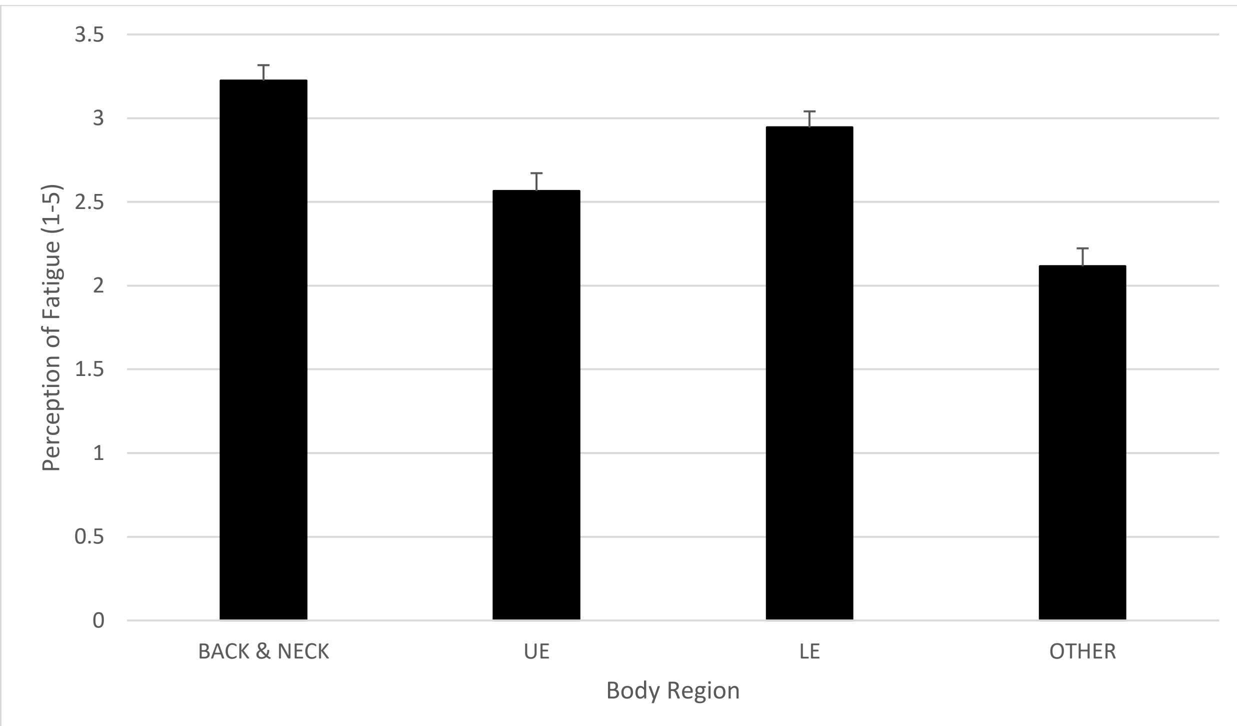


**Figure 16**. Mean (+ SEM) perceptions of fatigue (1 = least, 5 = most) at the time of injury, separated across general body regions.

### 4.3 Effect of Sex on Subjective Pain Reports, Including Those Relating to the Low Back

In addition to quantifying the anatomical distribution of musculoskeletal injuries, and the relative effect of neuromuscular fatigue on these injuries, as secondary aim of the online survey was to quantify any sex specific effects in the cause, duration, and severity of both an individual's self appraised most severe musculoskeletal injury, and any reported low back injury. This approach was taken to evaluate the severity and duration of low back injuries against those subjectively appraised as being the most severe. The first aim of this supplementary analysis was to quantify the most common activity being completed during each rower's self appraised most severe injury. These data are depicted in Table 2. Across both sexes, the most common activity during severe injury was indoor ergometer training; however, both scull and sweep on-water training also comprised a large proportion of the activities eliciting severe musculoskeletal injury.

**Table 2.** Most common activity during severe musculoskeletal injury.

| Activity | ALL (%$n_{tot}$) | FEMALE (%$n_{female}$) | MALE (%$n_{male}$) |
|---|---|---|---|
| **Sweep (Racing)** | 15 (10.9) | 10 (13.2) | 5 (8.1) |
| **Sweep (Training)** | 26 (18.8) | 11 (14.5) | 15 (24.2) |
| **Scull (Racing)** | 5 (3.6) | 3 (3.9) | 2 (3.2) |
| **Scull (Training)** | 24 (17.4) | 16 (21.1) | 8 (12.9) |
| **Ergometer** | 31 (22.5) | 16 (21.1) | 15 (24.2) |
| **Running** | 8 (5.8) | 4 (5.3) | 4 (6.5) |
| **Circuits** | 2 (1.4) | 1 (1.3) | 0 (0.0) |
| **Weights** | 15 (10.9) | 6 (7.9) | 9 (14.5) |
| **Cycling** | 2 (1.4) | 0 (0.0) | 2 (3.2) |
| **Aerobics** | 0 (0.0) | 0 (0.0) | 0 (0.0) |
| **Other** | 7 (5.1) | 6 (7.9) | 1 (1.6) |

**Note: $n_{tot}$ corresponds to the total number of respondents ($n_{tot}$ = 138), $n_{female}$ corresponds to the total number of female respondents ($n_{female}$ = 76), and $n_{male}$ corresponds to the total number of male respondents ($n_{male}$ = 62).*

To quantify the most common sensations of pain experienced by rowing athletes, respondents were also asked to select the term that best describes their perceptions of musculoskeletal pain. The most common descriptors of this musculoskeletal pain are depicted in Table 3. In general, both males and females noted that the most common sensations of musculoskeletal pain were perceived as ‘dull’ (77% of respondents) followed by ‘sharp’ (3% of respondents). No apparent differences existed between male and female athletes.

**Table 3.** Most common descriptor of week-to-week rowing-related musculoskeletal pain.

| Descriptor | ALL (% $n_{tot}$) | FEMALE (% $n_{female}$) | MALE (% $n_{male}$) |
|---|---|---|---|
| **Sharp** | 36 (26.1%) | 21 (33.9%) | 15 (26.8%) |
| **Dull** | 77 (55.8%) | 34 (54.9%) | 43 (76.8%) |
| **Burning** | 19 (13.8%) | 10 (16.1%) | 9 (16.1%) |
| **Tingling** | 18 (13%) | 9 (14.5%) | 9 (16.1%) |
| **None** | 15 (10.9%) | 9 (14.5%) | 6 (10.7%) |
| **Other** | 12 (8.7%) | 11 (17.8%) | 1 (1.8%) |

**Note: $n_{tot}$ corresponds to the total number of respondents ($n_{tot}$ = 138), $n_{female}$ corresponds to the total number of female respondents ($n_{female}$ = 76), and $n_{male}$ corresponds to the total number of male respondents ($n_{male}$ = 62).*

The relative impact (i.e., duration) of self appraised ‘most severe’ musculoskeletal injuries, and injuries to the low back on rowing-related training are depicted in Table 4. In general, musculoskeletal injuries identified as the most severe often caused a longer interruption in rowing-related training, whereas athletes tended to continue training after experiencing an injury to the low back region. Specifically, for severe musculoskeletal injuries 31.1% of athletes had a training interruption of 1-4 weeks; however, for low back related injuries 44.2% of athletes reported no interruption to their rowing related training regime.

**Table 4.** The relative impact (i.e., duration) of musculoskeletal injuries affecting rowing-related training regime.

| | Duration | ALL (% $n_{tot}$) | FEMALE (% $n_{female}$) | MALE (% $n_{male}$) |
|---|---|---|---|---|
| **Most Severe Injury** | None | 14 (10.1%) | 7 (9.2%) | 7 (11.3%) |
| | < 1 week | 14 (10.1%) | 11 (14.5%) | 3 (4.8%) |
| | 1-2 weeks | 17 (12.3%) | 7 (9.2%) | 10 (16.1%) |
| | 2-4 weeks | 26 (18.8%) | 13 (17.1%) | 13 (20.1%) |
| | 1-2 months | 22 (15.9%) | 10 (13.2%) | 12 (19.4%) |
| | 2-6 months | 14 (10.1%) | 8 (10.5%) | 6 (9.7%) |
| | 6-12 months | 10 (7.2%) | 8 (10.5%) | 2 (3.2%) |
| | > 1 year | 19 (13.8%) | 10 (13.2%) | 9 (14.5%) |
| **Low Back Injury** | None | 61 (44.2%) | 36 (47.4%) | 25 (40.3%) |
| | < 1 week | 11 (8.0%) | 3 (3.9%) | 8 (12.9%) |
| | 1-2 weeks | 13 (9.4%) | 7 (9.2%) | 6 (9.7%) |
| | 2-4 weeks | 18 (13.0%) | 13 (17.1%) | 5 (8.1%) |
| | 1-2 months | 8 (5.8%) | 3 (3.9%) | 5 (8.1%) |
| | 2-6 months | 8 (5.8%) | 4 (5.3%) | 4(6.5%) |
| | 6-12 months | 6 (4.3%) | 5 (6.6%) | 1 (1.6%) |
| | > 1 year | 7 (5.1%) | 3 (3.9%) | 4 (6.5%) |

**Note:* $n_{tot}$ *corresponds to the total number of respondents (*$n_{tot} = 138$*),* $n_{female}$ *corresponds to the total number of female respondents (*$n_{female} = 76$*), and* $n_{male}$ *corresponds to the total number of male respondents (*$n_{male} = 62$*).*

The mean severity, and relative duration of injuries classified as being ‘general’ or located specifically at the low back, have been depicted in Table 5. There was no significant difference in prevalence of LBP between male and female rowers (p = 0.256) (Table 5). Specifically, the prevalence of LBP in male rowers was 59.7% compared to 52.6% of female participants (Table 5), and the total prevalence rate of LBP was 55.8% across all participants. Further, there was no significant difference between males and females in the length of time that they have been affected by LBP (p = 0.485). Nor was there a significant difference between sexes for weekly LBP duration (p = 0.448), and LBP severity (p = 0.864). In terms of general pain, unrelated to the low back, there was no significant difference between weekly general pain duration (p = 0.289) and weekly general pain severity (p = 0.456) between male and female rowing athletes (Table 5).

**Table 5.** Median (inter-quartile range) reports of rowing-related pain, including any pain specifically localized to the low back region. Statistical comparisons indicate the assessment of a sex effect.

| Group | Weekly General Pain Duration (1-5) | Weekly General Pain Severity (1-5) | LBP Prevalence | Weekly LBP Duration (1-5) | Weekly LBP Severity (1-5) |
|---|---|---|---|---|---|
| **ALL** | 3.00 (1.00) | 2.00 (1.00) | 1.00 (1.00) | 2.00 (2.00) | 2.00 (1.00) |
| **FEMALE** | 2.00 (1.00) | 2.00 (2.00) | 1.00 (1.00) | 2.00 (2.00) | 2.00 (1.75) |
| **MALE** | 3.00 (1.00) | 2.00 (1.00) | 1.00 (1.00) | 2.00 (2.00) | 2.00 (1.00) |
| **p – value** | 0.289 | 0.456 | 0.256 | 0.448 | 0.864 |

# CHAPTER V: DISSCUSSION

The aims of the current work were threefold. The first aim was to assess the lifetime prevalence of musculoskeletal injures, based on different anatomical regions, including the perceptions of muscular fatigue as a contributing factor to these injuries in recreational rowing athletes. The secondary aims of the current work included the assessment of sex-specific effects in self-reported rowing-related injuries, including those related to low back injury and pain. In alignment with these research aims, the hypotheses for the current work were also threefold. The first hypothesis was that lower back injuries will be the most common in rowing athletes, and that muscular fatigue will play the largest role in injuries affecting axial structures. The second hypothesis was that muscle fatigue will have a larger association with injury in males vs. females. The third hypothesis was that the prevalence and severity of LBP will be higher in male athletes relative to female ones. In general, the results of the current study support the first hypothesis; however, the latter two hypotheses are largely refuted given the results of the current study.

## 5.1 Anatomical Distributions of Musculoskeletal Injury

Previous work has identified injuries to the low back to be the most common musculoskeletal injury experienced by rowing athletes (Pike, 2000, Newlands *et al.*, 2015). Although the lifetime prevalence of low back injury has been identified as high in rowing athletes, it is yet unclear if there is any elevated prevalence of lifetime low back injury relative to the general population (Maselli *et al.*, 2015, Trompeter *et al.*, 2017). Nevertheless, the results of this study indicate that rowing athletes suffer a higher proportion of injuries to the axial body region than any other assessed body region, more specifically the back was the most common injury site with a total of 103 participants having suffered a back injury, more than double the next injury site which was the shoulder at a total of 47 injuries, this agrees with previous literature as the back has commonly been found to be the most common injury site (i.e., Pike, 2000, Finlay *et al.,* 2020). Interestingly, the prevalence of back injuries reported in the current sample (i.e., Figure 13), mirror the approximate prevalence of low back pain reported in a general population (GBD 2015 and HALE Collaborators), suggesting no specific differences in the population sampled here relative to the more general population.

Despite the high prevalence of musculoskeletal injuries located within axial body regions in rowing athletes (Figure 12), there was no significant sex effect on the lifetime prevalence on rowing-related musculoskeletal injuries across any body region. This is in alignment with some previous reports (Finlay *et al.,* 2020); however, goes against others (Ng *et al.,* 2011), thereby contributing to the discourse present within the growing body of scientific literature. Although there are some potential anatomical, neuromuscular, and biomechanical differences between male and female rowing athletes, there are many other factors which may contribute to the inconsistent reports of sex-related effects on musculoskeletal injury lifetime prevalence. Some specific factors may include the age, experience, training load, and rowing specialization (i.e., sweep vs. scull) of the athletes being surveyed.

## 5.2 The Relative Effects of Muscle Fatigue on Musculoskeletal Injury

A large body of previous literature has come to suggest that the fatiguability of male and female athletes is variable. Specifically, female athletes appear to be more robust to any neuromuscular or biomechanical effects of muscle fatigue, suggesting a lowered fatiguability when compared to their male counterparts (Enoka *et al.,* 2008). This may be an additional contributing factor to any potential difference in musculoskeletal injury prevalence between male and female rowing athletes, or in the elevated injury prevalence at specific anatomical locations.

The results of the current study suggest that rowing athletes are more fatigued when an axial injury occurs than injuries to any other grouped location on the body (upper extremity, lower extremity, and other) (Figure 16). This may be a large contributing factor to the elevated prevalence of low back related musculoskeletal injuries in rowing athletes. While there is little evidence regarding the effect of fatigue on spine kinematics in rowing, previous literature has proposed that the cyclic flexion loading of the lumbar spine that has been demonstrated in the rowing stroke may be related to a higher incidence of LBP (Callaghan & McGill, 2001; Hangai et al., 2008), combined with the fatigue effects related to lowered muscle strength and encumbered coordination patterns (Turpin *et al.*, 2011), as seen previously as the lumbar flexion range of motion (% maximum ROM) increasing as a 2000-meter trial progressed (Caldwell *et al*, 2003) (Figure 8). As such, it is possible that factors such as reduced muscle strength, poor coordination, and added spinal flexion may be associated with additional muscular fatigue of the low back during the later stages of a rowing bout, result in elevated risk for musculoskeletal injury to axial structures in comparison to other body regions (i.e., Figure 15).

Although a clear sex effect has been demonstrated throughout the literature on the manifestation of muscle fatigue in males and females, no statistically significant sex effects were observed in the current study. Despite this, the data acquired here do suggest that some systematic differences between the perceptions of muscle fatigue at the time of injury may exist between male and female athletes, specifically in upper extremity anatomical regions (Figure 14). Given this, muscle fatigue may be a larger contributing factor for musculoskeletal injury in male athletes; however, it is clear that any potential added burden of muscle fatigue does not result in an increased lifetime prevalence for musculoskeletal injury. Further work is necessary to assess the relative impact of muscle fatigue in male and female rowing athletes, including if sensations of muscle fatigue may contribute and any potential sex-related difference in the lifetime or point prevalence of musculoskeletal injuries, including those associated with the low back. These should include the neurophysiological and biomechanical manifestations of muscle fatigue in rowing athletes (i.e., Willwatcher et al., 2020), and further subjective appraisal of rowing athletes regarding the perceptions of muscle fatigue at the time musculoskeletal injury.

**5.3 The Effect of Athlete Sex on Subjective Pain Reports**

In addition to the investigation of fatigue and lifetime injury prevalence in male and female rowers, and additional aim was to quantify the relative burden and subjective appraisals of musculoskeletal injuries across male and female athletes. These include phenomena such as the rowing-related activities most associated with musculoskeletal injury, the sensations of pain associated with musculoskeletal injury, and the relative duration and severity of such pain.

The results of this study suggest that some of the most common activities associated with rowing-related injuries are indoor ergometer training (22.5% of respondents), on-water sweep training (18.8% or respondents) and on-water scull training (17.4% of respondents). Although no apparent differences existed between male and female athletes, the risk associated with ergometer training has been identified elsewhere (Ng *et al.*, 2011), therefore the findings noted here corroborate previous reports. Some of the specific biomechanical risks associated with ergometer training may be, differences in technique compared to on the water as the body of the participant is not moving relative to the land, this could lead to more jerk. Further research will be necessary to continue evaluating any systematic differences between rowing on an indoor ergometer, versus on-water sculling and sweeping.

When quantifying the subjective description of musculoskeletal pain, the majority of respondents indicated that the pain experienced was either dull (55% of respondents) or sharp

(26% of respondents), while far-fewer indicated sensations of burning (14% respondents) or tingling (13% respondents). Although these reports are largely qualitative, they may suggest an increased prevalence of chronic over-use type injuries (i.e., dull/ache) rather than injuries provoked by some acute exposure or event (i.e., sharp/stabbing). This postulation would be in alignment with the theory that most injuries associated with rowing are linked to over-use or cumulative exposure to specific biomechanical risk factors. For the low back, these risk factors may include items such as (1) repeated spine flexion under a compressive load, (2) instances of high thoracolumbar spine flexion (Hemming *et al.*, 2018) and (3) compound postures involving a combination of spine flexion, lateral flexion, and rotation. Interestingly, when quantifying the relative impact of self appraised 'most severe musculoskeletal injuries', against those specifically associated with the low back, it was clear that injuries appraised as being severe required longer periods of rowing-related inactivity to facilitate recovery (Table 4). In contrast, an overwhelming proportion or respondents (60% respondents) indicated that lower back injuries did not affect their rowing-related training regime. This suggests that rowing athletes tend to train trough low-back related injuries and discomfort, potently further exacerbating any mechanical injury by further imposing additional cumulative loads and delaying recovery from injury.

When assessing the relative severity, duration, and prevalence of general musculoskeletal pain, and pain specifically associated with the low back, no systematic effects were observed. Specifically, the results of this study also found that there were no significant differences in prevalence of LBP between male and female rowers (60% and 53% respectively). Although this, this finding does not agree with Ng *et al.*, (2014), this may be due to the athletes surveyed having a more similar amount of training hours per week as having an increased amount of training hours has been linked to an increased prevalence of LBP (Newlands *et al.*, 2015), the Ng et al.,

(2014) study noted that males had a significantly higher prevalence of both lifetime and point prevalence of LBP, with this they noted that the male rowers performed significantly more hours of training than female adolescent rowers (Ng *et al.*, 2014). This difference could also be due to the age groups surveyed as the Ng study focused on adolescent rowers between the ages of 14 and 16, whereas the majority of participants in the current survey were between the ages of 18 and 25. Further to the prevalence data noted above, no significant difference was found between males and females in terms of the subjective duration and severity of LBP (Table 5), this may be due to similar factors as listed above. In addition to the LBP specific items, participants in the survey were asked several questions regarding general musculoskeletal pain duration and severity. Like the responses for the low back, there was no statistically significant differences noted between the responses of males and females. Further, the relative burden of 'general' musculoskeletal pain in terms of duration and severity appeared to be in alignment with the results specific to the low back. Further research will be necessary to quantify the relative burden of low back pain, in terms of pain severity and duration, relative to painful experiences in other body regions.

### 5.4 Strengths and Limitations of the Current Work

As noted previously, this work is one of the first to quantify the interplay between muscle fatigue and musculoskeletal injury. The approach taken here allowed for the acquisition of a relatively high number of participants (n = 138), giving strength to the trends reported throughout this thesis. Further, the approach taken here allowed for participants to reflect on their musculoskeletal injury history in a holistic manner by asking them to consider varying anatomical regions, rather than just the low back alone. Despite these strengths, the current work does not come without limitations. Some limitations of this study include the relatively low diversity in age of the respondents (75% of respondents between the ages of 18-24 years) generated through convenience sampling, and the potential influence that this biased sample may generate in terms of responses (i.e., non-responder bias, central tendency). Further, the subjective nature of the survey required substantial reflection on previous musculoskeletal injury events, and in some cases, the language used in the survey could lead to some confusion among participants. Specifically, the verbiage for injury, pain, and fatigue used within the survey are in some cases conflated and open to interpretation.

To address the first limitation regarding sample bias, a larger, more diverse sample could be recorded for future work, or athletes from specific demographic (e.g., age) bins may be targeted individually. Opportunities for targeted sampling may include the recruitment of athletes at specific rowing events, across a wide range of locations, ages, and disciplines (i.e., rowing vs. sculling). Additionally, a comparative sample of healthy non-rowers may be a useful addition for future work to facilitate comparisons between specialized rowing subgroups and the general population. In general, the use of a non-systematic sampling approach negates an effects of responder bias, to prevent this future research should take a more systematic approach to sampling. To address the second limitation regarding the structure of the survey used for the current study, future work should consider expanding on the survey initially implemented by Pike (2000), which was used as the basis of the survey implemented for the current work. Specifically, future work may consider implementing surveys of shorter length, to allow for the acquisition of more continuous survey-based data across a wide range of time-points. Further, for the purposes of the current work, many of the survey response options were categorized to reduce participant demand. Specifically, a 5-point Likert scale was chosen to optimize familiarity with the sample of rowing athletes. While not as reproducible as visual analogue scales and Borg scales (Grant *et al.*, 2015), the use of a Likert scale allows researchers to have the scale simply run from 1-5 making it familiar to participants as it is a similar style to that they would see in a training-based environment (Grant *et al.,* 2015). For future survey-based research continuous response fields (i.e., sliding scales) may be preferred. Finally, although the verbiage selected for the current survey was designed to be accessible for a group of pilot rowers (n = 10), future work should be concise in the verbiage around injury, pain, and MSDs, as these terms are often conflated across rowing athletes, and within the rowing literature. Given the retrospective nature of the survey there is likely some recall errors may have resulted in a central tendency of fatigue ratings at the time of injury. To prevent this, future studies should have athletes record their level of fatigue directly at the time of injury in a longitudinal study.

### 5.5 Conclusions

There are some interesting conclusions that can be drawn from the current work, some of which are novel, and some of which corroborate previous reports. First, the current study adds to the research literature by identifying muscle fatigue as an elevated risk factor for injury in axial anatomical regions. Second, the current study suggests that male athletes and female athletes are at increased risk for musculoskeletal injury, and the most common injury across both groups were those to axial structures, including the low back. Next, the results reported here suggest that common rowing-related movements associated musculoskeletal injury include tasks like ergometer use and on-water training, which is in alignment with previous reports (Ng *et al.,* 2011). Third the current study highlights the overwhelming sensation of dull/achy pain in rowing athletes, and the limited breaks taken by rowing athletes following low back injury, potentially affecting the longevity of such injuries. Finally, the current work suggests no systematic differences in the prevalence of low back pain between male and female rowing athletes, nor in the severity of duration of such pain experienced at the low back or in other more general body regions.

**CHAPTER VI: REFERENCES**

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# Appendix A: Origin and Insertion of Study Related Musculature

*Appendix A.1: Origin and insertion for trunk flexion muscles (Biel, 2014)*

| **Muscle** | **Origin** | **Insertion** |
|---|---|---|
| Rectus Abdominus | pubic crest and symphysis | cartilage of the fifth through seventh ribs and xiphoid process |
| External Oblique (bilaterally) | fifth to twelfth ribs | anterior portion of the iliac crest specifically the abdominal aponeurosis to linea alba |
| Internal Oblique (bilaterally) | lateral inguinal ligament, iliac crest, and thoracolumbar fascia | internal surface of the lower three ribs |
| Psoas Major (bilaterally, with the insertion fixed) | bodies and transverse processes of the lumbar vertebrae | Lesser trochanter of femur |
| Iliacus (with insertion fixed) | Iliac fossa | Lesser trochanter of femur |

*Appendix A.2: Muscles responsible for trunk extension (Biel, 2014)*

| **Muscle** | **Origin** | **Insertion** |
|---|---|---|
| Longissimus (bilaterally) | common tendon (thoracis) | Lower nine ribs and transverse processes of the thoracic vertebrae (thoracis) |
| Iliocostalis (bilaterally) | Common tendon (lumborum) | Transverse processes of lumbar vertebrae 1-3 and posterior surface of ribs 6-12 (lumborum) |
| Multifudi (bilaterally) | Sacrum and transverse processes of lumbar through cervical vertebrae | Spinous processes of lumbar through second cervical vertebrae (span 2-4 vertebrae) |
| Rotatores (bilaterally) | Transverse processes of lumbar through cervical vertebrae | Spinous processes of lumbar through second cervical vertebrae (span 1-2 vertebrae) |
| Spinalis (bilaterally) | Spinous processes of the lumbar and lower thoracic vertebrae (thoracis) | Spinous processes of upper thoracic (thoracis) |
| Quadratus lumborum | Posterior iliac crest | Last rib and transverse process of ribs L-1 through L-4 |

| | | |
|---|---|---|
| Intertransversarii (bilaterally) | Transverse process of L-2 through L-5 (lumbar) | Transverse process of L-1 through L-4 (lumbar) |
| Latissimus dorsi (when the arm is fixed) | Inferior angle of scapula, spinous process of T-7 through T-12, last three ribs, thoracolumbar aponeurosis, and posterior iliac crest | Intertubercular groove of the humerus |

*Appendix A.3: Muscles responsible for lateral flexion and/or axial rotation (Biel, 2014)*

| **Muscle** | **Origin** | **Insertion** |
|---|---|---|
| Iliocostalis (unilaterally) | Common tendon (lumborum) | Transverse processes of lumbar vertebrae 1-3 and posterior surface of ribs 6-12 (lumborum) |
| External oblique (unilateral) | External surface of 5th through 12th ribs | Anterior portion of iliac crest, abdominal aponeurosis to linea alba |
| Internal oblique (unilateral) | Lateral inguinal ligament, iliac crest, and thoracolumbar fascia | Internal surface of lower 3 ribs, abdominal aponeurosis to linea alba |
| Longissimus (unilateral) | common tendon (thoracis) | Lower nine ribs and transverse processes of the thoracic vertebrae (thoracis) |
| Quadratus Lumborum (unilateral) | Posterior iliac crest | Last rib and transverse process of ribs L-1 through L-4 |
| Psoas Major (unilateral) | Bodies and transverse processes of lumbar vertebrae | Lesser trochanter |
| Intertransversarii (unilateral) | Transverse process of L-2 through L-5 (lumbar) | Transverse process of L-1 through L-4 (lumbar) |
| Spinalis | Spinous processes of the lumbar and lower thoracic vertebrae (thoracis) | Spinous processes of upper thoracic (thoracis) |
| Multifudi (unilaterally) | Sacrum and transverse processes of lumbar through cervical vertebrae | Spinous processes of lumbar through second cervical vertebrae |
| Rotatores (unilaterally) | Transverse processes of lumbar through | Spinous processes of lumbar through |

| | | |
|---|---|---|
| | cervical vertebrae | second cervical vertebrae |

*Appendix A.4: Origin and insertion of additional relevant musculature (Biel, 2014)*

| **Muscle** | **Origin** | **Insertion** |
|---|---|---|
| Biceps Femoris | Long head: Ischial tuberosity<br>Short head: linea aspera | Lateral aspect of the head of the fibula |
| Rectus Femoris | Anterior inferior iliac spine and ilium | Tibial tuberosity via quadriceps tendon |
| Vastus Medialis | Intertrochanteric line of femur | Tibial tuberosity via quadriceps tendon |
| Gluteus Medius | Gluteal surface of ilium | Lateral aspect of greater trochanter of femur |

# Appendix B: Certificate of Research Ethics Clearance for Human Participant Research

Brock University

Brock University
Office of Research Ethics
Tel: 905-688-5550 ext. 3035
Email: reb@brocku.ca

Bioscience Research Ethics Board

## Certificate of Ethics Clearance for Human Participant Research

| | |
|---|---|
| DATE: | 6/11/2020 |
| PRINCIPAL INVESTIGATOR: | BEAUDETTE, Shawn - Kinesiology |
| FILE: | 19-310 - BEAUDETTE |
| TYPE: | Masters Thesis/Project STUDENT: Alex Johnston<br>SUPERVISOR: Shawn Beaudette |

TITLE: The Effect of Fatigue on Rowing Kinematics in Elite and Novice Rowers

**ETHICS CLEARANCE GRANTED**

Type of Clearance: NEW Expiry Date: 6/1/2021

The Brock University Bioscience Research Ethics Board has reviewed the above named research proposal and considers the procedures, as described by the applicant, to conform to the University's ethical standards and the Tri-Council Policy Statement. Clearance granted from **6/11/2020** to **6/1/2021**.

The Tri-Council Policy Statement requires that ongoing research be monitored by, at a minimum, an annual report. Should your project extend beyond the expiry date, you are required to submit a Renewal form before 6/1/2021. Continued clearance is contingent on timely submission of reports.

To comply with the Tri-Council Policy Statement, you must also submit a final report upon completion of your project. All report forms can be found on the Office of Research Ethics web page at http://www.brocku.ca/research/policies-and-forms/research-forms.

In addition, throughout your research, you must report promptly to the REB:

a) Changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) All adverse and/or unanticipated experiences or events that may have real or potential unfavourable implications for participants;
c) New information that may adversely affect the safety of the participants or the conduct of the study;
d) Any changes in your source of funding or new funding to a previously unfunded project.

We wish you success with your research.

Approved:

Craig Tokuno, Chair
Bioscience Research Ethics Board

**Note:** Brock University is accountable for the research carried out in its own jurisdiction or under its auspices and may refuse certain research even though the REB has found it ethically acceptable.

If research participants are in the care of a health facility, at a school, or other institution or community organization, it is the responsibility of the Principal Investigator to ensure that the ethical guidelines and clearance of those facilities or institutions are obtained and filed with the REB prior to the initiation of research at that site.

## Appendix C: Rowing Demographic and Injury History Questionnaire

SPINE BIOMECHANICS
& NEUROMUSCULAR CONTROL LABORATORY

# Rowing Survey

## Section A: About You

1. What is your sex?
   Male☐ Female☐

2. What gender do you identify as?
   Male☐ Female☐ If neither please specify☐
   ________________________

3. How old are you?
   Under 18☐ 18-24☐ 25-29☐ 30-35☐ 36-42☐ 43-49☐ 50-54☐
   55-59☐ 60-64☐ 65-69☐ 70+☐

4. How tall are you?
   <150cm ☐ 151-165cm ☐ 166-180cm ☐ 181-195cm ☐ 196-210cm ☐
   >211cm ☐

5. How much do you weigh?
   <50kg ☐ 51-60kg ☐ 61-70kg ☐ 71-80kg ☐ 81-90kg ☐
   91-100kg ☐ >101kg ☐

6. Which of the following describes your ethnic origins?
   African/Caribbean☐ Asian☐ UK☐ European☐
   Other (Please describe)☐_______________

7. Which of the following describes your employment status?

Senior management☐ Middle management☐
Other professional (please specify)☐______________
Other non-manuel (please specify)☐______________
skilled manual☐ Other manual☐ Student☐ Unemployed☐
Other (please describe)☐_____________________

8. What is your highest educational qualification?
No formal qualifications☐ High schol or equivelent☐
Undergraduate☐Graduate☐ Doctoral☐
Vocational qualifications☐

9. If currently a post-secondary student what year of your programme are you in?
1 ☐ 2 ☐ 3 ☐ 4 ☐ 5+ ☐

10. Other than rowing what sports do you participate in?
Team games (please specify)☐
_____________________________________________
Racket games (please specify)☐
_____________________________________________
Swimming☐ Athletics/running☐ Cycling☐
Aerobics/dance☐Weight training/keep fit☐ Equestrian☐
Other water sports (please specify)☐
_________________________________________
Other sports (please specify)☐
______________________________________________

**Section B: About Your Rowing**

11. In which of the following rowing events are you currently/were competing/training in?
Sweep☐ Scull☐ Both☐

12. If you sweep, is this most commonly in:
N/A ☐ a eight☐ a four ☐ a pair☐

13. If you sweep, what side do you row on?
N/A ☐ port (left)☐ starbord (right)☐ alternate ☐

14. If you scull, is this most commonly in:
N/A ☐ a four ☐ a pair☐ single☐

15. How long have you been actively involved in rowing?
<1 year☐ 1-2 years☐ 3-5 years☐ 6-10 years☐
10+years☐

16. How often do/did you train on the water per week?
less than once☐ 1-2 times☐ 3-5 times☐
6+times☐

17. How often do/did you train off the water per week?
less than once☐ 1-2 times☐ 3-5 times☐
6+times☐

18. What sort of training do/did you do off the water?
running☐ circuits☐ weights☐ rowing ergometer☐ cycling☐
aerobics☐ rowing tank☐ other (please specify)☐

## Section C: General Injury History

19. How many sports injuries have you sustained through your participation in rowing?
0☐ 1-3☐ 4-7☐ 8-11☐ 11+☐

20. Which body parts have you injured through participation in rowing?
Back☐ Neck☐ Shoulders☐ Wrist/forearm☐
Hands☐
Other arm injury☐ Groin☐ Shins☐ Knees☐
Thighs☐ Ankles☐ Feet☐ Other leg injury ☐
Head☐ Abdominals☐
Other injury (please describe)☐
__________________________________________

21. What types of injuries have you sustained (please indicate the number in each category)?

| | 0 | 1-3 | 4-7 | 8-10 | 11+ |
|---|---|---|---|---|---|
| Muscular soreness | ☐ | ☐ | ☐ | ☐ | ☐ |
| Strains/sprains | ☐ | ☐ | ☐ | ☐ | ☐ |
| Fractures (minor) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Breaks (Severe) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Other | ☐ | ☐ | ☐ | ☐ | ☐ |

If other, please explain

______________________________________________

22. What were you doing at the time of your most severe injury due to your involvement in rowing?

Sweeping (racing) ☐ Sweeping (training) ☐ Sculling (racing) ☐
Sculling (training) ☐ Using an erg ☐ Running ☐
Circuits ☐ Weights ☐ Cycling ☐ Aerobics ☐
Other (please specify) ☐

______________________________________________

23. When your injury how fatigued were you?

| Area of injury | 1 (least) | 2 | 3 | 4 | 5 (most) |
|---|---|---|---|---|---|
| Back | ☐ | ☐ | ☐ | ☐ | ☐ |
| Neck | ☐ | ☐ | ☐ | ☐ | ☐ |
| Shoulders | ☐ | ☐ | ☐ | ☐ | ☐ |
| Wrist/forearm | ☐ | ☐ | ☐ | ☐ | ☐ |
| Hands | ☐ | ☐ | ☐ | ☐ | ☐ |
| Other Arm Injury | ☐ | ☐ | ☐ | ☐ | ☐ |
| Groin | ☐ | ☐ | ☐ | ☐ | ☐ |
| Shins/Calves | ☐ | ☐ | ☐ | ☐ | ☐ |
| Knees | ☐ | ☐ | ☐ | ☐ | ☐ |
| Thighs | ☐ | ☐ | ☐ | ☐ | ☐ |
| Ankle | ☐ | ☐ | ☐ | ☐ | ☐ |
| Other Leg Injury | ☐ | ☐ | ☐ | ☐ | ☐ |
| Head | ☐ | ☐ | ☐ | ☐ | ☐ |
| Abdominals | ☐ | ☐ | ☐ | ☐ | ☐ |
| Other Injury | ☐ | ☐ | ☐ | ☐ | ☐ |

24. Which of the following have you omitted from you traing due to injury?

Sweeping ☐ Sculling ☐ Use of an Erg ☐
Running ☐ Circuits ☐ Weights ☐
Cycling ☐ Aerobics ☐ None ☐
Other (please specify) ☐

______________________________________________

25. If applicable, how long did your most severe injury prevent you from rowing?

N/A☐ <1 week☐ 1-2 weeks☐ 2-4 weeks☐ 1-2 months☐ 2-6 months☐ 6-12 months☐ >1 year☐

26. How long did your most severe injury affect your normal training regime?
N/A☐ <1 week☐ 1-2 weeks☐ 2-4 weeks☐ 1-2 months☐ 2-6 months☐ 6-12 months☐ >1 year☐

27. From whom do you normally seek professional help with your injuries?
None sought ☐ Doctor ☐ Physiotherapist ☐
Chiropractor ☐ Coach ☐ Osteopath ☐
Aromatherapist ☐ Masseur ☐ Chinese medicine ☐
Student Athletic therapist ☐ Athletic Therapist ☐
Other (please specify) ☐
________________________________________________

28. From whom did you seek professional help with for your most severe injury?
None sought ☐ Doctor ☐ Physiotherapist ☐
Chiropractor ☐ Coach ☐ Osteopath ☐
Aromatherapist ☐ Masseur ☐ Chinese medicine ☐
Student Athletic therapist ☐ Athletic therapist ☐
Other (please specify) ☐
________________________________________________

29. Please indicate which of the following your most severe injury required:
N/A☐ physiotherapy☐ surgery☐ pain-killer consumption (prescribed)☐ over the counter pain-killers (ie: Advil)☐ chiropractic☐ massage☐other (please specify)☐
________________________________________________

30. Did you follow any prescribed advice/rehabilitation programme?
None given ☐
Yes in full (please describe) ☐
____________________________________________
Yes, in part (please describe) ☐
___________________________________________
Yes, until I could return to training (please describe) ☐
__________________________
No (please give details) ☐
_______________________________________________

## Section D: Description of Rowing Related Pain

31. How normal is it for you to feel pain on a weekly basis (scale form 1-5)?
1(None) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Constant) ☐

32. How much pain do you experience on a weekly basis (scale from 1-5)?
1(None) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Severe) ☐

33. How would you classify your pain?
Sharp ☐ Dull ☐ Burning ☐ Tingling ☐
Other (please specify) ☐
______________________________________________

34. Do you commonly experience pain or discomfort in your low back? ( yes or no)
yes☐ no☐

35. If yes, how long has this pain or discomfort persisted?
N/A☐ 0-2 weeks☐ 2-4 weeks☐ 1-3 months☐ 3-6 months☐ 6-12 months☐ >1 year ☐

36. How often do you have pain or discomfort in your low back per week (scale from 1-5)?
1(None) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Constant) ☐

37. How much low back pain do you experience on a weekly basis (scale from 1-5)?
1(None) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Severe) ☐

38. Where is the low back pain primarily located?
None ☐ Left ☐ Right ☐ Centered ☐ All ☐

39. Do you consider your low back pain to be chronic or acute?
N/A ☐ Chronic (>3 months) ☐ Acute(<3months) ☐

40. If applicable how long did a low back injury prevent you from rowing?
N/A☐ <1 week☐ 1-2 weeks☐ 2-4 weeks☐ 1-2 months☐ 2-6 months☐ 6-12 months☐ >1 year☐

41. How long has a low back injury affected your normal training regime?
N/A☐ <1 week☐ 1-2 weeks☐ 2-4 weeks☐ 1-2 months☐ 2-6 months☐ 6-12 months☐ >1 year☐

42. What treatment options have you explored for any low back injury?

N/A☐ physiotherapy☐ surgery☐ pain-killer consumption (prescribed)☐ over the counter pain-killers (ie: Advil)☐ chiropractic☐ massage☐other (please specify)☐

43. Do you consider participating in rowing/sculling to be a risk to your body and/or your health?
    Yes☐ No☐ Prefer not to say ☐

44. If yes, to what degree:
    N/A ☐ Extreme risk☐ High risk☐ Some risk☐ Slight risk☐ Minimal risk☐

45. If yes, do you believe the benefits of participation outweigh the risks?
    N/A ☐ Yes☐ No☐

46. Have you ever willingly trained or competed whilst injured?
    N/A ☐ Yes ☐ No ☐

47. If yes, do you ever think about the risks of causing a more serious injury?
    N/A ☐ Yes ☐ No ☐ Sometimes ☐

**Appendix D: Informed Consent Form**

# Informed Consent Form

**Date:** June 2020
**Project Title:** The Effect of Rowing Style on The Occurrence of Low Back Pain in Elite and Novice Rowers

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**INVITATION**

You are invited to participate in a research study assessing the effect of rowing style (sweep or scull) as well as rowing experience, training load, and sex on the occurrence of low back pain. During this study you will complete a survey that will discuss your rowing history any well as any injuries you sustained throughout your career with and emphasis on low back pain (LBP).

**PURPOSE OF THE STUDY**

To assess the effect of rowing style (sweep or scull) as well as rowing experience, training load, and sex on the occurrence of low back pain and other sports injuries.

**WHAT'S INVOLVED**

If you volunteer to participate in this study, you will be asked to complete a short internet-based survey using a computer or mobile device. This survey will take approximately 15-20 minutes to complete.

To be eligible for this study, you must:

- Be between 18 (17 if a Brock student) and 65 years old
- Have been an occasional rowing athlete for at least 1 year of training and/or competition

**POTENTIAL RISKS AND DISCOMFORTS**

There are no known risks associated with participating in this study.
If you are uncomfortable answering any questions on the survey, you are free to skip them.

**POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY**

The data collected from the study has no direct benefit to you as a participant aside form using the time to reflect on current or previous rowing-related injuries. However, you will provide information that will create a need for more studies addressing rowing kinematics and assessing LBP in rowing athletes. More broadly, the findings from this study may allow for people in the rowing community to be more aware of potential risk as it relates to an athletes rowing style (sweep or scull) as well as rowing experience, training load, and sex and this could result in more time and effort put into both prevention and treatment of LBP in rowing athletes.

**CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. You will be given the opportunity to include your contact information for future in-person rowing related research; however, this is completely voluntary. Any information that may identify a participant will be kept confidential. The data will be stored on the investigator's password-protected computer and cloud-based backup server. Only the investigators of this study will have access to the data. All data will be kept for five years following the publication of the study, after which time the data will be destroyed.

**ABOUT QUALTRICS**

This survey is being conducted using Qualtrics Survey Software. Qualtrics is an enterprise survey technology solution that has been providing online services for over five years. Qualtrics retains survey information but does not have access to the data. Therefore, there is no way to match responses with personal identifiers. Qualtrics does hold all survey responses in their data centers. Their data centers utilize many security measures. Qualtrics' database access is restricted and requires authorization (i.e., password protected and accessible only to the researchers). All computer equipment (servers, SANs, switches, routers, etc.) is redundant and is in secure, environmentally controlled data centers with 24/7 monitoring. All information is secured via industry standard firewalls and stringent IT security policies and procedures. They utilize industry standard web application firewalls and DDOS protection. Qualtrics also uses panel partners who use multiple levels of security that include: redundant data centers, secure servers, encryption which includes one-way encryption, numeric IDs, secure .NET platforms, security clearance, industry standard firewalls, 24/7 monitoring of data centers, confidentiality agreements, and physical, electronic, and managerial procedures. Data will be downloaded from Qualtrics (password protected) and stored on a password protected computer to which only the research team has access.

**PARTRICPATION AND WITHDRAWL**

By submitting your responses at the end of the survey, you are implying that you consent to participate in this study. You have the right to withdraw from the survey at any time before you submit your responses, by simply closing your web browser. Any responses you had previously entered will not be recorded. You can also skip and questions you don't want to answer and remain in the study. Once you submit your responses, withdrawal will not be possible because the data will be anonymous. It will not be possible to identify your responses and remove them from the database. The investigator may withdraw you from this research if partial or incomplete data is submitted.

**SECONDARY DATA USES**

The data collected may be used in subsequent studies, publications, and presentations.

**FEEDBACK TO PARTICIPANTS**

If you wish to be informed on the results of this study please contact Alex Johnston via email at aj14pg@brocku.ca. A summary of results will be provided approximately 3 months following data collection.

**FUTURE RESEARCH**

If you are interested in future rowing-related research studies, occurring within the Niagara Region, please leave your name and contact information at the end of the survey. Please note that this is completely voluntary.

I have read and agreed to the above conditions and consent to participate in this research. By clicking yes, you agree to participate in the study and acknowledge that you are eligible to participate based on the above criteria.

**Yes☐** **No☐**